

Glucose Measuring Device with Advanced Data Processing and Improved Strip Detection

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Abstract—People suffering from diabetes mellitus are dependent on exact blood glucose concentration information. This information is vital for their successful treatment and protection against life threatening extremely low or high blood sugar levels. Solution described in this paper integrates blood glucose evaluation and treatment recommendation, where all the information like body sensitivity to insulin and carbohydrate to insulin ratio is used to calculate recommended amount of next insulin dosage or food. This solution also supports strip with damaged insertion signal line. Device prototype had been developed and successfully tested on three subjects with diabetes I and two with diabetes II.

Index Terms—Data processing, embedded system, glucose, insulin.

I. INTRODUCTION

Lots of people suffering from diabetes mellitus [[1]], disease causing wrong blood sugar level regulation is using devices for measuring blood glucose concentration. This information is vital for them and for their paediatricians. Based on the information of blood glucose provided by glucose measuring device user suffering from diabetes mellitus can improve his blood sugar concentration level and thus improve his quality of live, getting closer to the quality of healthy people life.

II. PROBLEM DESCRIPTION

There is a big number of commercially available devices [[2]] for blood glucose measurement but none of them providing the way to offer blood glucose trend analysis and provide recommendation without the need of additional computer processing and complex program understanding from user's side. User with diabetes mellitus usually needs the information from the device itself in the moment because an instant action can prevent further complication with hyper or hypo glucose. Simply put there is no time to connect glucose measuring device to the computer that has to have special software installed, download and analyze data. There are continuous blood sugar measuring sensors that provide information about glucose trend development

but these sensors are mainly available for diabetics with the first type of diabetes mellitus on the other hand all types of diabetics often at least have glucometer (glucose measuring device). Another disadvantage of commercially available devices is measuring strip insertion failure which is fixed in this purposed solution.

III. ADVANCED DATA PROCESSING GLUCOSE MONITORING SYSTEM PROPOSAL

Proposed solution includes own glucometer hardware design (*Glucose Meter Hardware Design and Implementation*), realization and analysis software implementation. Whole solution provides all information necessary for the user to successfully compensate his blood sugar level. Information provided by this solution consists of:

- 1) *Current blood glucose level concentration;*
- 2) *Current blood glucose trend based on two measuring's distant maximally 4hours from each other;*
- 3) *Average values for last 60 and 14 days;*
- 4) *Device construction provides further information for analysis, these are:*
 - a) *waveform of current blood glucose measuring,*
 - b) *waveform of last 15 blood glucose measurements,*
 - c) *selectable hardware low pass filter.*
- 5) *Another feature of this device includes damaged strip insertion detection by transition analysis (Chapter: Damaged glucose strip sensor insertion detection)*

Proposed solution is represented by the own glucometer construction and software implementation. Both of these parts will be described in following chapters.

IV. GLUCOSE METER HARDWARE DESIGN AND IMPLEMENTATION

Glucose meter hardware design function block diagram can be seen in Fig. 1. Device consist of two boards first board the "*mainboard*" contains all the necessary electronic parts for signal amplification filtration and digitalization. Second "*extension board*" provides user interface parts like buttons LCD screen and also extension components for mainboard like external EEPROM memory and RS232 level converter for PC communication support. Mainboard can operate without the extension board with limited functionality providing only blood glucose measurement and value storage in an internal EEPROM memory.

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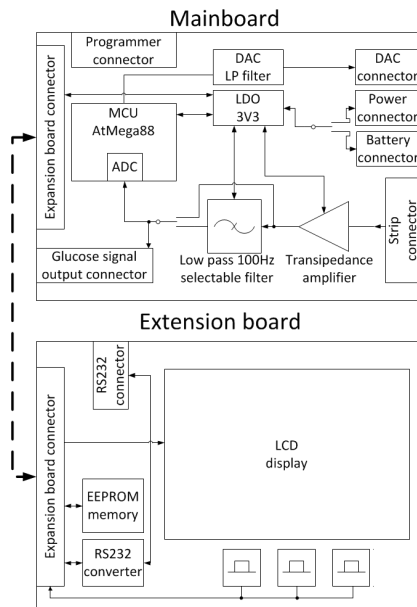


Fig. 1. Glucose meter main and expansion board function block diagram.

