Development of an Active Sensor for non-Invasive Arterial Blood Pressure Monitoring

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***Abstract*—The paper presents the latest results of developing a new method of noninvasive continuous blood pressure monitoring. This method is based on the principle of pulse wave compensation. It is shown that sensors for such a measurement should be not only smart, but also active. In this connection, the concept of smart sensors is expanded to the concept of active sensors. The technical design of the active sensor for noninvasive pressure measurement is described. The results of active sensor calibration and testing are under discussion. The main section of the report is devoted to the development of software for active sensor control - its intellectual stuffing. We describe and justify a new principle of active measurement of quasi-periodic processes - pulse wave compensation based on prediction patterns. The progress achieved in research and the ways for further investigation is outlined in the conclusion.**

Keywords- smart and active sensors; compensation method of measuring; noninvasive arterial blood pressure monitoring.

I. INTRODUCTION

The progress in information technology involves accelerating development and deployment of fundamentally new medical technologies of patients' evaluation, as well as a substantial revision of the classical ones. A central problem here is the development of informative, efficient and reliable methods for measuring and processing medical and biological data of the patient.

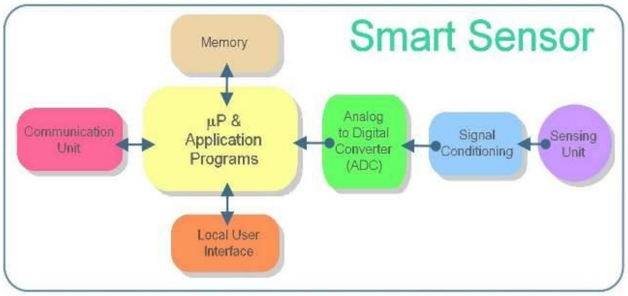

Figure 1. The principal components architecture of smart sensors [1].

One of the main trends in solving this problem, as well as in the broader field in the development of industrial control and monitoring systems is a full implementation of smart sensors, whose main task is maximizing automation of measurement and minimizing the role of man in this process [1]. An important feature of a hardware implementation of smart sensors is the use of microprocessors (µP) and as a rule the use of wireless communication units (CU), see Figure 1.

Our initial goal was to provide the features of a smart sensor for a popular medical device – arterial blood pressure (ABP) monitor. But it turned out, that the use of powerful computational tools, embedded in such a device (i.e., modern microcontrollers), can produce much better results than in the case of a standard digital tonometer. The reason for it is not in the nature of the measurement itself - continuous or single-sampled – it lies in the nature of the value measured. It is known that all the non-invasive measuring devices measure not the pressure itself, but some value associated with it (the volume of the blood vessel, its wall displacement, the force with which the wall acts on the sensor unit, etc.) [2]. Using *compensation method*, we succeeded in measuring the ABP in absolute units i.t., in mmHg. However, to measure the pressure by the method put forward we had to go even one-step further to introduce a feedback loop, depending on observed data sensor control. As a result, the idea of an active sensor was created, whose engineering expands the design of smart sensors as shown in Figure 2.

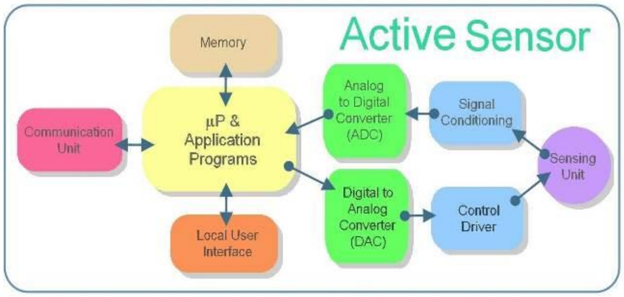

Figure 2. The principal components architecture of active sensors.

In this paper we present the latest results of research and development concerning the active sensor for non-invasive arterial blood pressure monitoring. After a short overview in Section 2 of existing non-invasive methods and after a short discussion in Section 3 of compensation based ABP monitoring principal, in Section 4 we describe in detail the structure and design of the sensor developed. In Section 5 we report the results obtained in real experiments with active blood pressure monitoring and in Section 6 we schedule ways to overcome the shortcomings associated with the incomplete compensation of time–varying blood pressure caused by a simplified structure of the PID (proportional–integral–derivative) feedback controller. Finally, the Conclusion briefly summarizes the problems discussed in the article.

