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TRIGGERING OF AMBULATORY BLOOD PRESSURE MEASUREMENT BASED ON PATIENT STATUS

Software Architecture and Implementation

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ABSTRACT

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Blood pressure is an important physiological parameter that is used for both assessing immediate health status of hospitalized patients and providing indications of various cardiovascular diseases. Invasive blood pressure measurement has stayed as gold standard of blood pressure measurement while oscillometric measurement has established its position as the primary measurement method in hospital wards and home care. However, research around continuous non-invasive blood pressure measurement (CNIBP) methodologies have been growing, and blood pressure monitoring devices using CNIBP have developed recently. Applied CNIBP methods include, but are not limited to, pulse wave velocity and pulse wave analysis.

In this thesis, a prototype software system for detecting significant and sustained changes in a patient's blood pressure was designed and implemented. The system is based on pulse wave analysis based continuous blood pressure measurement algorithm. The goal was to either trigger a cuff-based measurement automatically or to prompt the user to take a new cuff measurement when needed. Characteristics of the applied CNIBP method set requirements for the system. CNIBP measurement is affected by the patient's posture as well as movement, and therefore, information about the activity of the patient was needed. Furthermore, the ambulatory patient monitoring system, in which the prototype was integrated, set architectural requirements for the developed system. Signal fault conditions were essential to recognize and handle by the implemented software.

The implemented system consists of four parts: continuous blood pressure estimation, patient activity detection, evaluation of the need for the blood pressure measurement, and notifier. The system uses a photoplethysmographic signal from an oxygen saturation sensor as an input for the blood pressure estimator. Accelerometer signals from the patient's chest and wrist are used to detect the patient's posture and activity. Continuous blood pressure estimate and patient activity information are used in assessing the need for a cuff-based blood pressure measurement. The system is designed to operate alongside auto-cycling ambulatory blood pressure monitoring.

The algorithm that estimates blood pressure changes was provided by an external partner while the algorithm classifying the patient's activity was developed in GE Healthcare. The algorithm that estimates the need for the blood pressure measurement was developed in a collaboration with a team of engineers working on the project. The parts of the system mentioned above were combined into the functional system and integrated into the ambulatory monitoring system.

It was demonstrated that the system can detect significant and sustained blood pressure changes reliably, while at the same time discarding false readings in continuous blood pressure, as well as the blood pressure changes caused by the subject's activity. Therefore, the system can provide actionable information about the changes in patient blood pressure and adds new value to patient monitoring.

Keywords: NIBP, CNIBP, auto-trigger, blood pressure, non-invasive blood pressure measurement

TIIVISTELMÄ

Juho Herranen: Ambulatorisen verenpainemittauksen laukauisu potilaan tilaan perustuen
Diplomityö
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Verenpaine on tärkeä fysiologinen parametri, jota käytetään sekä arvioitaessa sairaalassa olevien potilaiden välitöntä terveydentilaa että antamaan viitteitä sydän- ja verisuonisairauksista. Invasiivinen verenpaineenmittaus on pysynyt verenpainemittauksen kultaisena standardina, kun taas oskillometrinen mittaus on vakiinnuttanut asemansa ensisijaisena mittausmenetelmänä osastoilla ja kotihoidossa. Viime aikoina jatkuvan ei-invasiivisen verenpaineen (CNIBP) mittausmenetelmien tutkimus on lisääntynyt ja CNIBP-menetelmiä käyttävät verenpaineen seurantalaitteet ovat kehittyneet. Käytetyt CNIBP-menetelmät perustuvat muun muassa pulssiaallon etenemisnopeuteen ja pulssiaallon muodon analyysiin.

Tässä opinnäytetyössä suunniteltiin ja toteutettiin prototyyppiohjelmistojärjestelmä, joka havaitsee merkittäviä ja pysyviä verenpaineen muutoksia. Tavoitteena oli, että tarvittaessa järjestelmä joko suorittaa mansettipohjaisen verenpaineenmittauksen automattisesti tai kehottaa käyttäjää ottamaan uuden mansettimittauksen. Järjestelmä käyttää pulssiaallon muodon analyysiin perustuvaa CNIBP-menetelmää. Vaatimuksia prototyyppijärjestelmälle asettivat CNIBP-menetelmän ominaisuudet. Järjestelmän täytyi kerätä tietoa potilaan asennosta ja aktiiviisuudesta, sillä ne vaikuttavat CNIBP-mittaukseen. Lisäksi signaaleihin liittyvät vikatilanteet oli tunnistettava ja niihin täytyi reagoida, koska prototyyppijärjestelmä integroitiin potilaan mukana kulkevaan monitorointijärjestelmään.

Toteutettu järjestelmä koostuu neljästä osasta: jatkuva verenpaineen arviointi, potilaan aktiivisuuden havaitseminen, verenpainemittauksen tarpeen arviointi ja ilmoittaja. Järjestelmä käyttää fotopletysmografista signaalia happisaturaatioanturista jatkuvan verenpaineen arviointiin. Potilaan asennon ja aktiivisuuden tarkasteluun käytetään rinnasta ja ranteesta kerättyjä kiihtyvyyssignaaleita. Jatkuvaa verenpaineen arviota ja asento- sekä aktiivisuustietoja käytetään arvioitaessa tarvetta mansettipohjaiselle verenpainemittaukselle. Prototyyppijärjestelmä ei suorita automaattisia mansettimittauksia itsenäisesti, vaan kehottaa käyttäjää suorittamaan uuden mansettimittauksen. Järjestelmä on suunniteltu toimimaan syklisen verenpainemittauksen rinnalla.

Verenpaineen muutoksia arvioivan algoritmin tarjosi ulkopuolinen yritys, kun taas potilaan aktiivisuutta luokitteleva algoritmi on kehitetty GE Healthcarella. Algoritmi, joka arvioi tarvetta verenpainemittaukselle, kehitettiin yhteistyössä projektissa työskentelevien insinöörien kanssa. Yllämainitut järjestelmän osat yhdistettiin toimintakuntoiseksi järjestelmäksi ja integroitiin potilasmonitorointijärjestelmään.

Toteutetua järjestelmää arvioidessa järjestelmän todettiin havaitsevan merkittävät ja pysyvät verenpaineen muutokset luotettavasti. Samanaikaisesti järjestelmä kykeni hylkäämään sekä väärät lukemat verenpaine-ennusteessa että verenpainemuutokset, jotka aiheutuivat testihenkilön aktiivisuudesta. Näin ollen järjestelmä kykenee tarjoamaan käyttökelpoista tietoa potilaan verenpaineen muutoksista ja tuomaan lisäarvoa potilasmonitorointiin.

Avainsanat: NIBP, CNIBP, automaattinen laukaisu, verenpaine, ei-invasiivinen verenpaine mittaus

PREFACE

This thesis work was done as a part of a larger project in GE Healthcare Finland. The project included collaboration with several engineers from our department as well as external organizations.

This project has given me an unique possibility to learn state-of-the-art technologies in healthcare and develop my engineering skills as an individual and as a team member. As part of this project, I have gathered important knowledge about medical technology development and the processes needed to bring new technologies to the market. I am sure these will benefit me greatly in the coming years. I am thankful for the opportunity to work on a project that is closely related to my field of study and arouses great enthusiasm in me.

I would like to take this opportunity to show my gratitude to my supervisor D.Sc. (Tech) Juha Virtanen, Ph.D. Panu Takala, and D.Sc. (Tech) Antti Vehkaoja. Your guidance and feedback during this work were exceedingly valuable. Additionally, I would like to thank my manager, David, for the opportunity to work on this thesis and for the flexibility in my work duties that made the completion of the thesis possible.

My time as a student at Tampere University has been irreplaceable for me. Many unforgettable memories have taken place during these years and new long-lasting friendships have originated from the halls of our university. I would like to thank all my friends whose paths have crossed with mine during these years. I will reminisce our shared time with warmth.

Finally, I would like to express my gratitude to my closest family members and especially to my partner, Krista, for supporting me during my studies and daily life throughout these years. I truly value all the help and encouragement you have given to me.

Tampereella, 3rd May 2022

Juho Herranen

CONTENTS

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LIST OF SYMBOLS AND ABBREVIATIONS

BP	Blood pressure
CBPE	Continuous Blood Pressure Estimator algorithm
CNIBP	Continuous Non-Invasive Blood Pressure
CPU	Central Processing Unit
DBP	Diastolic Blood Pressure
ICG	impedance cardiography
IPC	inter-process communication
IR	Infra-red
IRR	Impedance Respiration Rate
kB	kilobytes
MBAN	Wireless communication used in monitoring system
MBP	Mean Blood Pressure
MCU	micro controller unit
NaN	Not-A-Number Value
NIBP	Non-Invasive Blood Pressure
ODT	On-Demand Trigger
OTS	Off-The-Self Software Component
PAT	Pulse Arrival Time
PEP	pre-ejection period
PPG	Photoplethysmography
PTT	Pulse Transit Time
PWA	Pulse Wave Analysis
PWV	Pulse Wave Velocity
SBP	Systolic Blood Pressure
SpO2	Peripheral Oxygen Saturation
UI	User Interface

1. INTRODUCTION

Blood pressure (BP) is caused by blood against the circulatory system. It is generated by the heart and arterial tree that resist the blood flow. Blood pressure is often linked to medical conditions that can cause risk to patient health and therefore, blood pressure measurements are one of the most common measurements in doctoral appointments, intensive care units (ICU), and wards.

Nowadays, the most commonly used blood pressure measurement methods are invasive and oscillometric blood pressure measurements. While invasive blood pressure measurement is accurate and continuous, it is not commonly used outside critical care, surgeries and post-anesthesia because of its invasiveness. On the other hand, oscillometric method is the most common measurement method in wards because it is non-invasive and fairly easy to perform. However, oscillometric method can only provide intermittent blood pressure readings.

Multiple different continuous non-invasive blood pressure (CNIBP) measurement methods have been developed during the last decades to overcome the downsides of the currently used blood pressure measurement techniques. However, their measurement accuracy and reliability have not reached to level where CNIBP could be directly used i.e. for ward patient monitoring. Therefore, a hybrid design that uses CNIBP to evaluate changes in blood pressure but does not provide clinical data directly, can bring an intermediate solution to the problem. A similar system has been used in patient monitoring earlier [1, 2].

The purpose of this thesis is to design and implement a prototype software system that estimates blood pressure changes based on CNIBP and provides additional clinical information in the form of notifications and auto-triggered oscillometric blood pressure measurements. However, the system does not provide an actual continuous blood pressure reading for users. The prototype system is integrated into a patient monitoring system. Building blocks for this system was already done in collaborations with other companies and institutes as well as in earlier works [3, 4]. The focus of this thesis is to integrate the knowledge and ready-made software into one prototype system that can deliver significant input for future development work in this field.

2. BACKGROUND

2.1 Blood Pressure Measurement

Blood Pressure

The human cardiovascular system consists of the heart and blood vessels. The system can be divided into two circulation loops: pulmonary circulation and systemic circulation. The pulmonary circulation provides gas exchange in the lungs. The deoxygenated blood absorbs oxygen while releasing carbon dioxide by diffusion. The oxygenated blood then circulates to the systemic circulation via the heart's left atrium and ventricle. The systemic circulation delivers oxygenated blood and other nutrients to tissues everywhere in a body while removing wastes and returning the deoxygenated blood to pulmonary circulation. [5]

Blood vessels can be divided into three different categories: arteries and arterioles, veins and venules, and capillaries. In general, arteries and arterioles deliver high oxygenated blood with high pressure around the body while veins and venules transport the deoxygenated blood back to the lungs. An exception to this is the pulmonary circulation where arteries deliver the deoxygenated blood to the lungs while veins deliver oxygenated blood towards the heart and systemic circulation. Capillaries are the thinnest of blood vessels and run through every tissue in the body. They allow the exchange of nutrients, wastes, and gases between blood and tissue through a thin endothelium. Capillaries connect arterioles and venules. [6]

Blood pressure (BP) is generated by arteries and arterioles that resist the blood flow that the pumping heart generates [5]. The resistance of blood flow is called peripheral vascular resistance and is mainly generated by arterioles [7]. When blood pressure is referred to in a clinical environment or as a measurable parameter, it refers to arterial blood pressure in systemic circulation within large arteries [8].

Blood pressure varies during a cardiac cycle. The cycle can be divided into two phases: systole and diastole. The systolic phase can be roughly defined as the period between the closing of the mitral valve and the closing of the aortic valve. This period involves a contraction of the left ventricle and following ventricular ejection where the arterial pressure reaches its maximum value. When measuring blood pressure, the maximum value of

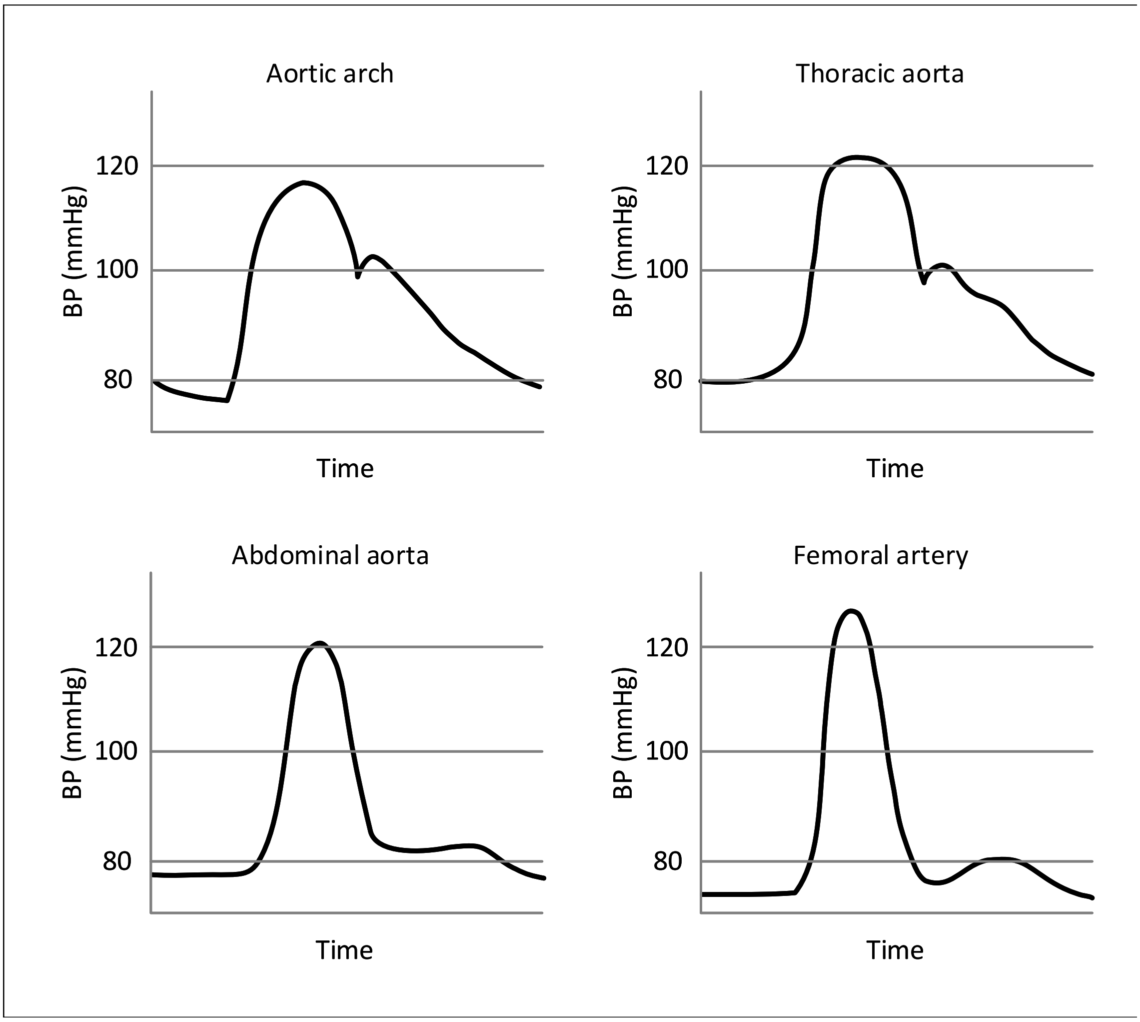

Figure 2.1. *Blood pressure waveforms demonstrated in four different location in human arterial tree; aortic arch, thoracic aorta, abdominal aorta and femoral artery. [5]*

blood pressure during the cardiac cycle is known as systolic blood pressure (SBP). During the diastole, the relaxation of the heart's ventricles takes place and the arterial blood pressure decreases until the next systole and ventricular ejection, which then builds the pressure up again. The lowest blood pressure value during the cardiac cycle, known as the diastolic blood pressure (DBP), is reached right before the opening of the aortic valve in the systolic phase. Figure 2.1 shows the blood pressure waveform in different sites in a body during one cardiac cycle. One important parameter that is often examined during blood pressure measurement is mean arterial pressure (MAP). MAP is not the average of systolic and diastolic blood pressure but can be calculated from the integral of the blood pressure waveform during one cardiac cycle. [6, 9]