A. Mainboard

The mainboard consist from the input connector for the glucose measuring electrodes and uses amperometric measuring method. It measures the current between two electrodes on an external measuring strip where an electrolytic reaction start due to blood sample application. Detail chemical reaction description can be found in [3]. Oxygen diffusing through semipermeable membrane and voltage -400mV is applied to the Pt electrode reducing O_2 to H_2 . Between two strip electrodes CE and RE the buffered voltage of -400mV is applied from the buffered voltage source IC2A (Fig. 2). Current generated by this sensor needs to be amplified and converted to the voltage that can be measured and sampled by an analog to digital converter (ADC hereinafter) this is performed by the transimpedance amplifier IC5B (Fig. 2). Current to voltage equation is given by basic operation amplifier properties and it is defined by the feedback resistor value.

From here the signal goes to active low pass filter 2nd order Sallen-Key topology IC5A (Fig. 2) which is selectable by jumper connector JP2 (Fig. 2). Next signal is sampled and digitalized by the 10-bit ADC built-in the microcontroller unit (MCU hereinafter) AtMega88.

Whole design is powered either by an external power source or battery power source, resulting in 3.3V on the output of low dropout regulator LE33CZ. This symmetrical voltage needs to be further changed in order to achieve negative voltage of -400mV for glucose sensor. Therefore an IC2B (Fig. 2) is used to create virtual ground on the half of the power supply 3.3V which equals to 1.65V . In order to achieve -400mV between strip electrodes the buffered power source IC2A must had been set to 1.25V .

MCU AtMega88's built-in ADC is used to digitalize and store glucose data. This MCU is also used to communicate with computer via RS232 on an expansion board and to interact with user via expansion board's user interface. This MCU also contain algorithm for glucose calculation, trend analysis with user treatment recommendation and damaged glucose strip sensor insertion detection algorithm based on

transient phenomenon of strip voltage difference between strip insertion and blood sample application.

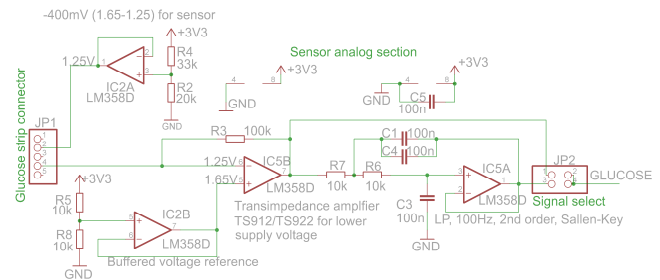


Fig. 2. Mainboard analog section schematic.

B. Expansion board

Expansion board's main purpose is to provide user interface with its LCD display and four push buttons. This expansion board is connected to the main board via an expansion board pinhead connector (Fig. 4). This board also contains Atmel 24C16 – 16kB EEPROM memory for blood glucose results storage and MAXIM MAX232 level converter RS232 communication support with the computer.

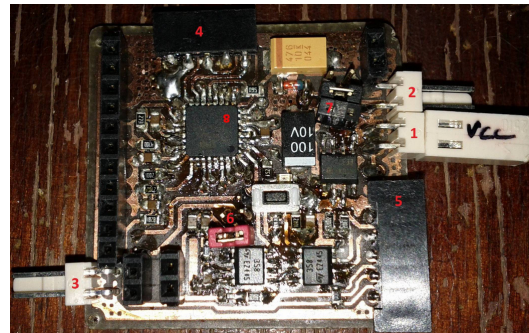


Fig. 3. Mainboard prototype.

C. Hardware implementation

Circuitry was implemented on two dual layer printed circuit boards connected via pinhead connector connecting power supply and data lines between main (Fig. 3) and expansion board (Fig. 4).

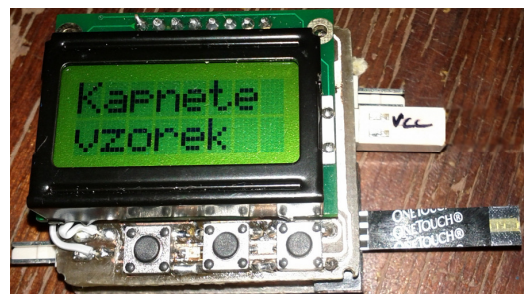


Fig. 4. Extension board connected on mainboard – prototype.