II. CURRENT ABP MONITORING APPROACHES

Jan Peňáz was among the first to put forward a method of continuous non-invasive blood pressure monitoring [3]. His method described in 1973 was aimed at reducing the risks of arterial cauterization. The Peňáz method employed the idea of “vascular unloading”, based on the assumption that in the “unloaded state” the pressure inside the blood vessel is equal to the outside pressure.

The basic element of the device proposed by Peňáz is a small finger cuff (Figure 3 (A)) that has an infra-red (IR) light source on one side and a light receiver on the opposite side. The blood volume of the finger is estimated via the absorbance of IR light. The signal obtained by such a plethysmograph is further used in a feedback loop to control the pressure in the cuff. The pressure is controlled in such a way that blood volume in the finger is kept constant in time and equal to the volume which corresponds to the unloaded vessels state defined during the calibration process. In this case the oscillations of the controlling pressure are approximately equal to pressure in the arteries. Later some formulae were proposed for recalculating pressure from finger vessels to brachial arteries, which made it possible to verify the method with respect to classical procedures.

Figure 3. Modern approaches to ABP monitoring systems .

Another technique which provides continuous non-invasive blood pressure monitoring is arterial tonometry [4]. Like the Peňáz method arterial tonometry is based on pulse oscillation estimates, but here the principal of arterial unloading is different. In this case the cuff is placed on the wrist, so the sensor is over the radial artery (Figure 3 (B)). The sensor presses the artery to the radial bone until it is flattened enough but not occluded. At this intermediate position arterial wall tension becomes parallel to the tonometer sensing surface and arterial pressure is then the remaining stress (perpendicular to the surface) measured by the sensor. The pressure needed to flatten but not occlude the artery is known as the “proper hold-down pressure” and is calculated by a complicated algorithm which includes the preliminary estimate of systolic, diastolic and pulse pressures over a range of “hold-down pressures”.

Currently the devices employing these methods include in particular the CNAP^{TM} (Peñáz’s approach, Figure 3, left) and T-line from Tensys Medical (arterial tonometry approach, Figure 3, right).

The methods of continuous non-invasive blood pressure monitoring have both advantages and disadvantages [5]. We believe that the main drawback of these non-invasive methods is the following: irrespective of the method of vascular unloading the control of the unloading is exercised on the basis of integral parameters (blood vessels filling, overall sensor force, sensor displacement, etc.). It enables monitoring an average pulse wave of ABP but does not guarantee the details of the pulse form. We proposed a new method of arterial blood pressure monitoring that is aimed at local unloading of arterial walls by compensating local pressure.

III. COMPENSATION BASED APPROACH TO ABP MONITORING

When analyzing well–known methods of non–invasive continuous measurement of blood pressure, we can conclude that the best results of monitoring non–stationary dynamics of blood pressure are achieved by the so–called compensation methods or methods similar to them.

Compensation methods are applied for measurement of various physical quantities and are based on the compensation of an unknown measured value by controlled counter value and nullification of their difference. The simplest example of the compensation method is the use of balance scales on which unknown mass W_u is measured using a set of weights W_v, Figure 4 (A). The predetermined position of the balance beam or the associated arrow serves as a null indicator of the balance scales.

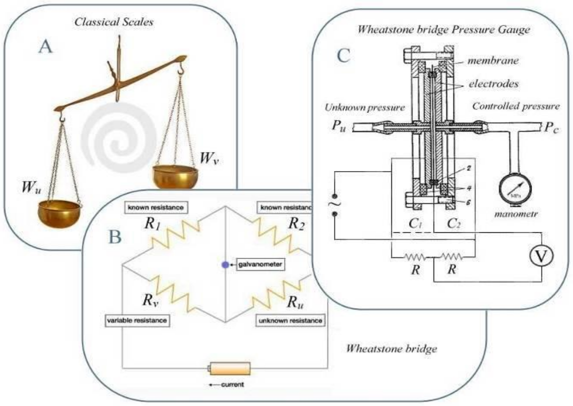

Figure 4. Measurement of physical quantities by compensation methods.

Compensation methods as methods of high precision are used for mechanical and electrical measurements, in embodiments having a bridge and half-bridge circuits, Figure 4 (B, C). Note that compensation methods are usually used to measure the static variables – constant unknown resistance R_u in bridge circuit on Figure 4 (B) and the steady pressure P_u in aggressive environment on Figure 4 (C) .