As can be seen from Figure 2.1, pressure waveform and amplitude vary in different sites of the arterial tree. When moving down in the arterial tree, the pulse shape converts to more tapered and gains amplitude [5]. In addition, a spike called incisura, which is caused by the reflux of blood to the left ventricle right before the closing of the arterial valve, is clearly visible in the aortic arch but gets softened when moving down in the arterial tree and lastly disappears in femoral arteries. Incisura is replaced by the dicrotic notch which is rather caused by the peripheral vascular resistance than closing of the arterial valve [10]. The pulse shape alteration is due to the properties of arteries and branching of the arterial tree. For example, the branching of the arterial tree creates reflection sites that reflect the pressure wave towards the aorta and the heart. As a result, pressure waveform at different sites consists of also reflected waveform components and thus, has different characteristics. [5, 6]

Blood pressure is maintained by complex mechanisms that include baroreceptors in blood vessels, hormones like an antidiuretic hormone (ADH), and Renin-Angiotensin-Aldosterone System (RAAS) [8]. Maintaining a sufficient level of blood pressure is vital for nutrient and oxygen delivery as well as keeping homeostasis in the biological system. In contrast too high blood pressure is known to be associated with cardiovascular diseases (CVD) [11], which can lead to e.g. organ damage or failures.

Blood pressure is one of the most important parameters which represent a patient's state of health, and it is indeed one of the most measured vital signs in healthcare for example at doctoral appointments, at wards, and during surgical operations. Hypertension increases the risk of organ damage and deaths associated with circulatory diseases. In the last decades', cases of hypertension in the population have been greatly increased [12]. When hypertension can cause organ damage in long run and is related to premature deaths, hypotension can lead to the same result but in a much shorter time. Loss of blood pressure causes failure of delivery of oxygenated blood to organs and tissue and can lead to life-threatening situations or cause permanent damage to a patient [13]. Therefore, the early detection of either hypertension or hypotension is crucial for a patient's health [14].

Invasive Blood Pressure Measurement

Invasive blood pressure measurement is a direct method of measuring blood pressure. An intravascular cannula needle is inserted inside a patient's artery. The needle is connected to a catheter system which includes a pressure transducer. The pressure of the artery is delivered to the transducer and the intravascular blood pressure wave is directly measured. Systolic blood pressure is the peak of the pressure wave whereas diastolic blood pressure is the minimum value. Mean arterial pressure can be calculated from the pressure wave. An invasive blood pressure measurement has been treated as the gold standard of blood pressure measurement and other non-invasive measurement methods are compared with this when estimating the performance and the accuracy of the methods. It is especially used in intensive care units. [15, 16]

The downside of the invasive measurement method is a risk of complications for patients. Since inserting an intravascular cannula needle is an invasive procedure, it gives rise to vascular insufficiency as spasms, thrombosis, or pulselessness. Similarly, there is a risk for other complications like bleeding or infections. In addition, it can be mentioned that the invasive blood pressure measurement is not feasible in all patient cases since plenty of limitations are added to a patient's movement. [17]

Auscultatory Method

An auscultatory method of measuring blood pressure is non-invasive measurement. It is based on Korotkoff sound which in sort is caused by the turbulence of blood flow in an artery. An auscultatory method is an indirect measurement of blood pressure because no direct contact with a circulation system is made. An auscultatory blood pressure monitor device consists of two main parts: a sphygmomanometer to apply pressure over an artery, and a stethoscope to listen to Korotkoff sounds. Sphygmanometers of different kinds can be used. Mercury-based, aneroid based or hybrid versions of sphygmomanometers are commonly used. A simplified process of one blood pressure measurement with an auscultatory method consists of three steps: a sphygmomanometer's cuff is inflated over systolic blood pressure (a blood flow in the artery is blocked), the cuff is deflated gradually under diastolic blood pressure, and Korotkoff sounds are listened to during a deflation period to determine blood pressure levels. During the deflation period, blood flow is re-established along with the sound that originates from blood flow and oscillations inside an artery. [18]

There are different views for the origin of the Korotkoff sound but commonly it is viewed to be originated from turbulent blood flow in occluded and restricted arteries [19]. The sound of blood flowing during the measurement can be divided into five phases during a deflation period [18, 20]: The first phase is at systolic blood pressure where a clear tapping sound appears. In the next phase sound converts to longer and softer. In phase three, the change of the sound is crisper and louder. Next, the sound changes to muffled and softer. In the last phase, sound completely disappears, which corresponds to diastolic blood pressure.

The accuracy of auscultatory blood pressure measurement has been debated before. It tends to give lower values for systolic blood pressure and higher values for diastolic blood pressure when compared with intra-arterial blood pressure [19]. Especially, the point which represents the diastolic pressure shares opinions, and opinions differ when measuring blood pressure from adults, children, and pregnant women [20]. Still, especially the mercury-based auscultatory method has been the gold standard for non-invasive blood pressure measurements [18].

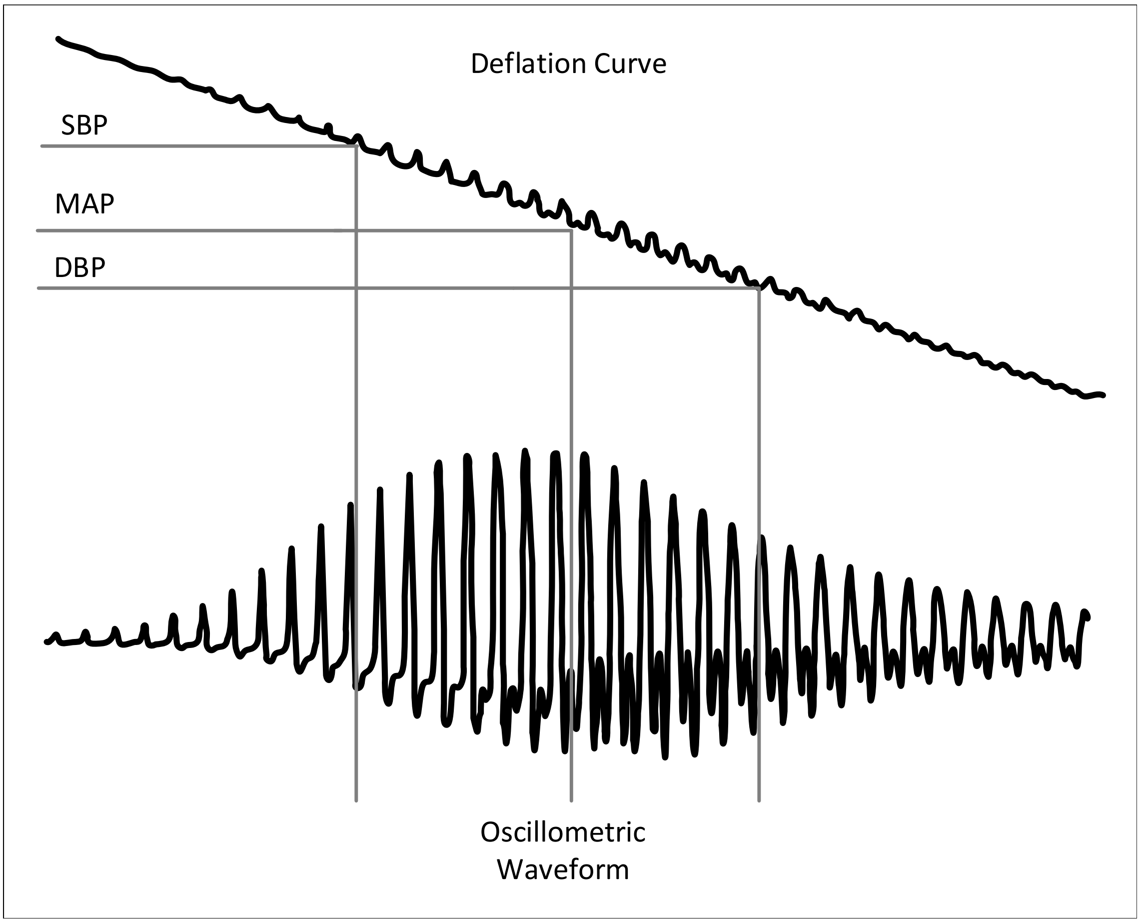

Figure 2.2. *A cuff pressure during deflation period. Lower part shows pressure oscillation of the cuff pressure during the measurement. Systolic, mean and diastolic pressures are visualized in the figure. [21]*

Oscillometric Method

An oscillometric method is also a non-invasive and indirect method like the auscultatory method. An oscillometric measuring system consists of a sphygmomanometer like the auscultatory method. The difference in measurement instrumentation is that instead of a stethoscope, a pressure transducer is used to determine blood pressure levels. Oscillometric blood pressure measurement is based on small pressure oscillations in the cuff's pressure during the deflation period. Oscillations are monitored with the pressure transducer. [14]

One blood pressure measurement with the oscillometric method consists of three parts. An air-fillable cuff is inflated over the expected systolic blood pressure. Usually, the measurement point used is the upper arm's brachial artery. Once the cuff pressure is at the level in demand, the pressure of the cuff is gradually deflated under diastolic blood pressure. During a deflation period, the cuff's pressure waveform is recorded. [21]

Blood pressure is determined from the amplitude of the oscillations in the cuff pressure during the deflation. This is visualized in Figure 2.2. The upper part of the figure shows cuff pressure whereas the lower part shows oscillation of the pressure i.e. oscillometric waveform. Three points in the oscillometric waveform are under interest. Mean arterial pressure is determined at the point where the oscillation amplitude is at the maximum. Systolic and diastolic blood pressure are determined by the change in the oscillation amplitude. Systolic blood pressure corresponds to the point where a large increase in the oscillation amplitude is detected. Respectively, diastolic blood pressure is determined at the point where a large decrease in the oscillation amplitude is detected. To calculate SBP, MAP, and DBP, algorithms are used that calculate signal features from the pressure waveform. Different approaches to estimating blood pressure levels can cause differences between oscillometric blood pressure monitors. [14, 21]

A modern blood pressure monitor that uses the oscillometric method, uses a microcontroller unit (MCU) to control and read the pressure of the cuff. Moreover, signal processing algorithms are used to determine the point of the maximum oscillation amplitude and to find the largest shifts in the oscillation amplitude. Oscillometric blood pressure measurement is easily automated because it does not need direct input from a user. [21]

Automation, ease of use, and non-invasivity are reasons why oscillometric measurements have taken their place as a standard blood pressure measurement method in modern patient monitoring systems. Monitoring systems can provide two ways of measuring blood pressure with oscillometric measurement. In manual mode or spot check mode, measurement is triggered by a clinician and then the system will perform the measurement and show a result. Another measurement mode is automatic or auto-cycling. In auto-cycling mode system automatically measures patient blood pressure at a preset interval. The interval can be chosen by a user and usually, it can be 15 minutes or 1 hour for instance. Nevertheless its many advantages, the oscillometric blood pressure measurement can only provide intermittent blood pressure readings. [22]

Multiple factors affect the oscillometric-based measurements but physiological factors affecting blood pressure play a big role in the accuracy and success of the measurements [23, 24]. It has been noticed that oscillometric blood pressure measurement devices can fail to give accurate BP readings [25]. A good example that is affecting oscillometric measurement is the patient's posture and activity [21]. The movement of the patient can cause false readings to be recorded by the system or even cause measurement failure. Therefore, the oscillometric method is preferably performed on inactive patients for higher fidelity measurement results. In addition, it is crucial to use correctly functioning measurement equipment when performing oscillometric blood pressure measurements [26]. For example, a wrong-sized cuff will most likely cause false blood pressure readings.

Volume Clamp

Volume clamp method (aka. vascular unloading technique) of measuring arterial pressure is a non-invasive blood pressure measurement. This method is continuous measurement and was first introduced by Jan Peňáz. Even though the volume clamp is a continuous measurement, it differs from other continuous methods described in this section since it includes a partial occlusion of the artery to gauge blood pressure. The basic volume clamp system consists of infrared light, an infrared light detector, an inflatable cuff, and a pneumatic motor-control unit. Human extremities, usually fingers, are illuminated with light. The same area is pressurized with the cuff. A light and a light detector are used to generate a photoplethysmogram signal (PPG). PPG signal measures variation in light absorption in illuminated tissue. Different kind of tissue properties, like blood volume and oxygen richness of blood, affects to tissue's ability to absorb light. [13]

A basic principle of a vascular unloading technique is to keep a blood volume in the finger for instance, constant by controlling the cuff's pressure with an electro-pneumatic control loop. The tissue is illuminated with IR light which generates a PPG signal. This signal is proportional to blood volume under the illuminated area. The blood volume on the other hand is proportional to blood pressure because of properties of arteries like elasticity. Therefore, the PPG signal is also proportional to the blood pressure. During the cardiac cycle, blood pressure varies, and ergo so does the PPG signal. This variation of the PPG signal can be used as an input for the pneumatic control unit which drives the cuff pressure. When the PPG signal indicates an increase in blood pressure, the pneumatic control unit drives higher pressure to the cuff which reduces blood volume in the tissue, and thus also a variation of the PPG signal is canceled. Vice versa, when the PPG signal indicates a decrease in blood pressure, the cuff pressure is decreased. Hence, blood volume in tissue can be kept constant by controlling cuff pressure with a PPG signal. This pressure waveform in the cuff corresponds to intra-arterial pressure. [14]

Normally vascular unloading technique is applied to the patient fingers. Blood pressure in fingers does not correspond directly to blood pressure in arteries which normally is the blood pressure that is clinically assessed. Thus, a transfer function is needed to estimate the actual arterial blood pressure. Unfortunately, applying the transfer function to the signal creates errors in the estimated pressure which reduces the clinical value of the measurement. Moreover, a volume clamp has certain other drawbacks. To be able to follow blood volume changes, it needs highly responsive and accurate instrumentation to react to PPG signal changes. Also, pneumatic control instrumentation needs to be fast and accurate to inflate and deflate the cuff on time. This can make the manufacturing costs of the devices high. Also, average pressure applied in the measurement area causes discomfort for the patient when used in long intervals and can disturb for example regular sleep cycle. [14]

Nonetheless, the volume clamp method combines two important aspects of clinical measurement. It is continuous like an invasive intravascular cannula, and it is non-invasive, as the sphygmomanometer measurement, which makes it a promising method of measuring blood pressure.