D. Glucose meter software implementation

Biggest part of the signal processing and data storage is done in 8-bit MCU AtMega88. Blood glucose concentration represented by voltage converted from sensors current by transimpedance amplifier is sampled by internal 10-bit ADC. Blood glucose concentration is computed from sensor voltage measured after exactly two seconds from the beginning of measurement. This voltage is used to calculate

blood glucose concentration in the mmol/L units by the equation (1). Software implementation is also visible on UML activity diagram displayed on Fig. 5

$$C = \left\{ \left[\left(0.003226 \text{ ADC}_{\text{SAMPLE}} \right) - 1.65 \right] \times 922.23 - 107 \right\} \times 0.0522. \quad (1)$$

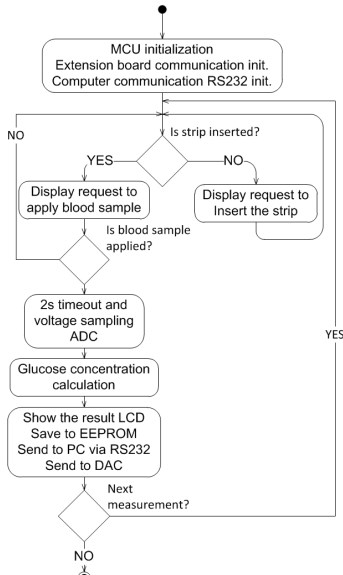


Fig. 5. Software UML activity diagram.

E. Damaged glucose strip sensor insertion detection

Some of the strips insertion indicators (Fig. 6) which are on the sensors are damaged by the users themselves or are already damaged before use. Cost of the one strip is around 0.5€ and with the average consumption of 3–4 strips a day the cost is raising rapidly. Current commercial glucometers don't deal with this issue event though the solution is quite simple. The detection algorithm is based on a voltage transient phenomenon where the difference between strip insertion and blood sample application is in the slope of the voltage curve (rate of voltage change – voltage derivative in time).



Fig. 6. Glucose electrode – strip.

Voltage derivative in time value is significantly lower when user is applying the blood sample then when the strip is being inserted. When the insertion indicator is not corrupted the derivative is very high as the transition is a fast peak. When the insertion indicator is damaged there is no information about the strip insertion but the MCU is still monitoring the change on the input and when the blood sample is applied and specific ((2), (3)) voltage derivative in time for 100ms is found blood glucose concentration is calculated by equation (1) in 1.9 seconds.

Constants in (1) are given by empirical measurements and tests, where 1.65 is $\frac{1}{2}$ of U_{CC} and 0.0522 is a conversion constant between mg/dl to mmol/l units as the original equation has been developed for mg/dl units. Other constants are given by empirical testing and series of measurements expressing approximation constants for sensor and 10-bit

analog to digital converter:

$$\frac{du}{dt} > K, \quad (2)$$

$$\frac{du}{dt} > A \text{ and } \frac{du}{dt} < B. \quad (3)$$

$K = 15$, $A = 1$, $B = 15$ for sampling frequency 62.5kHz (Fig. 7).

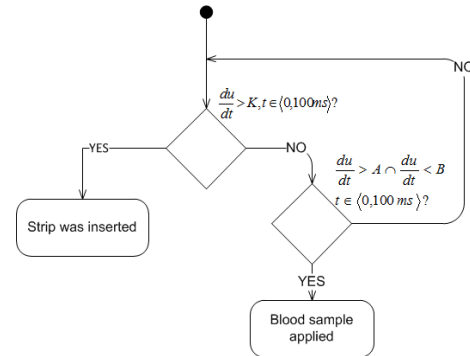


Fig. 7. Transient phenomenon strip detection UML activity diagram.

V. GLUCOSE TREND CALCULATIONS AND TREATMENT RECOMMENDATIONS

Glucose trend calculations and treatment recommendations are based on following information:

- 1) Measurements not older than 4 hours from the previous one;
- 2) Insulin type used by user (if any);
- 3) Carbon hydrate to insulin ratio [[4]];
- 4) Insulin/treatment sensitivity [[4]];
- 5) Next meal carbohydrates (in grams).

Measurements older than 4 hours are not valid due to insulin effect curve [[3]] for any kind of insulin and behind this time artificial insulin effect is very weak and cannot be used in a calculation. Insulin type is vital to select for its different effect during time. Carbon hydrate to insulin ration is another vital information for the recommendation algorithm, it expresses how many carbohydrates is covered by one unit of insulin (IU) = 45.5 micro-gram of pure crystalline insulin [[4]].