We consider the compensation method as the fundamental basis to measure the varying blood pressure. The application of this method for measuring the non–static dynamic quantity has become possible, for two reasons. Firstly, the fact that blood pressure changes are not so fast, its rhythm is of the order of one beat per second, and its spectrum fits into the range of a few tens of Hz. Secondly, there are relatively cheap, high performance microcontrollers available for which a change in pressure is quasi-static.

IV. THE STRUCTURE AND DESIGN OF THE SENSOR

As noted above, our method of measuring ABP is aimed at local, without cuffs, unloading of arterial walls by means of compensating intra–arterial pressure by controlled pressure. Our method of measurement is similar to the method of bridge measurement of unknown pressure P_u in Figure 4 (C), but it has dynamic, “adaptive” features as in the Peňáz method [3]. The appearance of the device developed for continuous ABP monitoring and its typical use for measuring intra–arterial pressure is presented in Figure 5.

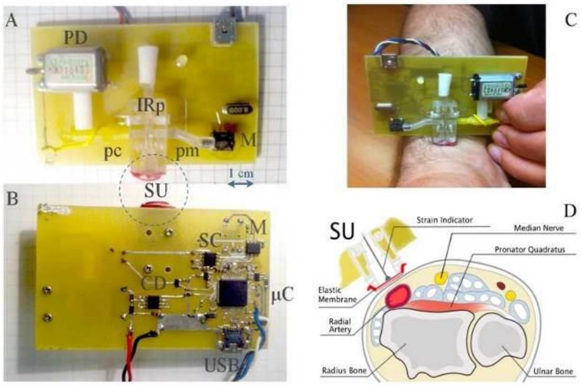

Figure 5. Active sensor for continuous blood pressure monitoring and its typical arangement on the patient’s wrist.

Note that the device developed (Figure 5(A,B)) conforms exactly to the concept of an active sensor (see Introduction, Figure 2). The main role here is played by the programmable microcontroller μC (STM32L152RBT), that has the communication I/O (USB) on one side, and on the other side it has *pm* (pressure monitor – signal line) and *pc* (pressure control – control line) interfaces to the measuring element SU (sensor unit). The signal line *pm* contains membrane displacement indicator SC (signal conditioning) and pressure gauge with instrument amplifier M, the control line *pc* includes the pump PD and the chip for pump control CD (control driver). Both lines – *pm* and *pc* – are tubes coming from the fluid-filled cavity of the measuring element SU. SU is a camera with an aperture covered by an elastic membrane (of red color in Figure 4(D)) and containing a thin rod with one end attached to the membrane, the other end partially overlaps IR-radiation flux inside optoelectronic infrared pair IRp. Thus, this rod gives us a way to measure the membrane deformation as it serves as an indicator of displacement.

When the pressure in the SU chamber and directly behind the membrane are different, the membrane will be deformed in one or the other direction by moving the rod in the direction of deformation. This movement will bring about a change in the area of IRp flux, which is registered by displacement indicator SC. If the controlling pressure in the SU returns the membrane to flat, not deformed state, we can conclude that pressures on both sides of the membrane are equal, thus external pressure will be measured. If SU is arranged above the radial artery, as shown in Fig. 5(C,D), then, assuming that at certain SU position the external pressure is equal to ABP, we will measure its value. This is precisely the key concept, underlying our compensation measurement technique.

V. EXPERIMENTS WITH THE SENSOR DEVELOPED

The above qualitative description of the sensor can be illustrated by quantitative results obtained in the device calibration and testing. Figure 5(A) shows the deformation of the membrane displacement (in ADC units of SC indicator) in response to a uniform increase over time of the pressure P inside the SU at constant external atmospheric pressure. ΔP in Figure 5(A) is the pressure readings of M measured from atmospheric pressure, so ΔP is the pressure difference across the membrane. It can be seen from the graphs that for small (± 5 mmHg) difference in pressures on both sides of the membrane the signal of displacement indicator SC is linearly proportional to the pressure difference. Figure 5(B) shows the dynamics of the membrane displacement and the corresponding changes of pressure P within the SU when external pressure uniformly increases and control line *pc* is enabled for its compensating.