2.1.1 Continuous Non-Invasive Blood Pressure Measurement

This sub-section describes some of the proposed and used continuous blood pressure measurement methods that are non-invasive and do not include partial or full occlusion of the artery. These methods are also called cuffless non-invasive blood pressure measurements (CNIBP). All methods described here are based on pressure pulse wave velocity in the arterial tree. They are divided into two groups; methods that measure directly pulse wave velocity, and methods analyzing properties of pressure pulse waves that are related to wave velocity [27].

As discussed before, the invasive blood pressure measurement method and methods based on occlusion of the artery are either directly measuring blood pressure that is transmitted from a catheter to pressure transducer or they measure pneumatic pressure of cuff that indirectly corresponds to blood pressure of the patient. In cuffless blood pressure measurements, pressure is not measured directly but pulsatility energy generated by arterial pressure waves progressing in arteries is measured. It creates anatomical structural changes in the artery and surrounding tissues which can be measured with various methods. Impedance cardiography, photoplethysmography, tonometry, and ultrasound are examples of measuring principles that can be used in CNIBP to estimate blood pressure. The pulsatile waveform is further analyzed with a signal-specific algorithm to extract pressure-related information. Different analyses are used including analysis in time, amplitude, and frequency domains. [27]

Because the cuffless blood pressure measuring methods do not measure direct pressure, absolute blood pressure cannot be measured directly without additional input, but a variation of blood pressure can be tracked. Furthermore, a transfer function is needed to convert input signals to pressure units. For this purpose, various initialization methods can be used to calibrate measurement and extract the absolute blood pressure reading. For example, absolute blood pressure reading from the oscillometric method can be fed to a cuffless system to calibrate the measurement and then get continuous blood pressure readings based only on the pulsatile signal. [28]

Pulse Wave Velocity

Pulse wave velocity (PWV) methods are based, as the name suggests, on the velocity of the pressure wave. A relationship between blood pressure and pressure wave veloc-

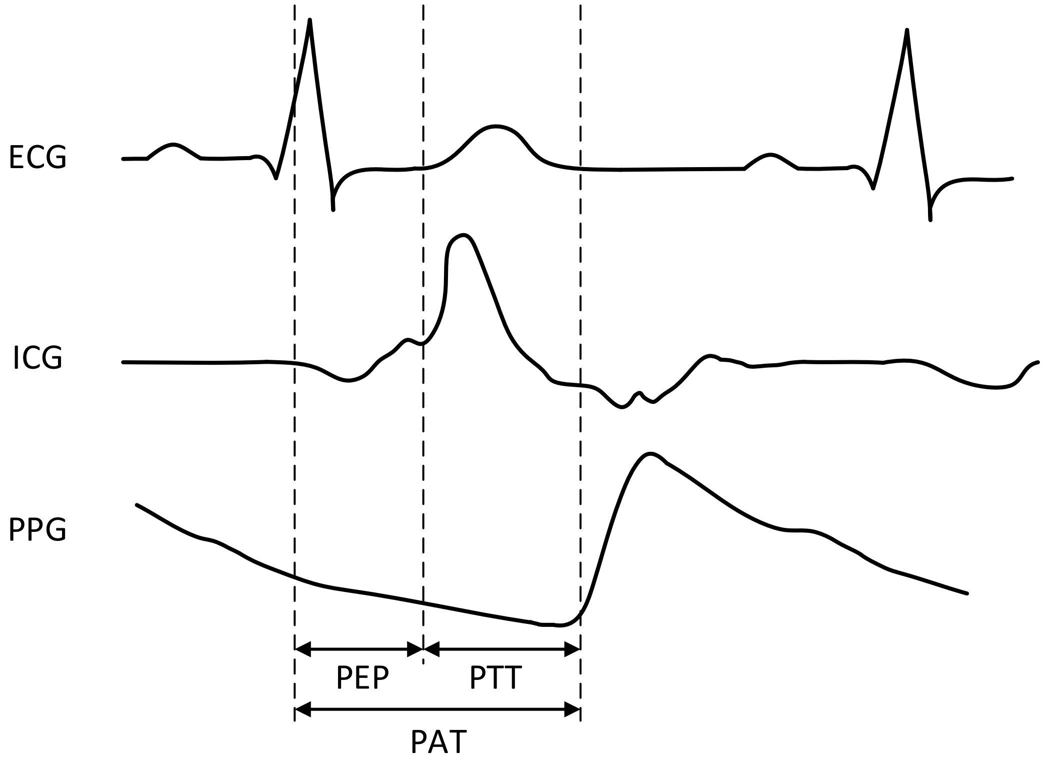

Figure 2.3. *Relationships between different signals in pulse wave velocity method. PAT consist of PEP and PTT. PTT cannot be measured using ECG, thus, another signal source is needed ie. ICG. [30]*

ity is the stiffness of the arterial walls [29]. When blood pressure increases, vascular tone increases, and arterial walls become stiffer. Therefore, the velocity of propagating pressure wave in arterial tree increases [30]. PWV analysis needs at least two signal sources [29]. One example is to measure the electrical activity of the hearth with electrocardiography (ECG) and a distal pulse wave with photoplethysmogram (PPG). The time between ECG's QRS complex and PPG signal's pulse corresponds to the time it takes for the pressure wave to propagate from the heart to a measurement location of the PPG signal. Therefore, PWV can be calculated

$$PWV = \frac{L}{t}, \tag{2.1}$$

where L is the distance the pressure wave travels and t is the time how long it takes the wave to travel the distance. Length varies between cases but stays the same within one measurement. Since it can be hard to measure, the propagation time alone can be used to estimate a change in PWV over time. [30]

In reality, the propagation time of the pressure waves has other aspects that need to be considered. ECG is a measurement of the electrical activity of the heart. The beginning of the QRS complex yields to the start of the depolarization of the heart ventricles but does not correspond to an opening of the aortic valve which is the actual time point when pressure wave enters the aorta. A time interval between the electrical activity of the heart and a mechanical pumping wave is called a pre-ejection period (PEP). This period consists of an electromechanical activation time and isovolumetric contraction time. PEP varies under physical circumstances and is affected by e.g., hydration status or patient posture, thus adding error to PWV analysis if ECG and pulsatile signal are used directly [31]. Figure 2.3 shows time relations between ECG, impedance cardiography (ICG) and PPG. ICG measurement is related to pressure wave propagation in the aorta since blood pressure change causes a change in impedance properties of the chest [30]. Therefore, PEP can be measured from ECG and ICG signals.

PWV analysis methods are further divided to pulse arrival time (PAT) and pulse transit time (PTT) analysis. PAT is directly a time between the start of heart electrical activity (QRS) and pulsatile signal (ie. pulse in PPG) while PTT measures the actual propagation time of pressure wave. PAT consists of both PEP and PTT (see Figure 2.3). [30]

PAT measurement is rather simple to do with current sensor devices used in a clinical environment. ECG and Spo2 signals are commonly collected and therefore the same signals can be used in PAT measurement. However, as described before, PAT is not an accurate measurement of blood pressure because it includes the pre-ejection period that is affected by non-blood pressure-related changes [32]. PTT on the other hand measures quite accurately PWV, and therefore it is a much better indication of the variation of blood pressure than PAT. Still, the measurement is affected by various kinds of interference like movement artifacts and electrical noise. [33] In addition, PTT measurement requires an input signal source that measures the actual point of pressure wave leaving the heart (like ICG) which is not commonly measured. Therefore, using PTT to measure continuous blood pressure would add another sensor device attached to the patient which is not a desired situation at least in ambulatory monitoring.

Pulse Wave Analysis

Pulse Wave Analysis (PWA) methods of measuring continuous blood pressure examine features of the pulsatile waveform. Pulsatile waveform includes information about blood pressure. One methodology is pulse decomposition analysis (PDA). In Figure 2.4, aorta and its junctions are represented. When a pressure wave advanced through the aorta it encounters junctions. This branching causes impedance mismatch on surrounding tissue and causes reflection of pressure wave back towards the heart. Reflection is summed back to the original pressure wave and can be seen in the final pulse wave. This is represented in Figure 2.5. When pressure wave travels faster in the aorta, the timing of the reflected waves changes also. Wave velocity is related to blood pressure, and therefore, information obtained from the timings of the reflected pressure pulses can be used to calculate changes in blood pressure over time. [34, 35]

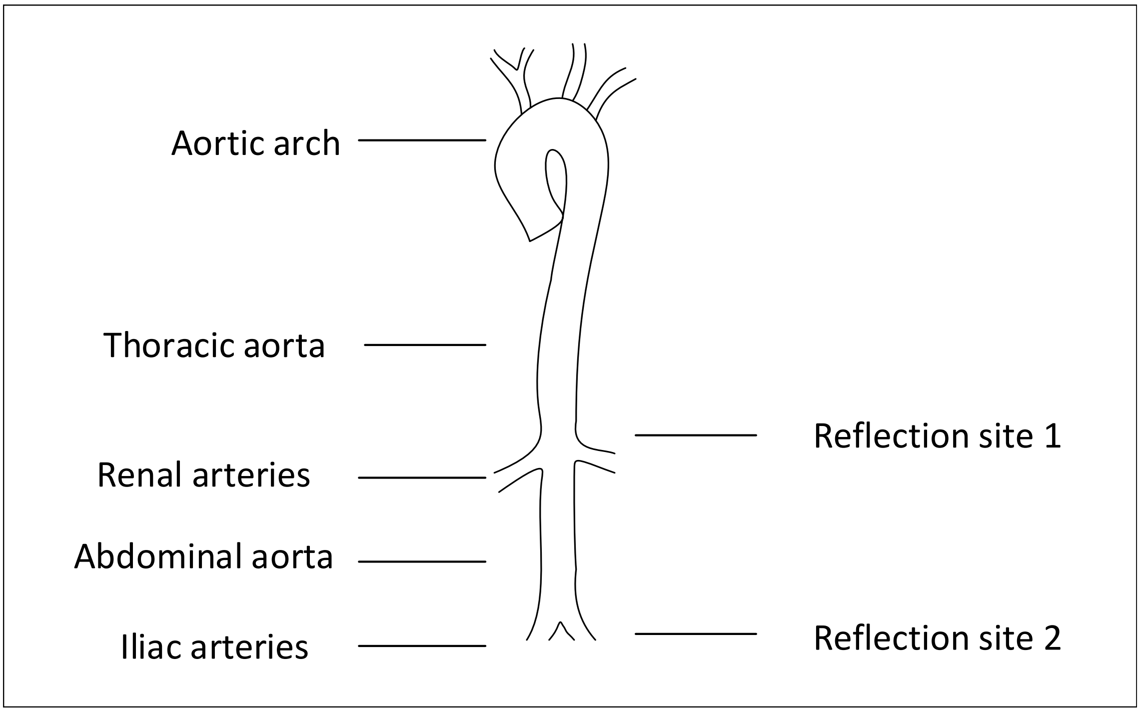

Figure 2.4. *Structure of aorta and main lower body reflection sites of pressure waveform. First reflection site is at the junction of the renal arteries and the second one at the junction of the iliac arteries. [34]*

The pulsatile waveform can be further analyzed using morphological analysis of pulse waves. The pulsatile wave includes information about ventricular ejection and elastic and geometric properties of the arterial tree. For example like in PDA analysis, the timing of backward reflected wave can be used to determine arterial stiffness, and thus, blood pressure. Also, integral and derivative analysis of the signal features are under interest. Areas of different parts of signals like the diastolic part, systolic part, or ratios of these are usually examined because they include information about the circulatory system. Ascent and descent rates of the signal like time reaching a systolic peak can also provide crucial information and are therefore used. It is worth mentioning that these are only examples of a very complex signal processing to derive the information about changes in the vascular system and also other morphological analysis methods are used. [36]

In addition, transfer functions are needed when features are transferred to blood pressure. This is especially the case when using non-pressure wave, like photoplethysmogram signal, but also otherwise because pulse wave traveling in peripheral arteries has a lot of differences from waves traveling in central arteries. Central arteries are much better at assessing cardiovascular state than peripheral arteries but central artery pulse wave is almost impossible to measure without an invasive catheter. Peripheral pulse wave still includes much useful information, and thus transformation can be done. [36]

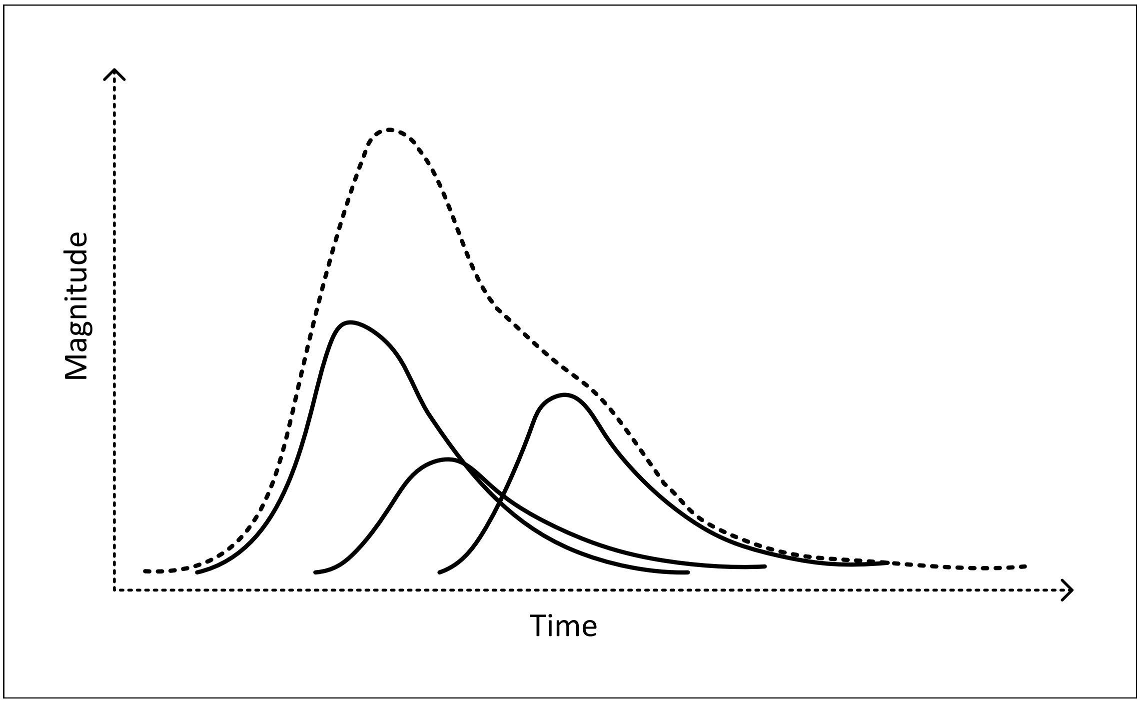

Figure 2.5. *Representation of pulse pressure wave and its decomposition into a main and reflected pressure wave. The main pressure wave is the pulse wave generated by the heart and the reflected waves are reflections from the main reflections sites in the arterial tree. [35]*

PWA methods have one evident advantage over other CNIBP methods mentioned. The instrumentation only needs one sensor where the necessary information can be derived. In PWV methods, always two source signals are needed to detect pulse departure and arrival. On the other hand, when compared to the volume clamp a simpler pneumatic system is enough to detect the pulsatile signal, or photoplethysmography can be used individually. PPG has been an area of interest lately because PPG signal is already measured in oxygen saturation sensors which are commonly used in hospital wards and high acuity care. Hence, a PWA-based CNIBP system does not necessarily need to bring new hardware to the system at all but existing system components can be utilized for a new purpose.