Last vital information is an insulin sensitivity that expresses how much is the blood glucose covered by one insulin unit. Based on all of this information the recommendation of treatment is calculated according to (4 and 5). This algorithm was implemented into designed device and extends all known implemented algorithms by estimated purposed insulin dosage amount based on all provided information especially known insulin efficiency. This formula was created based on a series of empirical testing's and theory described in [5], [[6]]. It is not a topic of this article to describe medical glucose prediction oriented algorithm. Following formulas were derived by the authors of this article

$$P_{IU}(t) = \frac{P_F}{RR_{IS} E_I} e^{\frac{dG_C}{dt}} - P_{IUOFF}(t) \quad (4)$$

and

$$P_{IUOFF}(t) = \left((G_{CLAST} - (TG_{MAX} - TG_{MIN})) (R_{IS}(t)) \right) e^{\frac{dG_C}{dt}}, \quad (5)$$

where $R_{CHR}(t)$ – carbon-hydrate ratio [g/IU]; $R_{IS}(t)$ – insulin sensitivity [IU/(mmol/L)]; RR_{IS} – overall insulin sensitivity ratio; E_I – insulin efficiency ratio – dependent on insulin type; dG_C/dt – glucose change rate in time; G_{CLAST} – last glucose concentration [mmol/L]; TG_{MIN} – target glucose minimum [mmol/L]; TG_{MAX} – target glucose maximum [mmol/L]; P_F – planned food carbohydrate units [g]; P_{IU} – proposed insulin units [IU].

VI. MEASUREMENTS AND TESTS

Device (Fig. 8) had been tested with 7 commercially used strips and 6 types of prepared glucose solutions. Average values of these measurements and standard deviations expressing deviations in all measurements are displayed in table (TABLE I). Every measurement was repeated 3 times which gives total number of 126 measurements. Average value and standard deviation of glucose concentration was calculated from 21 tests for every glucose level.

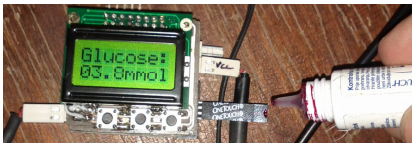


Fig. 8. Device testing with prepared glucose solutions.

TABLE I. TABLE OF GLUCOMETER TESTS.

Lab prepared glucose concentration [mmol/L]	Average of measured values [mmol/L]	Damaged strip / Correctly detected (Deviation σ)	Standard deviation σ [mmol/l]
4	3.978	Yes / Yes (0)	0.126
8	8.093	Yes / Yes (0)	0.291
12	12.15	No / Yes (0)	0.322
15	14.735	No / Yes (0)	0.381
20	21.092	Yes / Yes (0)	0.982
40 (Hi)	42.064	No / Yes (0)	0.898

Data sent to PC and can be seen in the Fig. 9.

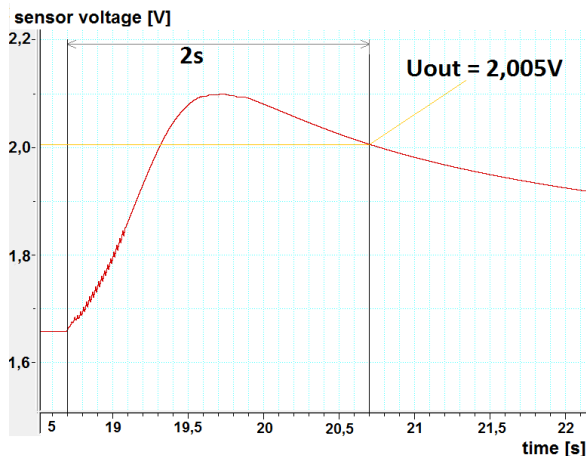


Fig. 9. Glucose data send and vizualized on PC.

VII. CONCLUSIONS

Glucometer device detection algorithm with damaged strips was working in all tested cases, glucose levels were in the maximum of standard deviation in all of its tests in 0.982mmol/l in the tested glucose solution of 20mmol/L. These results show the successful hardware and software implementation for both the damaged strip insertion detection and glucose level calculation.

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