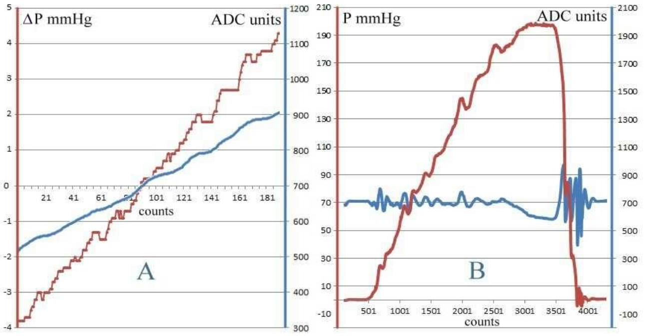

Figure 6. The dynamics of the SU membrane displacement (ADC units) in response to changes of the pressure difference inside and outside the SU.

The compensating pressure P in SU is produced by the pump when the PWM (pulse-width modulated) voltage, formed by CD chip, is applied to the PD.

Not specifying the details of the mechanism of formation, the resulting P may be thought of as proportional to the control signal, which the microcontroller sends to CD in response to the measured by SC membrane displacement (as well as its previously stored values). The algorithm of simple PID [6] controller was originally selected as feedback control algorithm.

On the basis of the calibration data numerous experiments on monitoring blood pressure were carried out. The results of one of the measurements are given in Figure 7. The lower part of the figure graph shows that the use of the PID control makes it possible to hold the membrane close to undistorted (flat) state for all the time of blood pressure measurement. The quality of such regulation can be estimated by the value of uncompensated difference in pressures equivalent (proportionate) to deviations of the membrane from the flat position (a kind of the membrane jitter). To illustrate the compensation, Figure 7 (top) shows a graph of pressure *P* inside the chamber SU (the data from pressure gauge M), as well as the same data corrected by the membrane jitter values.

It can be seen that in comparison with *P* uncompensated difference in pressures Δ*P* is not large. Figure 7 also shows that *P* coincides generally with the corrected blood pressure, but at times with the rapid change in the shape of the pulse wave, the controller fails to keep track of these changes.

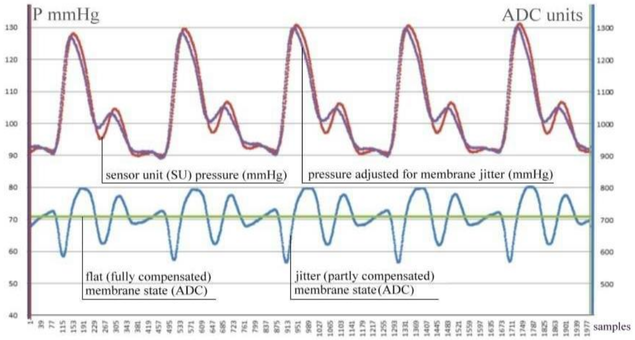

Figure 7. The dynamics of the SU membrane displacement (ADC units) while compensating the time-varying outside blood pressure.

The overall impression of the first results of monitoring blood pressure with the help of the above–described active sensor is ambivalent. On the one hand, the sensor does its task – it can be used not only to measure the main parameters of blood pressure – systolic and diastolic blood pressure (range of ABP), but also to observe the varying pulse wave, and not through indirect measurements but by measuring the pressure itself (in mmHg). On the other hand, as we could initially assume a simple PID controller does not provide full compensation, which leads to the distortion of the pulse wave components. Practically, the compensation algorithm based on PID control proved to be very difficult in changing its settings.

VI. Pulse Pressure Compensation Control on the Basis of Pulse Wave Patterns

These shortcomings associated with the incomplete compensation of time–varying blood pressure have a simple explanation.

Firstly, the PID controller used is the special case of linear regulators class and it is well known that linear methods for treating biological signals, especially, linear adaptation methods are used in limited ranges of their changes and only under strictly controlled (for example, laboratory) conditions. This is due to highly non-linear non–equilibrium nature of living systems [7]. Even a small change in physiological state can lead to considerable changes in the result.

Secondly, PID control takes into account only local characteristics of the signals, as it is customary in the theory of dynamic systems. In the case of dynamic systems, such a regulation is natural, as such systems are deterministic. However, living systems and their subsystems are known to be poorly described by models of dynamic systems, even if there is a freedom of choice of corresponding differential equations coefficients [7]. Living systems are much more consistent with models of stochastic, non–deterministic systems.