2.1.2 Continuous Non-Invasive Blood Pressure Measurements in Clinical Environment

Some aspects could require attention in blood pressure measurement methodologies that are currently used in a clinical environment. Invasive blood pressure measurement provides direct and continuous blood pressure reading and therefore can be considered the most accurate method of measuring blood pressure. However, an invasive method causes risks to a patient like described in Section 2.1, and limits patient movement. Therefore, it is not suitable for example in hospital wards where patients can be mobile and continuous monitoring can disturb daily activities. Thus, invasive blood pressure measurement is considered an unnecessary risk and not suitable for ambulatory monitoring. Instead, cuff-based non-invasive methods are preferred.

An oscillometric method is regularly used in hospitals when an invasive method is not feasible. Its ease of use, low patient risk, and quick measurement have made it a standard measurement method in hospital wards and home care. Nevertheless, oscillometric measurements can only provide intermittent blood pressure readings. A normal auto cycled NIBP measurement can screen blood pressure changes well if the cycling is done in short intervals but with longer intervals, there is an increase in the risk of not detecting blood pressure changes in time. Therefore, choosing too infrequent cycling places the patient at risk of trauma. On the other hand, using too short intervals causes unnecessary stress to the patient and for instance, can distract a regular sleep cycle. In addition, a result of an oscillometric measurement can be highly affected by the placement of the cuff, patient activity, and other non-measurement-related aspects. The measurement is highly affected by the professionalism of a performer.

Volume clamp method which was described earlier in Section 2.1, provides continuous and non-invasive blood pressure measurement which makes it a promising method to measure blood pressure. Nevertheless, it also has characteristic drawbacks like measurement instrumentation and patient discomfort in the long. In addition, transfer functions that transfer blood pressure at the fingertip to a central arterial blood pressure induce inaccuracy to absolute blood pressure. Some volume clamp based blood pressure monitoring devices like CNSystem's CNAP®[37] or Finapres®[38] have reached to the market but they have not done a breakthrough as a commonly used clinical measurement method.

CNIBP methods that use pulse transit time to measure blood pressure changes over time are interesting alternatives for measuring blood pressure because they can tackle many of the shortcomings of other methods described. They are non-invasive, continuous, and utilize already used sensor technologies to measure blood pressure. For example, ECG and SpO2 signals can be used to derive necessary information for blood pressure measurement. However, also these methods are struggling with inaccuracy and instrumentation of the measurement [33].

Nonetheless, CNIBP methods are used before in a clinical environment to assess a patient's blood pressure continuously and non-invasively. In an earlier developed system, CNIBP measurement is used to assess changes in blood pressure continuously but not to measure absolute blood pressure value. In the device developed by Nihon Kohden, a new oscillometric blood pressure measurement was triggered automatically, if a change that exceeds set limits is detected. Used CNIBP method is based on PWV. [39, 40]

PWV was discussed in Section 2.1.1. Like all PWV methods, also these devices developed by Nihon Kohden use two different sensors to track blood pressure changes continuously. Pulse wave velocity is extracted from ECG and SpO2 signals. The continuous blood pressure measurement system is working with auto-cycled oscillometric measurements. Thus, CNIBP measurement was not assessing the patient's state individually but was used to provide more information to clinicians about the patient's state. [1, 2]

In addition to continuous blood pressure measurement devices based on vascular unloading technique and PWV, there are also devices using PWA methods to measure continuous non-invasive blood pressure. For example, CareTaker™ monitor uses PDA methodologies to measure continuous blood pressure and has obtained both FDA approval and CE mark [41]. Another blood pressure monitor that uses PWA methods is Aktiia [42]. Aktiia has obtained CE mark, and it is currently aimed for home monitoring and consumer markets.

2.2 Description of the Patient Monitoring System Used in This Work

A base patient monitoring system used in this work is a patient monitoring system manufactured by General Electric. The prototype system (On-Demand NIBP) that was designed and integrated in this thesis was integrated to this patient monitoring system. As a top-level description, the entire monitoring system can be divided into 4 components: Wireless Sensors, Ambulatory Hub, Database, and Patient Data Viewer.

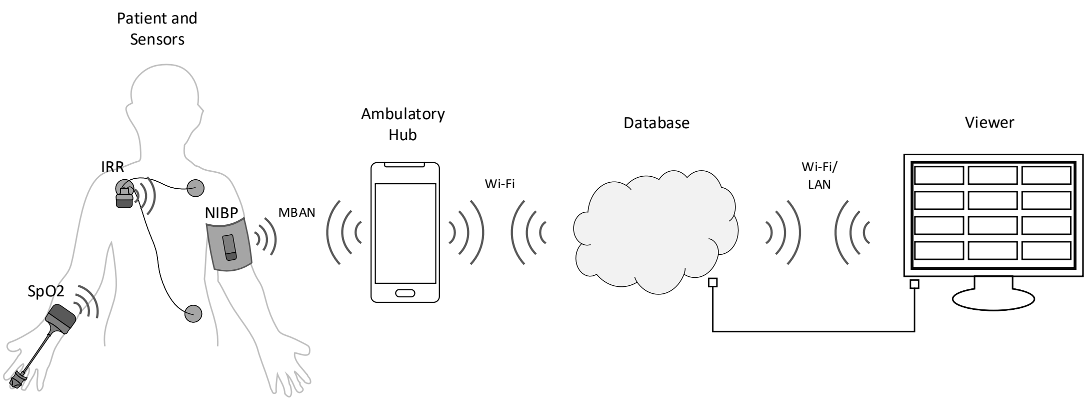

Figure 2.6. *Structure of the Ambulatory Monitoring System used in this work*

The structure of the system is represented in Figure 2.6. The sensors are wireless devices that can measure analogous signals from a patient and turn them into meaningful health parameters. Examples of the parameters are blood oxygen saturation level and respiration rate. The ambulatory hub can be considered a pocket-sized patient monitor. Ordinarily, patient monitors are much bigger devices located next to patient beds (Bedside monitors). The ambulatory hub implements the same functionalities as a regular patient monitor. A database can be determined as back-end data storage where all the parameters collected from patients are saved. It also works as an interface between, an ambulatory hub, a patient data viewer, and other supporting systems. A patient data viewer can display measured parameters from one patient or they can be multi viewers which display multiple patients at the same time for example one ward at a time. They are usually located remotely from a patient in the hospital's control rooms. Hereby, clinicians can monitor multiple patients at the same time without being next to them. The ambulatory hub and sensor, on the other hand, are located near the patient or on the patient.

A patient data viewer and a database are not described more closely in this work because they are out of the scope of this thesis. A closer look is done at the ambulatory hub and sensors.

Wireless Sensor

A wireless sensor consists of two devices: a sensor and a battery device. The sensor is a device that performs the actual measurement of parameters with an analog measurement unit. Parameter measured can be for example oxygen saturation or respiration rate. In the current patient monitoring system, oxygen saturation (SpO2) and impedance respiration rate (IRR) can be measured. As an example, the SpO2 sensor measures photoplethysmogram produced by light passing through the tissue, and the IRR sensor measures an impedance variation at the chest. A sensor is not only a 'dummy' device that measures analogous signals but also has processing units which e.g., converts a signal from analog to digital, does processing for signals, packs the produced data according to predefined protocol, and sends it forward towards the next node in the system via serial communication. Furthermore, many modern sensor devices are producing the signal for themselves. For example, the SpO2 sensor emits the light and the infra-red light which it will then collect later with a photodiode. In Figure 2.6 patient is wearing three sensors: a SpO2 sensor, an IRR sensor, and a non-invasive blood pressure (NIBP) sensor.

An individual sensor device is needed to measure each parameter. This means that there is no one general-purpose measurement device that can be utilized to measure all the parameters. Measuring each parameter needs a separate, specifically designed sensor device that includes specific hardware and software.

The sensors collect analog signals, process them, and send them forward to the next node in the system. In this system, the next node is a battery device. The battery device provides power for a wireless sensor and works as a proxy for the sensor in the system. This device uses a wireless connection called MBAN to communicate with the ambulatory hub. Therefore, all patient data that the sensor measures and sends forward are handled by the battery device and forwarded to an ambulatory hub. The battery device has a processing unit that is used to communicate with both devices, the connected sensor, and the ambulatory hub. In addition, the battery device has a three-axis accelerometer.

An acceleration data has great importance in the On-Demand NIBP system; thus, the battery device not only provides a communication interface for the sensors but also generates important information about the patient's state. In the On-Demand NIBP system, acceleration data is used to determine patient's activity and posture. For simplicity, the sensor and the battery device are addressed as one wireless sensor device in the rest of this thesis.

Ambulatory Hub

The ambulatory hub is a miniaturized patient monitor. Generally, patient monitors, or bedside monitors, are the size of a computer screen but heavier and thicker. They can be placed on a holder with wheels that make them somewhat mobile. In the used patient monitoring system, the patient monitor, the ambulatory hub, is the size of a mobile phone but still provides more or less the same functionalities as a general patient monitor device.

Patient monitors have normally certain responsibilities. First of all, it collects data from the sensors like electrocardiography sensors. The collected data is further processed inside the patient monitor. In the case of ECG, it can include for example r-peak detection, heart rate calculation, and different kinds of anomaly detection steps. Furthermore, monitors use alarming systems to alarm clinicians when patient parameters are exceeding limits or there is some other problem in the system like the sensor is not connected correctly to a patient. This is one of the most important responsibilities that a monitor has because failure in the alarming system can lead to an unnoticed change in patient's state of health which on the other hand can lead to trauma or even death.

The patient monitor also displays the data on its screen. This important feature is for clinicians to see patient vitals next to the patient e.g., during treatment procedures. With a display interface, clinicians can also control certain settings of the monitor or set the monitor in another mode. In addition to mentioned tasks, patient monitors are forwarding received sensor data and processed parameters to hospitals' data centers and for example to centralized patient monitoring rooms.

The ambulatory hub has two communication interfaces: MBAN to communicate with wireless sensors and Wi-Fi to communicate with the database and patient data viewers. It can connect to and receive data from multiple sensors simultaneously. Communication interfaces are completely wireless making the device portable.

The implemented system described in Sections 3 and 4, On-Demand NIBP, is run in the ambulatory hub. The hub has far more processing power than a sensor device so it can perform more complex and heavy operations in a much smaller time. It also collects the data from all sensor nodes and has the necessary information about the patient. Thus, it has all the necessary information for the On-Demand NIBP system available directly. In addition, the hub has a display that can be used to show the notifications for clinicians which will be important for the system that is created.

2.3 Expected Challenges in Time Constrained Wireless System

This subsection considers problem areas in a group of wireless systems that are required to provide data with high fidelity and data rates. Problems caused by data bandwidth, timing, synchronization, and loss are common for wireless systems but in medical applications, it is crucial to address these problems [43]. It is worth mentioning that wireless systems do not exclusively induce problems but can improve patient monitoring in many aspects like increasing patient satisfactory [44] and allowing remote monitoring of patients [45]. Coverage of this topic is not all-inclusive but topics are chosen concerning the system described in Section 2.2.

Data bandwidth

Data bandwidth means the maximum amount of data that can be delivered through the system. It is also referred to as a maximum throughput. Battery-powered wireless systems like on-body devices suffer from low transmission bandwidth because of minimized power consumption and limited processing and storage capabilities [46]. Also, systems with multihop architecture suffer from limited bandwidth [47]. When designing a wireless system, the data bandwidth need should be considered beforehand because changing the system architecture afterward is extremely hard.

Each data source uses a certain amount of the available data bandwidth in the system defined in Section 2.2. In case of too many nodes are connected to the same endpoint all data sent through cannot be handled properly and the result can be data loss, packet overlapping, and malformed packets. Moreover, mobility of the system can cause dynamic bandwidth needs [48]. Considering a situation where one sensor node moves and changes its connection point. This causes a situation where data through the new connection point increases if this point already had another sensor node. Therefore, the bandwidth needed for the connection increases dynamically.

In addition, data is wrapped in protocol-defined packets in wireless communication. The packets include a protocol-specified header, payload, and possible trailing bytes. For example Bluetooth® defines general packet format in three parts: access code, header, and payload [49]. Even though using protocol is necessary to route packets correctly in the system it adds overhead to data delivery, especially in low-energy devices where bandwidth is very limited. That is why the header to payload ratio is tried to keep minimal i.e. to use as much bandwidth as possible to transmit the payload. One way to keep this ratio low is to increase the amount of data in one packet. Thus one packet can include tens or hundreds of samples of data.

Timing

Considering a system described in Section 2.2, data is transmitted in a manner where one packet includes multiple samples of data. In a highly time-sensitive system, this can cause a problem because the exact time when the sample is measured is not corresponding to the time when it is sent out in the packet and even less to the time when the data is received and handled in the receiving node. A direct solution for the problem is to timestamp each data sample or data packet. However, timestamping is not a feasible solution in every system like battery-powered sensor devices. This was shortly discussed in this section before.

Moreover, there can be random fluctuations in timings at wireless systems. The characteristics of a wireless system create a change that packets are routed differently, get lost and are resend, or get completely lost. Especially mobility of the system nodes can cause this kind of behavior when the connection points are changed on the fly [48]. Therefore, packet-to-packet timing can vary or they can arrive completely in the wrong order.

Delay is a timing-related problem that is produced in wireless systems. In the system described in Section 2.2, packeting causes delay because data samples are buffered for a prescribed time, wrapped in a packet, and then sent out. The amount of delay caused by packeting is more related to the definition of the send interval in the system. For example in a system where a buffering time is 100 *ms*, the delay must be defined as at least 100 *ms*. In addition, nodes in the data path increase the actual delay of transmission. Delay is affected e.g., by the chosen routing approach and the dissemination strategy [46]. Also, other timing aspects in transmission events like sending time and reception time are affecting delay [50]. Calculating, measuring, or estimating the data path delay is an important aspect that should be taken into consideration when implementing a time-constrained system where data must be delivered inside a defined interval.