Thirdly, in solving technical problems low order of PID control is preferred due to its ease of implementation. When we deal with a complex biomedical signal, particularly, an ABP signal, low order of control is a drawback.

These facts indicate that the pulse wave of blood pressure is much more similar to a wideband pulse signal than the sum of harmonic components. In view of the foregoing it can be assumed that a random point process is a closer mathematical model of blood pressure pulsating. A point process is an increasing sequence of time moments (points) of certain homogeneous events, such as the arrival pulse wave, with a random length of time intervals between them. Excluding the changes in the pulse wave pattern, and treating them as a stream of homogenous sequence of events, it would be legitimate to use theoretical methods dealing with the problems associated with the heart rate.

One such well-developed theory today is the theory of radar signal processing. A major problem of this theory is determining the unknown arrival time of an electromagnetic pulse emitted by radar and reflected from a target. The method of matched filtering should be noted as one of the most effective methods for solving this problem. In this method the filter response is matched with the radar pulse, so that the maximum signal of the filter output is observed at time, when the reflected pulse arrives. Essentially, the matched filter generates a covariance of sent and received pulses, and it is well known that if both pulses have the same, up to a constant factor, shape, the maximum of the covariance will be achieved when they coincide. The corresponding displacement between pulses will estimate the time of arrival.

The principle of the matched filtering could be interpreted in a different way, more suitable for our tasks. Let’s assume at some moment, the time *T* between the ABP pulse wave is known along with the shape of the current pulse, further considering the shape of next pulse to be same as the current one, we can easily predict the future signal.

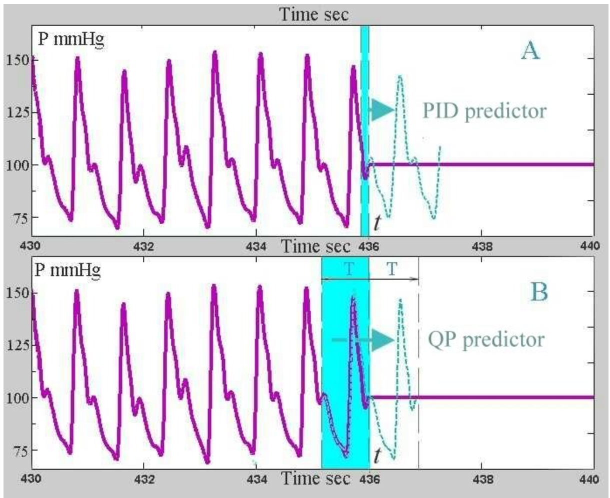

Figure 8. Two methods of predicting the pulse signal future: A - by PID regulation and B - based on the local quasi-period (QP) estimate.

For this purpose, we should take an existing fragment of the signal of duration *T*, immediately preceding the current time and move it to the time *T* into the future (see Fig.7). From the theory of the matched filter, it follows that the expected ABP pulse will coincide with the prediction. This idea is illustrated in Fig.7, which also shows a comparison of the proposed signal prediction with the prediction carried out by PID. As stated above, the PID controller makes a prediction on the basis of current, local estimates of the fundamental frequency, the amplitude of the main component and amplitudes of neighboring harmonics.

VII. CONCLUSION

Summing up the results of the investigation we can conclude that when we use compensatory ABP measurement it is the current pattern of the pulse wave which efficiently predicts the expected signal. This pattern must be dirigible enough to change significantly with changes in the state of the object measured as well as changes in the conditions of its active measurement.

For this reason, realized by the classic regulators including the PID controllers, patterns in the small parametric models of ABP waves are of little use for active blood pressure measurement. An idea of forming the adequate patterns in the task is given in the above qualitative reasoning. It is based on the property of quasi-periodicity of ABP signal.

This property lies in the fact that high variability of the period of heart contractions occurs only at long time intervals, whereas at short time intervals of several seconds or a few heart beats its changes are generally small and fall within a couple of percent.

Therefore, estimating the current period, more precisely the quasi-period *T*, we can get a pulse wave pattern as a signal fragment of *T* duration immediately preceding the current time moment. Thus, the task of building a pattern for current pulse of the signal is reduced to the task of effective evaluation of its current quasi-period.

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