Reliability of Data Delivery

It is characteristic for an over-the-air system to have a loss of data or deliver malformed data over the connection. Especially mobility of the system causes difficulties to deliver packets reliably [48]. Changing connection properties such as signal attenuation and interference creates a dynamically changing environment, and the loss of data can be hard to predict. In medical applications, quality of service (QoS) is important because of the nature of data which can have an impact on the health of the patient [51]. For example, an ECG signal is not tolerant of interference, and thus its QoS should be high [43]. On the other hand, QoS requirements can differ between medical parameters [51]. ECG as a critical parameter needs high fidelity data with low latency but body temperature is usually tolerant to delays.

Extra steps should be considered when securing the reliability of data delivery during transmission. There are several different practices used in commonly known communication protocols for this purpose. For example, the Bluetooth Low-Energy protocol implements cyclic redundancy checks (CRC) and data retransmissions to increase QoS [52].

Data Synchronization

A precise data synchronization can be troublesome, especially in systems that have multiple sensor nodes transmitting data through the network. Synchronization problems raise from two aspects: data delay and non-ideality of clock sources [50]. For example, the system defined in Section 2.2 can have multiple sensors that transmit data simultaneously to a common hub. The precise synchronization is problematic because the length of the data paths can vary between source signals and it can even change dynamically when circumstances change. Therefore, it is nearly impossible to know when the actual measurement is done precisely. Timestamping can be used but it adds a tremendous amount of overhead to data transmission and processing, and normally it cannot be afforded in the low-power sensor systems. Without any extra sync methods or knowledge about a global clock, the sensor nodes can work only relying on the internal clock source of a microcontroller. Therefore, nodes are not synchronized with each other, and synchronization between the signals received from different sources cannot be known accurately.

Moreover, system clocks can cause synchronization errors in the long run. Clock sources are not ideal and they can skew, jitter, and have offsets but also environmental variables like temperature affect to clock source [50]. All these non-idealities add new aspects to data source synchronization. For example, a signal defined to be sampled at a frequency of 100 *Hz* can be measured with a source clock that had a small offset. Thus, the sampling of the signal was not precisely 100 *Hz*. In the long run, these variations in clocks cause synchronization offset between two measuring sources. Clock skew is the worst kind of problem because the error is increasing constantly.

One way to solve synchronization problems is to send recurring sync messages which can be then used to fix clock errors [50]. Still, data path length can be hard to take into account. Precise synchronization is hard to do, if not impossible. Still, it should be done in a reasonably manner or at least considered by the design.

3. ON-DEMAND NIBP SYSTEM DESIGN GOALS

The definition process for the design goals of the On-Demand NIBP system has involved people from several teams. For instance, system designers, regulation offices, software developers, clinicians as well as third parties have contributed to defining the design goals. Regarding the author's contribution, top-level design goals are mostly defined by other people on teams whereas the lower-level goals related to software implementation have more author's contribution. This section defines first high-level design goals for the On-Demand NIBP system, and then, design goals for each sub-software section separately. On-Demand NIBP system design can be divided into four subsections that are data processing, blood pressure estimation, activity and movement recognition, and deciding the need for blood pressure measurement.

3.1 On-Demand NIBP System Overview

On-Demand NIBP monitoring system is designed to provide solution to current problems in CNIBP methods. The system does not provide continuous blood pressure readings that clinicians could use for decision making. The On-Demand NIBP system provides additional information on a patient's blood pressure in moments where it would not be available otherwise. The system works as one kind of guard that triggers a new blood pressure measurement or provides a request to make a blood pressure measurement when a possible change in blood pressure is detected. In this manner, the system provides additional information for clinicians about the patient's state of health indirectly. For this purpose, the CNIBP method is used. PWA analysis was chosen as the most suitable CNIBP technique. The algorithm monitors blood pressure changes based only on the PPG signal. The PPG signal is already available on most patient monitoring systems in the sense that oxygen saturation is a common parameter monitored in modern monitoring systems. The SpO2 sensor provides the PPG signal for the On-Demand NIBP system. Thus, any additional sensors to the monitoring system and patient's skin are not attached, which would be the case when using PWV techniques or Volume Clamp. Also, utilizing already an available sensor device has a positive effect because there is no need for the development of new sensor devices and integration of them into the system.

In addition, common problems of CNIBP methods are considered. A possible drifting of

CNIBP reading is not a huge problem in the On-Demand NIBP system because CNIBP measurement values are not shown outside of the system and thus diagnoses are not based on continuous blood pressure values. CNIBP methods are only used to detect possible changes in blood pressure and trigger a new oscillometric blood pressure measurement which is then used to make an actual diagnosis of the patient health. Thus, the worst outcome from the drifting or wrong reading is an additional, unnecessary blood pressure measurement. Several unnecessary measurements cannot be allowed because they can distract the patient. Those can be handled within time limits.

The decision to not show continuous blood pressure values also eases regulation processes. For example, European Union regulation on medical devices (MDR) defines in Annex VIII, Chapter III, Rule 10 that medical devices that monitor vital physiological processes and variations in the monitored process can result to immediate danger of the patient are classified as Class IIb [53]. Blood pressure falls in that category. When the On-Demand NIBP system does not provide direct clinical information or no treatment decisions are made based on the system, the classification can be relaxed. For instance, if the On-Demand NIBP system is considered as an individual software component which only intention is to provide requests for a clinician to make a new blood pressure measurement when a possible blood pressure change is detected, then the system is not providing diagnostic information directly. Therefore, validation processes can be more relaxed for this system compared to a monitoring system that provides direct diagnostic information.

Motion artifacts are handled using an accelerometer. In a used patient monitoring system, an accelerometer signal is available from sensors' locations to detect the movement and posture of a patient. The used patient monitoring system is described in Section 2.2. An accelerometer can detect a movement and therefore at the event movement is detected a CNIBP reading can be ignored. PWA analysis affected by motion artifacts does not affect the output of the system in this case at all. An accelerometer data can be also used in this system to try to prevent artifacts in an oscillometric blood pressure measurement. In case of movement or unsuitable posture blood pressure, which are known to affect a blood pressure measurement performed with the oscillometric method, a measurement could be delayed until the patient status is desirable.

3.2 High Level Design Goals for the On-Demand NIBP System

Preconditions and Performance Characteristics

The highest-level design goals for the system consider preconditions when the system can be used, performance characteristics, operating modes, and operating conditions. From an input parameter point of view, the system needs a PPG signal source (SpO2

Sensor) and at least one three-axis accelerometer signal source from the location of the PPG signal. If these input signals are not present, the system cannot function properly and is disabled. In addition, the system provides automated triggers only if at least one set of calibration values for blood pressure (SBP, MAP, DBP, PR) are available from a cuff measurement. A cuff reference is received from an NIBP sensor. Otherwise, the system stays idle until calibration values are provided.

In addition, the On-Demand NIBP system is active only in certain physical conditions and patient groups. A system operating range for systolic blood pressure is 60 to 210 *mmHg* and for diastolic blood pressure is 40 to 110 *mmHg*. Moreover, a pulse rate should be between 40 and 120 beats per minute. A reference blood pressure and pulse rate are based on the last cuff measurement. A patient's age should be 16 years or older.

From the performance point of view, an initial target for the On-Demand NIBP system is to detect 80 % of blood pressure changes that are larger than 15 % from the calibration value. The reference for the blood pressure is mean arterial pressure which is derived from the latest cuff measurement. Also, the same performance target applies to pulse rate changes than for the blood pressure. Both targets apply only when a patient is laying on the bed.

In case any of the conditions mentioned above is not fulfilled, the system is disabled and does not provide information about blood pressure changes. The system informs the current state of the system to medical staff.

Operating Modes

The On-Demand NIBP system provides two new operating modes that are extending manual and auto cycling modes. The standard modes are briefly discussed in Section 2.1. Figure 3.1 shows different operation modes of the prototype NIBP system and their relations with each other. The two new modes that On-Demand NIBP system implements are pleth-supported auto cycling and pleth-supported notification modes. The pleth supported auto cycling can be considered as an auto cycling mode but with a blood pressure change detection system and an automatic triggering of cuff measurement when desirable conditions are met. Pleth-supported notification can be defined as manual auto cycling where the system prompts notifications to take a cuff measurement at a user-defined interval but also uses the blood pressure change detection system and notifications at change events. The distinction to the standard auto cycle is that the system does not trigger the measurement automatically but requires a manual measurement by a clinician. Names are derived from the system's nature to use a PPG signal to detect blood pressure changes and act based on that. The preconditions mentioned above apply to both modes. Modes are enabled by a clinician the same way as a standard spot check or a standard auto cycling mode is enabled when an NIBP sensor is connected to a pa-

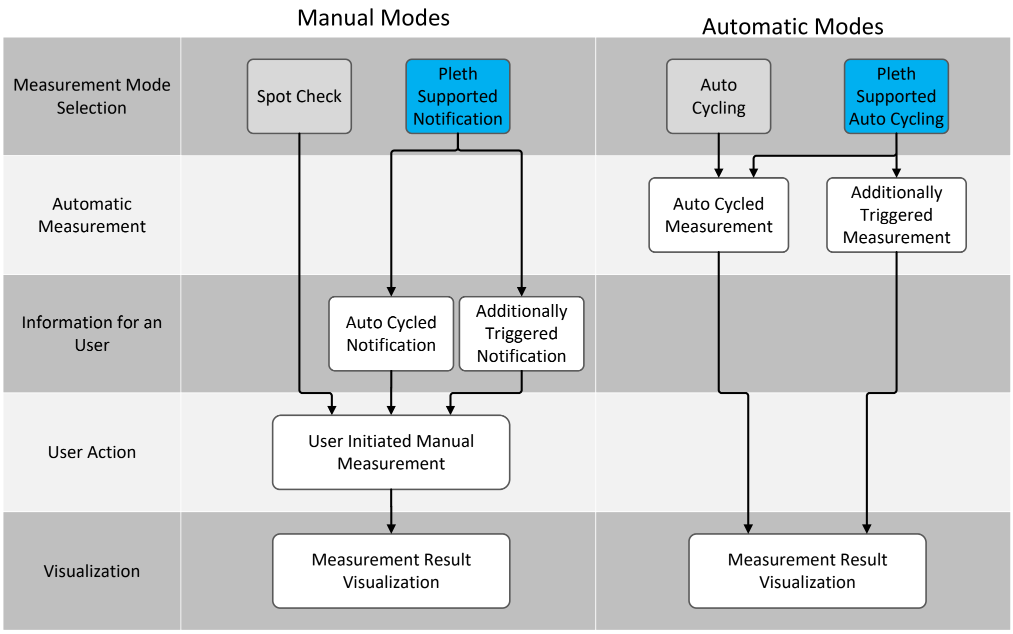

Figure 3.1. *Relationships between NIBP system components. Modes marked with blue background are new designed modes.*

tient monitoring system. The system also informs with a symbol when the blood pressure change detection system is in use.

Pleth-supported auto cycling works in parallel with auto-cycling where a user has defined an interval for automated blood pressure measurement. In addition, On-Demand NIBP system continuously monitors blood pressure changes and triggers additional blood pressure measurements between automated ones when a set of conditions are fulfilled. The conditions are presented in Section 3.6. The automated trigger of blood pressure measurement by On-Demand NIBP system can only happen when an auto cycled interval of blood pressure measurement is defined. Furthermore, the cycle time of auto cycling must be set over 15 minutes. The additional trigger can be considered as a cycled measurement when the triggered measurement takes place less than 10 minutes, or 30 % of cycle time, from when an auto-cycle measurement should have happened.

In a pleth-supported notification mode, a direct trigger of a blood pressure measurement by On-Demand NIBP system is not allowed. Therefore, the NIBP sensor is not required to be continuously present in the patient monitoring system after the first calibration measurement. In this mode, On-Demand NIBP system keeps monitoring blood pressure changes in the background and when conditions are fulfilled, a notification is prompted to inform a clinician to take an additional spot-check measurement with an

NIBP sensor. A notification stays displayed until it is acknowledged by a clinician, even in a situation where conditions have changed again and they are not fulfilled anymore. The pleth-supported notification mode is not allowed to operate individually without auto cycling. Thus, a notification prompt interval must be set which prompts notifications for clinicians to take blood pressure measurements regardless of the status of On-Demand NIBP. From a regulatory perspective, an individually operating system would need extra steps to take into use.

3.3 Data Processing

Design goals for data processing consist of a pre-processing of input signals, dispatching a status of need for a blood pressure measurement forward, and handling the system's sub-parts as well as sensor connections. These definitions control the functioning and flow of the whole On-Demand NIBP system.

System's input signal processing

An infra-red pleth signal with 109 *Hz* sample rate, a one cuff measurement for initial calibration, and a three-axis accelerometer signal with 50 *Hz* sample rate from the location of a PPG signal are mandatory to input data for On-Demand NIBP system. Also, signal quality indices of oxygen saturation and impedance respiration rate measurement are used to determine the reliability of the system. Thus, SQIs of the measurements are input signals for the system. IRR SQI is optional for the system.

On-Demand NIBP system pre-processes input signals of the system. System converts and buffers the data before broadcasting signals towards algorithms that consume signals. For a continuous blood pressure estimator (CBPE) algorithm, which calculates continuous blood pressure estimate, a PPG input signal is converted to a floating-point number. For a patient context classification algorithm, an accelerometer signal is converted to a fixed-point number. Input buffer sizes for the blood pressure estimation algorithm and the activity classifier are defined in Table 3.1 and Sections 3.4 and 3.5. An infra-red pleth and an accelerometer signal are also time-stamped by a sample basis. Relative timestamps are sufficient in On-Demand NIBP system.

Pre-processing of the input signals includes also detecting gaps and invalid data values before being saved into input buffers. A gap detector detects when packets are lost over the air connection and fills gaps with invalid values. This keeps timings of signals and algorithms intact which is crucial for the system that solely trusts on a fixed and predefined sample rate. In addition, gaps are categorized based on the size. The system is not required to be able to recover from large data gaps. A gap of over 5 minutes (300 s) is considered not recoverable. In the event of a data gap over 5 minutes, On-Demand

Table 3.1. *On-Demand NIBP system input parameters, formats and buffer sizes. Note that only a one accelerometer signal from the SpO2 sensor's location is mandatory. Other accelerometer signals are optional.*

Input Parameter	Data Format	Sample Rate (Hz)	Buffer Size	Mandatory
IR PPG Wave	Floating point	109	1635	x
SpO2 SQI	Floating point	1	None	x
IRR SQI	Floating point	-	None	
BP Measurement	Integer	-	None	x
Accelerometer Wave	Fixed Point	50	1000	x

NIBP system issues reset for input buffers and algorithms. Invalid values are changed to invalid values defined by the algorithm that consumes the input signal.

Sensor Connection Handling

Furthermore, connections to available sensors in a patient monitoring system are needed to be considered. The system observes current connections and connection changes to sensors. A PPG signal from the SpO2 sensor is mandatory for On-Demand NIBP system, thus, making the SpO2 sensor mandatory. Disconnection of the SpO2 sensor should disable the system and reset the algorithms and input buffers. Moreover, a connection break to the SpO2 sensor is needed to examine. A too-long break in data flow could cause unexpected behavior of the system and thus need to be handled. This goes along with a gap detecting definition. A connection break of over five minutes should raise On-Demand NIBP system reset. From an accelerometer data point of view, the same applies in regards to resetting the system. Separation into PPG signal breaks is that a long break on an accelerometer data should reset only buffers and algorithms related to that specific accelerometer data source. The same applies to the disconnection of an accelerometer data source.

System's Output Handling

On-Demand NIBP system is also dispatching output status forward. An output of On-Demand NIBP system consists of information about the need for blood pressure measurement. A receiver of output depends on whether the operating mode is in use. If a pleth supported notification is active, the output is passed to the user interface and upstream towards a patient data viewer. Both targets are responsible to inform clinicians about the need for blood pressure measurement. If again, pleth-supported auto cycling is chosen as the operating mode, a result of the output should be directed towards an NIBP sensor to trigger a new measurement directly. In this case, the target would be a sensor data communicator.

3.4 Optical Blood Pressure Estimation Library Specifications

Blood pressure estimation is provided for the system by an algorithm which is referred to in this work as CBPE. This algorithm is responsible for calculating delta blood pressure and pulse rate. The calculation is based on pulse wave analysis that was discussed in Section 2.1.1. CBPE algorithm is developed and owned by an external company and it is considered as an Off-The-Self (OTS) software. The design goals of the library are done with the external company.

Algorithm's Input

CBPE algorithm estimates blood pressure changes based on infra-red PPG signal. CBPE uses an input signal length of 15 seconds. The sensor provides IR pleth signal with a sample rate of 109 Hz. The buffer size can be calculated:

$$S_b = t_w * f_a, \tag{3.1}$$

where S_b is buffer size in number of samples, w_s is window size in seconds (*s*) and f_a is the sampling frequency of the input data. Thus, the input buffer is 1635 samples. In addition to IR pleth signal, the input of the algorithm requires a timestamp array where each IR pleth sample is time-stamped individually. The timestamp array should be in the format of floats and timestamps should correspond to seconds. In reality, the CBPE algorithm is processing two minutes or 13080 samples of IR pleth signal every time input is fed to the algorithm. This means that a sliding processing window of 2 minutes is used where 15 seconds of new data is appended to the end of the processing window. The algorithm expects IR pleth input signal in the range 1 to $2^{24}-1$ (or 16 777 215). Zero input value is considered as an invalid value by the algorithm. The behavior of the library is not defined with input values that are outside of this range. In addition, the timestamp array's maximum input value is 900 seconds. This is due to the loss of precision in float type variables in larger values which causes errors in the estimation calculation. In addition to IR pleth signal and timestamp array, optionally reference blood pressure and pulse rate from cuff measurement can be passed for the library at any time point. This reference measurement result needs also a timestamp.

CBPE library has one time per initialization input variable that consists of biometrics of the patient. These are age, weight, height, and gender. This information is fed for the library ones every time the algorithm is initialized or re-initialized e.g. when the patient is changed. The biometrics information is optional input and if it is not available in the system, minus one (-1) value can be used to notify of the missing input. The version of the CBPE library at the time of writing does not use patient biometrics information in the calculations of blood pressure estimation.

Algorithm Output

The output of the library is in two parts. Firstly, the algorithm outputs a state of the library which can be 'Result Available', 'Result Not Available', and 'No Valid Initialization'. 'Result available' means that processing was finished correctly, and output is valid while 'Result Not Available' means that processing could not be done, and the output of the library is not valid. 'No valid Initialization' states that the library was not initialized correctly, and thus, processing of the input data was not done. The second part of the output consists of an actual estimate of the delta blood pressure, a pulse rate, and the quality index of the estimation. Delta blood pressure values are provided for systolic blood pressure, mean arterial pressure, and diastolic blood pressure. Delta blood pressure value corresponds to a change of blood pressure from the last valid value that the library has outputted. The first valid estimation is always zero. In a case of invalid output, delta blood pressure values are set to Not-A-Number (NaN). In addition to the output mentioned above, CBPE outputs lists of active warnings from the last data processing. Examples of warnings provided by CBPE are warning of the insufficient valid input samples, wrong sampling rate, and non-physiological signal. In case of invalid output, the library should inform the interface about a failure or a problem with active warnings.

3.5 Patient Activity Classification

The goal of the patient activity detection in On-Demand NIBP system is to detect a movement on a location of PPG signal source, a patient movement generally, and the patient posture. There are two reasons for this design goal. Firstly, blood pressure measurement used in the system is an oscillometric-based measurement that is highly affected by the posture of the patient. This is shortly discussed in Section 2.1. A posture needs to be desirable when triggering a blood pressure measurement automatically. A second reason considers the CNIBP method in use. PWA analysis based on PPG signal is affected by motion artifacts that generate erroneous readings to blood pressure estimation. Therefore, a motion of the hand where the Spo2 sensor (a PPG signal source) is located is detected by the system. To detect patient activity, three-axis accelerometer data is used. It can provide movement detection as well as posture status by using feature calculation of accelerometer signal. Based on the reasons described earlier, a patient activity classification needs to support at least two accelerometer signal sources.

In Section 2.2 the used patient monitoring system was described. In the system, accelerometer sources are available on the locations of the sensors. For hand movement detection, an accelerometer of the SpO2 sensor is mandatory. In addition, the hand movement can be used to detect an overall movement of a patient. For posture classification two possible sources are available: an IRR sensor and an NIBP sensor. A natural selection for this is an IRR sensor because it is located at the patient's chest, thus providing a good location to assess the posture. Nevertheless, an IRR sensor is not defined as a mandatory sensor for On-Demand NIBP system. In some situations, the patient might not need respiration rate monitoring and therefore, a clinician can decide not to connect an IRR sensor to the patient monitoring system at all. Ergo, accelerometer data for posture calculation is not available. In that case, an NIBP sensor's accelerometer can be used to assess the posture of the patient. The location of the NIBP sensor is not optimal for posture estimation but provides more reliable estimation than using the SpO2 sensor that is located at the wrist. Therefore, the patient activity classification supports three different accelerometer data sources. Moreover, the sources are itemized from each other, and classification of patient activity is done separately for each source. In addition, for developing purposes, the system extracts a wide range of different features from the accelerometer data including heuristic, time-domain, and frequency-domain features. This eases the development of activity classification further in the future.

Similarly as continuous blood pressure estimation, patient activity classification is intended to buffer input data and perform analysis in set intervals. Each buffer consists of three-dimensional accelerometer waveform (x, y, z) from one source. Based on earlier work [4], feasible windowing length for calculating activities from accelerometer data is 20 s. The system provides 50 Hz sampling frequency for the acceleration waveform. Therefore, using equation 3.1, a buffer size for each input signal is 1000 samples. Notice that one sample here means one value for each axis and a timestamp.

During the definition process, there was observed a possible need for activity status outside On-Demand NIBP system. Therefore, an activity classifier should be implemented as an individual block that can be queried to provide a new classification for a patient activity. When asked, an activity classifier uses the most recent 20 seconds of acceleration data from each available source, extracts features, and classifies activities. As a result, activities from each available source are returned.

3.6 Decision Making for New Cuff Measurement

An algorithm called Smart Trigger was defined for deciding the current need for additional blood pressure measurement. The main design goal of the algorithm is to detect sufficient and sustained change in the patient blood pressure. In addition, it considers the current state of the patient to detect a feasible situation to perform blood pressure measurement. The design goals of Smart Trigger are defined mostly by other team members.

Six input parameters were defined for determining if a new blood pressure measurement

Table 3.2. *Smart trigger input parameters. Table shows validity limit for input parameter as well as time limit to fulfill conditions for new blood pressure measurement. All conditions are required to be fulfilled before a measurement can take place*

Input Parameter	Parameter Validity	Time Limit
Time from last Calibration	> 15 min	-
Signal SQIs	> 50 %	-
Hand Movement	No Movement	5 min
Patient Posture	Lying	5 min
CBPE Output Status	Valid	5 min
MAP Change	> 15 %	5 min

is needed. Five precondition inputs are time from the last calibration, SQIs of different source signals, movement of the hand, a posture of the patient, and CBPE algorithm output status. The sixth input parameter is a change of mean arterial blood pressure from the last calibration value. Smart Trigger has three output statuses: ”Measurement needed”, implying a new blood pressure measurement should be performed, ”Measurement not needed”, no large enough change in a mean arterial pressure is detected and ”Conditions not fulfilled”, at least one precondition is not fulfilled, thus a blood pressure measurement is not considered as needed or conditions are not suitable for measurement. Only when an output state is set to ”Measurement needed” does the system trigger new blood pressure measurement or prompt a notification based on the current operating mode. Table 3.2 shows all input values, their validity limits, and time limits how long parameters need to stay valid.

Next, input parameters’ roles setting the output state are explained. There are six conditions that all need to be fulfilled before a new blood pressure measurement can be triggered or notification prompted.

Trigger Prevention Interval

Time for last calibration (aka. trigger prevention time) is used to not overload the patient or the medical staff by continuously triggering blood pressure measurements or prompting notifications. In addition, this allows the patient to settle down after a blood pressure measurement as a measurement situation can cause stress or at least movement which affects blood pressure and PWA analysis. The algorithm requires at least 15 minutes elapsed from the last calibration before a state can be set ”Measurement needed”. Thus, if trigger prevention time is not elapsed from the last calibration, the output is set ”Conditions not fulfilled”.

Low Hand Movement and Suitable Patient Posture

Too much movement in the hand where the SpO2 sensor is located is considered as a preventing factor for blood pressure measurement or notification prompt. This is due to the nature of movement to cause artifacts to the PPG signal and thus erroneous reading to the continuous blood pressure estimation. Moreover, a patient's movement generally is not a suitable situation to perform oscillometric-based blood pressure measurement. Additionally, the posture of the patient is checked. In case of the patient's posture being anything else than lying, new blood pressure measurements should not be triggered. Both, hand movement or unfavorable patient posture sets output to ”Conditions not fulfilled”. In addition to the posture and movement check, both use 5 minutes of settling time. This means that if there is movement detected at the hand or a posture change to any other than lying or sitting during the last five minutes output will be set to ”Conditions not fulfilled” and new blood pressure measurements should not be triggered.

CBPE Algorithm Output Validity

CBPE algorithm output must be valid for a required time before any measurements can be triggered or notifications prompted. CBPE provides the actual estimate of blood pressure change that is used to determine sufficient change in blood pressure and thus, the need for blood pressure measurement. Therefore, the CBPE output needs to be valid for a required time to reliably use its output for determining the need for blood pressure measurement. The validity time is set to 5 minutes. An invalid output of CBPE algorithm or not met time window sets the output to ”Conditions not fulfilled”.

Signal Quality Indices Level

Signal quality indices of the CBPE algorithm, SpO2 measurement, and, if available, respiration rate measurement are used to validate the current status of the other input parameters. For example, low SQI in SpO2 reading can correspond to incorrect estimation of continuous blood pressure. Therefore, SQIs must be high enough to trigger cuff measurement or prompt notification. The required level for SQIs is over 50 % to set the output to ”Measurement needed”. The SQI level being too low sets the output directly to ”Conditions not fulfilled”.

Mean Arterial Blood Pressure Exceeds the Set Limits

The last input parameter, mean arterial pressure, is used to detect an actual change in blood pressure. If the mean arterial pressure change with respect to the calibration value stays over a set limit for a set time, the output of Smart trigger is set to ”Measurement needed” in case of all the other conditions mentioned above are fulfilled. The limit is set currently to ± 15 %. The deviation time, meaning the interval MAP reading needs to exceed the limit is set to 5 minutes. If MAP reading is not over the limit or deviation time is not fulfilled, output is set as ”Measurement not needed”.

4. SYSTEM IMPLEMENTATION

The prototype implemented in this work differs from the system specified in Section 3 mainly because of a lack of dependent software systems. In addition, the prototype does not necessarily fulfill all design goals but can provide development data for the future. The most important missing dependencies to fulfill design goals are the lack of communication handlers with NIBP Sensor and customized messages from an ambulatory hub to a patient data viewer. The lack of NIBP sensor communication components prevented the integration of auto cycling behavior and a measurement auto triggering defined in Section 3 to this prototype. The calibration of the On-Demand NIBP system to cuff measurement was also left out. Moreover, a custom notification was implemented for the purpose to show clinicians when a new blood pressure measurement is needed. The notification implementation will not be the final solution to inform clinicians because it cannot communicate with a patient data viewer nor the notification can be shown in a viewer.

4.1 Overview of the Implementation

The software implementation of On-Demand NIBP system is divided into four entities which are a blood pressure estimation calculation, a patient activity classification, determining the need for blood pressure measurement, and a notifier. Entities and their interfaces between each other are represented in Figure 4.1. The blood pressure estimation entity consists of IR PPG input waveform processing and the CBPE algorithm. The patient activity entity consists of an accelerometer input waveform processing and a patient activity classification algorithm. The blood pressure measurement determination entity consists of algorithms handling and Smart Trigger algorithm. Lastly, a notifier entity handles user interface actions like prompting a notification and handling user actions. The data processing is shared between blood pressure estimation and blood pressure measurement. This so-called On-Demand NIBP system's data processor handles IR pleth input data as well as triggering of the algorithms inside the entire On-Demand NIBP system. A communication server between UI- and data processes are now considered under the notifier entity since it is the only subsystem that is listening to the server state changes in the current prototype. The server is an inter-process communication (IPC) server that operates as an individual communication interface thus, it is not part of the notifier.

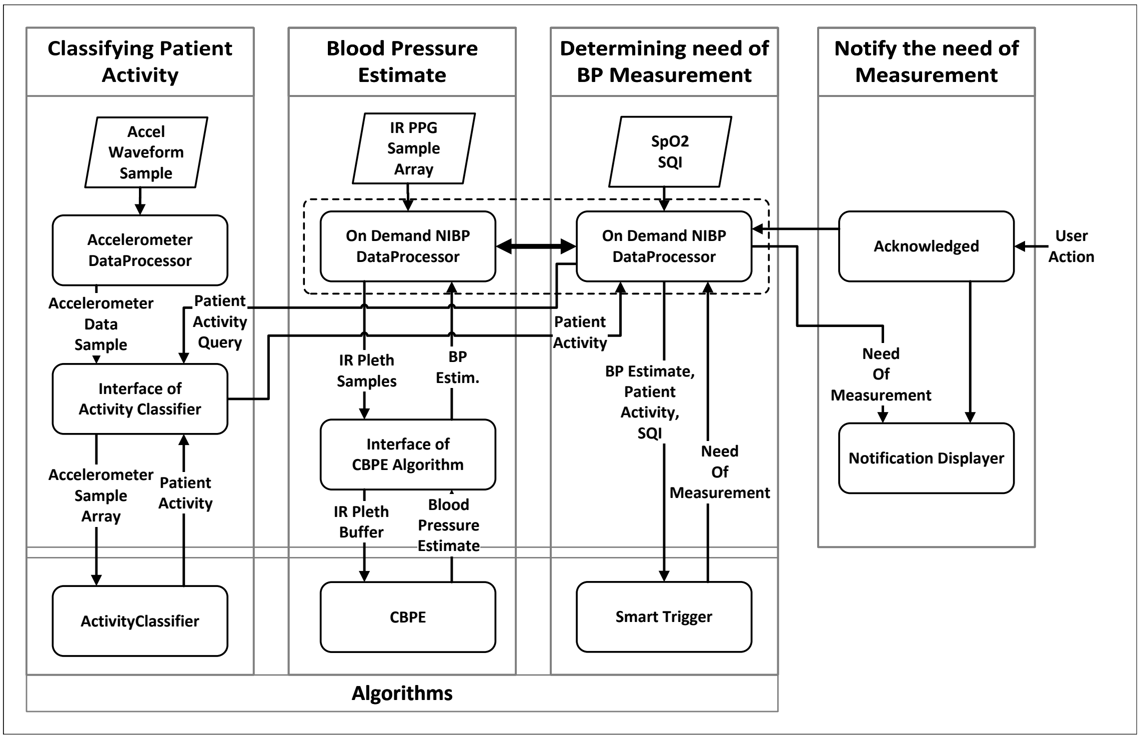

Figure 4.1. *Overview of the Implemented On-Demand NIBP System. Based on subsystem purpose, the system can be split into four major parts: activity classification, blood pressure estimation, determining the need for BP measurement, and notifier. Earlier mentioned data processing is implemented inside of each subsystem. The On-Demand NIBP data processor implements data processing of the blood pressure estimation and determining a need for blood pressure measurement.*

The system has three types of input signals. The IR pleth waveform is mandatory to make a continuous estimation of the blood pressure change. Three-axis accelerometer waveforms from all connected sensors are used to determine patient movement and posture. The possible sensors used in the On-Demand NIBP system are a SpO2 sensor and an IRR sensor. An NIBP sensor is not currently supported by the patient monitoring system and therefore there is no support for NIBP sensor in the On-Demand NIBP system. In addition, signal SQIs are optionally used in determining the need for blood pressure measurement albeit not used currently.

The system operates based on IR Pleth input signal received from the SpO2 sensor. The IR pleth signal is saved in a data buffer that can hold 15 seconds of pleth data with 109 *Hz* sample rate. Filling the buffer up to maximum capacity triggers other On-Demand NIBP subsystems in a chain which at the end outputs a status for the need of blood pressure measurement. Therefore, the IR pleth signal is controlling the execution of the On-Demand NIBP system. An On-Demand NIBP system's data processor is responsible for handling incoming pleth signal, triggering other algorithms in the system, and sending the output status forward to the other systems. A Figure 4.2 represents the execution of the On-Demand NIBP system's data processor when the SpO2 sensor connection is

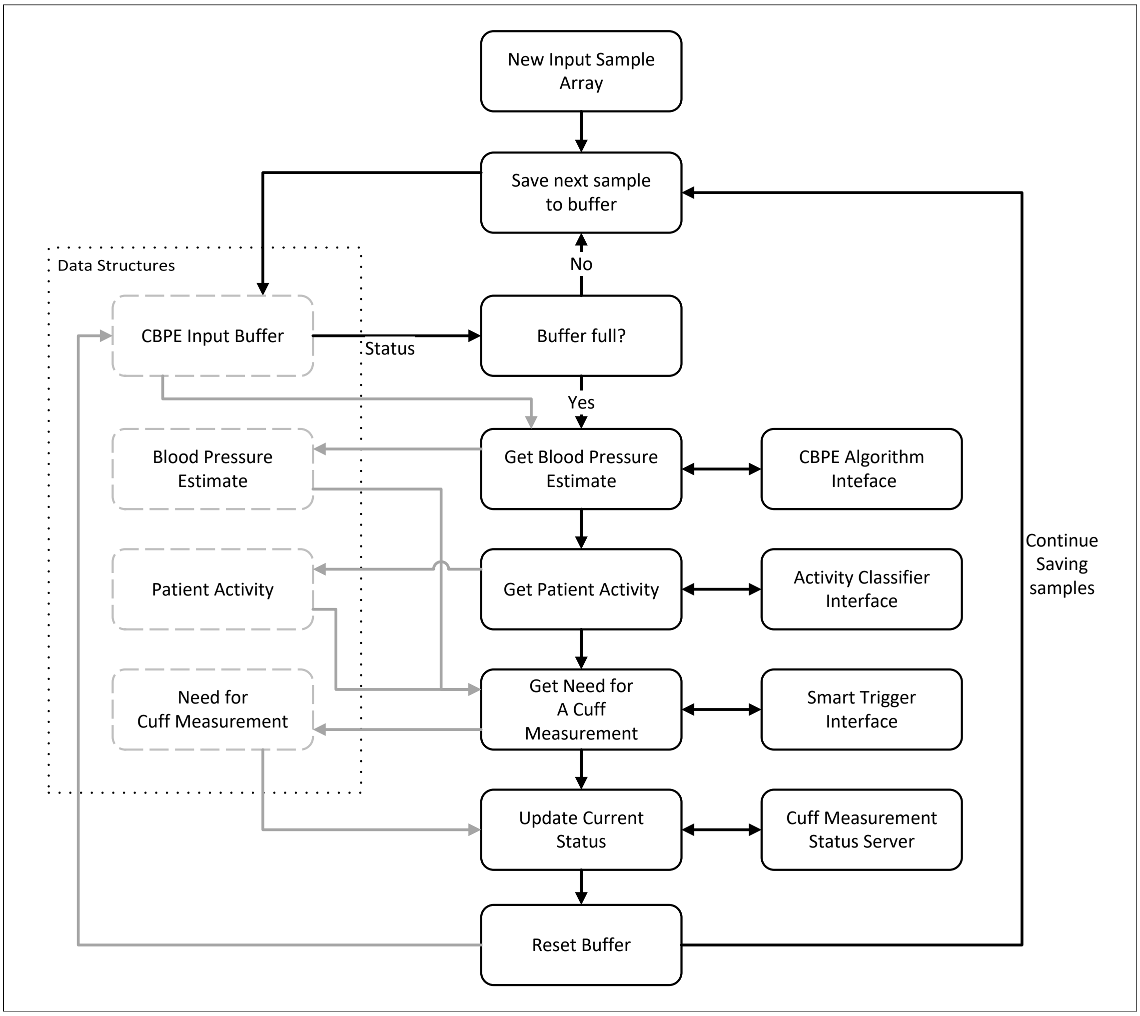

Figure 4.2. *On-Demand NIBP System execution handling. When IR Pleth input array is full, algorithms are triggered in sequence and data saved to data structures. Grey arrows and boxes are representing data handling and data structures.*

stable. In the figure, grey arrows and boxes represent data handling while black arrows and boxes represent state changes and algorithm calls.

As stated before, the system saves IR pleth input samples to the buffer if there is room in the buffer. In addition, the accelerometer input waveform is continuously saved to buffers by an accelerometer data processor. Other subsystems in the On-Demand NIBP system stay idle at this point. A more detailed description of input data handling is described in Section 4.2. A full IR PPG input buffer triggers a determination of the need for blood pressure measurement by triggering algorithms in following order: CBPE, the activity classifier, and Smart Trigger. The 15 seconds of IR PPG signal is fed into the CBPE algorithm which outputs blood pressure estimation as a delta change. The change is appended into a blood pressure estimation trend. The activity classifier outputs a patient activity based on current accelerometer waveforms available in input buffers. The patient activity is calculated by every available source individually. A blood pressure estimate and a patient activity are then fed into Smart Trigger which provides the need for a blood pressure measurement as an output. Lastly, the output state of Smart Trigger is forwarded using a blood pressure measurement status server which broadcasts the state to all systems that are listening to the state of the server. In the current implementation, only the UI process is listening to the status which then handles prompting of the message. Moreover, if the auto-acknowledge mode is used, output status is automatically acknowledged and status is not updated to the server. Different operating modes of On-Demand NIBP system are described in Section 4.2. After the cycle, the system continues to the next iteration as represented in Figure 4.2.

Saving of Development Data from the On-Demand NIBP System

In addition to specifications, the system implements development data (i.e., research data) saving functionality which saves On-Demand NIBP system-related parameters during execution. The development data files are not comparable to system logs where e.g., error logs or state changes are saved but are instead .csv files where each column represents parameter to be saved and each row represents the time point the recording was done. The parameters are described by the header of the file. The saved data files include output and warnings of CBPE, blood pressure trend, features and classifier output of each sensor location, and the smart trigger's output and parameters. Every new association of the SpO2 sensor creates a new folder for this data with a timestamp when recording started. The header of the file is written to the first line in file creation. Data entries are appended to a new line. Other parts of the system can call the writer to save one line at a time. The saving to the folder continues if a SpO2 sensor connection is maintained. In case of disconnection, On-Demand NIBP system is disabled, and thus, the saving of data is discontinued.

4.2 Data Processing

The data processing is not implemented as an own entity because each entity implements its own data processing. Data processing includes handling sensor connections, parsing input data, and dispatching data and status forward to other parts of the On-Demand NIBP system. Nevertheless, the implementation, that fulfills design goals defined in Section 3.3, is explained here since the implemented structure of input data parsing or handling sensor connections is similar between entities.

The input data processing is handled in two entities which are an accelerometer data processor and an On-Demand NIBP system's data processor. The accelerometer data processor handles accelerometer-related input data and On-Demand NIBP system's data processor handles SpO2 input data. Both entities register as an observer for the related data packets that are routed from a wireless sensor node over MBAN connection to a message-receiving end in the Ambulatory Hub software. The basic accelerometer and

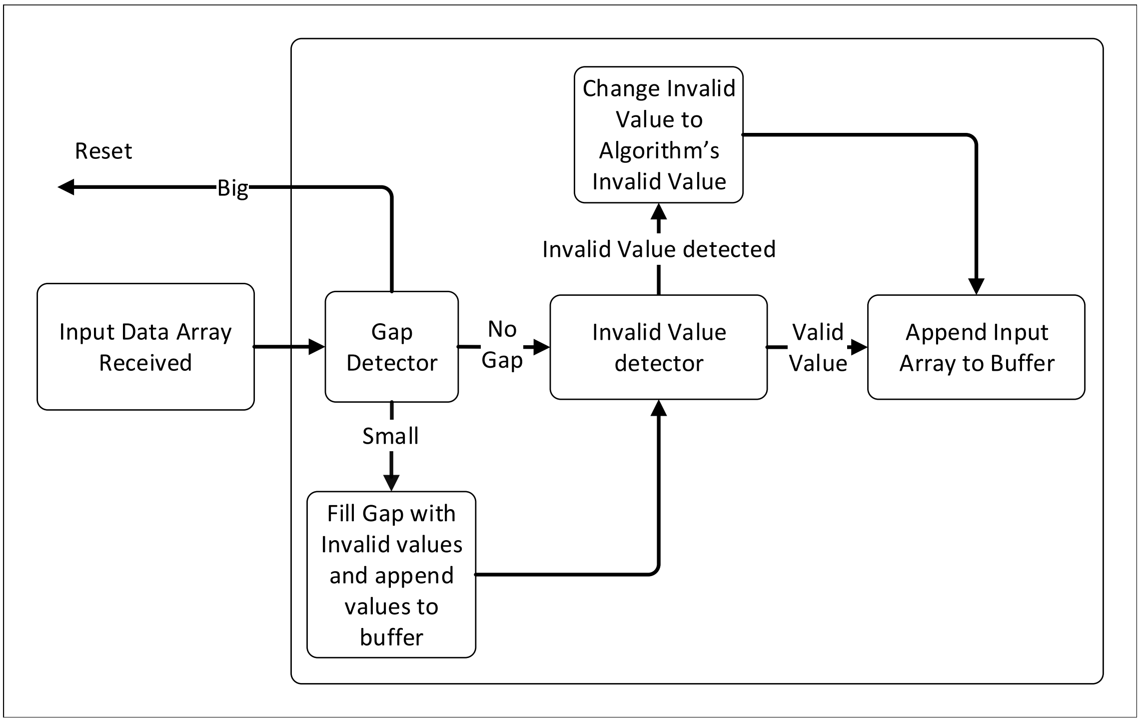

Figure 4.3. *Basic implementation for input data. Input data is received as arrays of samples for both IR pleth and accelerometer. At first, gaps are detected and then invalid values from input samples are changed to corresponding invalid values for the target algorithm and lastly array is appended to buffer for a sample at a time.*

IR PPG input waveform handling is illustrated in Figure 4.3. The On-Demand NIBP data processor is responsible for handling the system's execution.

Input Data Processing

In wireless communication, the waveform is sent in packets that include a portion of a waveform. In addition, packets include a sample index of the first sample in the packet to track the integrity of the waveform signal. Thus, the On-Demand NIBP system receives its input waveform as data packets rather than a sample at a time. Data processing blocks use sample indices included in the packets to notice lost packages and determine the size of gaps. In the event of a gap, an array of invalid values is created and appended to the input buffer before processing the actual received data. Then, the received waveform samples are checked for invalid values and appended to the buffer. Moreover, a gap size is checked. Gaps sized under 5 minutes are filled with invalid values. Detection of a bigger gap initiates a system reset. Every waveform source has its entity of the gap detector that follows only the one input waveform. Therefore, sample indices and gaps are not mixed between the waveforms. The buffer size for the IR pleth signal is 1635 samples. As described before, when IR pleth input buffer is fulfilled, a chain of data processing is executed resulting in the status of need for a blood pressure measurement. After that, the buffer is reset and started to fill back up from the first slot of the array. The accelerometer

Table 4.1. *On-Demand NIBP system operating modes.*

Operating Mode	Action	User Actions	Note
Disabled	No actions	-	-
Auto-Acknowledge	Acknowledge Change	Automated	For development
Prompt-Notification	Notification	Acknowledgement	-
Auto-Trigger	Trigger BP Measurement	Automated	Not implemented

waveform buffer is 1000 samples long for each axis and sensor. The accelerometer buffer is a circular buffer, so it behaves differently. When it is filled to the maximum capacity for the first time and a new sample is received that could not be saved anymore, samples are started to be overwritten from the buffer the oldest sample first. Therefore, buffer always contains 1000 newest samples of the received accelerometer waveform, and the latest 1000 samples are used to classify activity whenever it is asked. The implementation of the circular buffer is done in earlier work on the topic [3].

Sensor Connection Handling

Sensor connections are observed in both input data entities. The hub application has a separate sensor connection manager to which different subsystems can register and listen the state changes. Every time a state changes it is updated inside the On-Demand NIBP system. Making a new connection to a sensor triggers algorithm and input buffer initialization while disconnecting sensor triggers reset of the algorithms and input buffers. Depending on a connected or disconnected sensor, the effect will be different. In the case of pairing an SpO2 sensor, the On-Demand NIBP system is initialized meaning the CBPE input buffer and CBPE algorithm are initialized. Also, Smart Trigger algorithm is initialized. Moreover, the accelerometer data processor is initializing a buffer and an activity classifier for the accelerometer waveform coming from the SpO2 Sensor. The event of disconnecting the SpO2 sensor resets the aforementioned buffers and algorithms. Connecting the IRR sensor only initializes buffer for accelerometer data and the activity classifier. There is no effect on other subsystems in On-Demand NIBP system. The same applies to the disconnection of the IRR sensor. Only the activity classifier for an IRR sensor location and the related input buffer is reset.

Operating Mode

The On-Demand NIBP system's data processor controls triggering the algorithm and passing data forward in the system like described in the Figure 4.2. Four operating modes are implemented in On-Demand NIBP system. These are Disabled, Auto-Acknowledge, Prompt-Notification, and Auto-Trigger. These are represented in Table 4.1.

The operating mode is used to determine the next action after calculating the need for a blood pressure measurement. If the operating mode is set to disable, no action at all is taken place in the system including initializing algorithms or buffering input data. The system needs to be enabled to initialize subsystems or parse input data. The operating mode being an auto-acknowledge, the smart trigger output is automatically acknowledged, and the algorithm is recalibrated to current blood pressure readings calculated by the CBPE algorithm. Status messages are not forwarded to other systems in this mode. The auto-acknowledge mode is used for developing purposes to collect continuous data e.g., overnight, and later examine the system functioning. In prompt-notification mode, the need for a blood pressure measurement status is forwarded to the IPC server that notifies listening systems about the status update. In this mode, messages are forwarded to the UI process which then shows the notification. More detailed description of the notification is described in Section 4.6. If a new blood pressure measurement is needed, On-Demand NIBP system waits for an acknowledge message that then triggers recalibration and continuing of normal operation. Acknowledge message is received through the server after a user has acknowledged the state. Auto-Trigger mode intends to automatically trigger a new blood pressure measurement using an NIBP sensor connected to the system. However, missing implementation for the NIBP sensor connection prevented to implementation of this feature and only a place holder was created.

4.3 Hand Movement Detection and Patient Posture Recognition

Implementation Options

There were three different proposals for the activity classification implementation:

1. As part of the On-Demand NIBP system
2. An own implementation where classification is triggered by the component that needs activity at that time
3. An individual implementation as a server that provides a new status when enough input data is received for the classification.

The first proposed design is solely owned and controlled by the On-Demand NIBP system. This was considered as a weak design approach because the activity classification could not be used by other systems in the Hub application and there was already discovered a need for activity classification outside On-Demand NIBP system. The second proposal gives a possibility to other components in the system to ask for activity status and use it for its purposes. This design provides new activity status when an outer component (e.g., On-Demand NIBP system) asks it based on the latest received accelerometer data. This approach gives a possibility to synchronize other data streams with the activity classification. The last option is a server implementation where any system that needs activity status registers as an observer of the server status and gets an updated status when the server updates its status. In this implementation, a problem arises from the synchronization of the input data and the output of algorithms inside the On-Demand NIBP system. Even though the time difference between events e.g., the latest posture status and the latest blood pressure estimation could be known, there is no easy way to synchronize these two events to happen in the same moment in this implementation. Therefore, when using patient activity as part of the other data processing, the activity status would not be done at the same moment but some seconds ago, and the time difference should be considered. In addition, handling time differences between signals in the Hub's application violates the current architecture of the software that operates with predefined input data and sampling rates. When different nodes of the system use their clocks, different clock sources can have a small offset or a jitter. This also causes the actual sampling frequencies to differ from the defined ones. Even a small error in sampling frequency of pleth signal, acceleration signal, or both causes synchronization error between these two signals over time. Based on data synchronization and possible future need of the activity status outside the On-Demand NIBP system, option two was chosen as the most suitable design pattern.

Structure of Implemented Subsystem

The implemented activity classification component can be divided into three parts: data processing, a wrapper for the algorithm, and an activity classification algorithm. A simplified structure is illustrated in Figure 4.4. The input accelerometer data and sensor connections are handled by an accelerometer data processor where the input data handling follows the approach described in Section 4.2 and Figure 4.3. The functionality of handling input data fulfills partially specifications set for input data handling presented in Section 3.3. The accelerometer data processor forwards the data to a patient activity classifier. In addition, a data processor handles connections to active sensors in the systems and acts like defined in 4.2. Therefore, only input buffers and classifiers for active sensor nodes are active.

A classifier wrapper implements an interface for the activity classifier and its sub-parts. The wrapper implements two interfaces which are the handler interface, which is used to initialize algorithm, feed input data into buffers, and handle active sensor, and the user interface, which is used to ask for a classification based on current data and retrieve the latest activity result.

The activity classification consists of a pre-processor, a feature extraction, and an activity classification. These are based on earlier work [3], where pre-processor and feature extraction are entirely identical implementations. The activity classification shares interface with earlier library while implementation is changed to be more suitable for this proto-

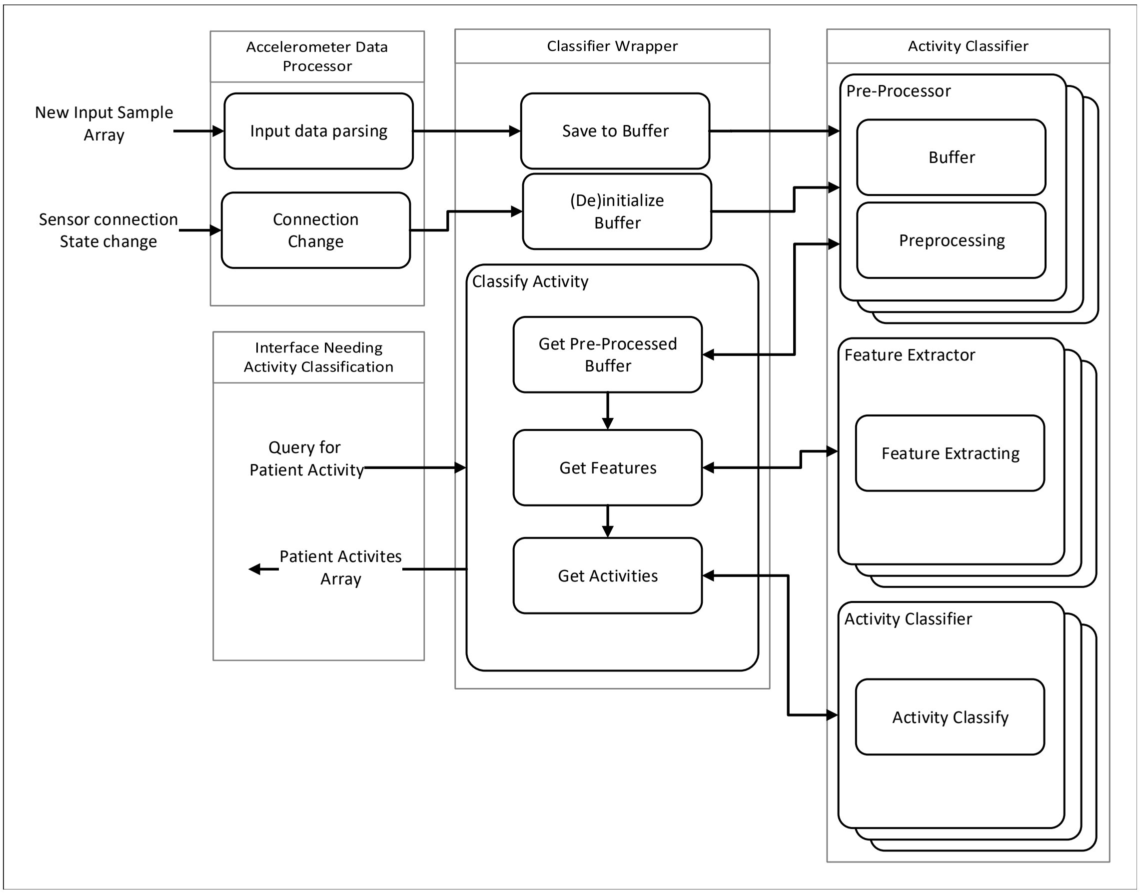

Figure 4.4. *Patient activity classification implementation structure*

type. The pre-processor, the feature extractor, and the activity classifier in the prototype are implemented as their own libraries. The design choice was done for easier individual algorithm development. Also, changing from one library implementation to another is easier in this design. The pre-processor takes care of the input buffer and calculates preliminary results that are used in the feature extractor and activity classifier. Average accelerations of the three-axis input buffer are calculated as well as standard deviations (SD) of the signals. In addition, the power spectral density of the signal is calculated by the pre-processor. The input buffer, as well as pre-calculated results, are fed into a feature extraction. The feature extractor extracts in total 17 different features from input data including heuristic, time-domain, and frequency-domain features. The calculated features can be used in classifying the patient activity. Nevertheless, in an early phase of development, the patient activity classifier is kept simple and detects only well-defined activities. Therefore, in the current implementation, only the SD of the input signal or the pitch angle of a sensor is used depending on the location of the input data. The activity classifier supports input data locations of a wrist and a chest. A wrist location is used to only detect hand movement with an SD value combined from all axes. The chest location is used to detect patient posture. Since the pitch is used alone, only detectable postures are lying and not lying.

The activity classifier which includes pre-processor, feature extractor, and classifier is implemented as each data source, i.e., sensor type has its instance of a pre-processor, a feature extractor, and a classifier. The pre-processor implementation is not supporting multiple input buffers from multiple data sources and thus, prevented processing multiple accelerometer sources in one instance. The current activity classifier subsystem supports a SpO2 sensor at the wrist location and an IRR sensor at the chest location. Other sensor types are ignored, and accelerometer data sent by them is not processed. Multiple same type sensor is not allowed by underlying software and therefore does not need to be taken care of in this system. A SpO2 and an IRR sensor were chosen as supported sensor types for the following three reasons. An IRR sensor location on the chest is a natural selection for posture classification. SpO2 sensor is providing data for CBPE algorithm and a possible movement at signal source is important to detect. Also, the overall movement can be detected from the hand. Lastly, IRR and SpO2 sensors are already supported by the current patient monitoring system.

4.4 Continuous Blood Pressure Estimation

Blood pressure estimation entity includes an IR PPG input data handling, interface for CBPE algorithm, and CBPE algorithm. Because the CBPE algorithm is provided by an external company, its implementation is not described. The definition of the algorithm is given in Section 3.4. Therefore, only passing the input data to the algorithm needed to be implemented. The input data handling follows the approach defined in Section 4.2 and is implemented to On-Demand NIBP data processor.

The data processor passes the input data forward to a wrapper that communicates with CBPE. This wrapper also includes the complete input data buffer that is passed to CBPE. A Figure 4.5 describes methods and communication with the CBPE algorithm. In initialization, patient biometrics, which includes height, weight, and gender are passed to the wrapper which initializes the input buffer for IR Pleth signal, and the CBPE algorithm itself. In the current implementation, invalid values for patient biometrics are passed, which means that patient biometrics are not used in determining the blood pressure estimation. Calling reset for the wrapper resets the CBPE to its initial state. Also, the input buffer is reset. The 'Clear Buffer' method resets the buffer back to zero but does not reset the CBPE algorithm. In normal operation, the wrapper appends the input sample to buffer on one sample at a time when 'Add Sample' is called. In addition, artificial timestamps are generated for each sample in a manner that the first sample received after reset or initialization gets a timestamp of zero. The timestamp is then increased by $1/f_s$ every time a new sample is added. f_s corresponds to a sampling frequency of the input signal. Because a floating-point unit loses precision in large values, the time stamp is reset to zero every 900 seconds. Each addition to the buffer returns the buffer status to the calling

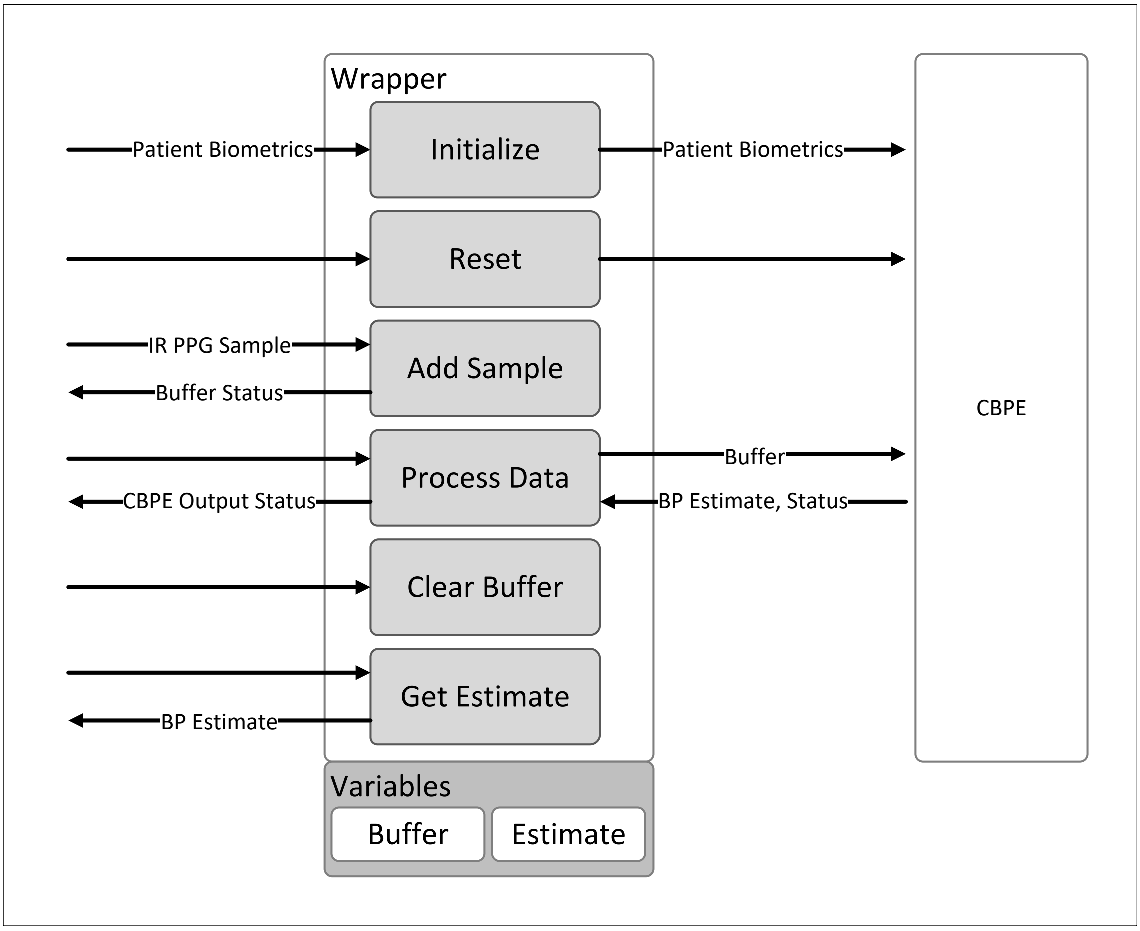

Figure 4.5. *Description of interface that drives the CBPE algorithm. The arrow text describes what kind of information (if any) is passed and returned when method is called.*

interface that represents the current state of the buffer. Every time the buffer is filled to the maximum value, the wrapper returns buffer full status. After that, it is the responsibility of the calling software to ask for blood pressure estimation from the wrapper and reset the buffer. This is done by calling 'Get Estimate' which in turn returns the latest processed blood pressure estimation.

4.5 Decision for a New Blood Pressure Measurement

Smart Trigger algorithm was implemented in collaboration with another team member so that author was responsible for implementing an algorithm compatible with the rest of On-Demand NIBP system and the Ambulatory Hub. Smart Trigger interface has four own variable types which are input and output structures, configuration structure, and configuration changed structure. The input structure consists of input parameters that are used for determining the need for blood pressure measurement. These are patient postures, blood pressure estimate, status of CBPE output, time point of last blood pressure estimate, and signal quality indices. The output structure consists of the status of need for blood pressure measurement, output status of Smart Trigger, and acknowledgment status. The configuration status has multiple parameters that are used to initialize and calibrate the smart trigger algorithm. The configuration changed structure consists of bool values that inform which of the configuration parameters have changed. Smart Trigger algorithm has a controlling interface that can be used to initialize, reset and re-calibrate. These are used at the start of the program to get the algorithm to a correct state, start detecting blood pressure changes, re-calibrate the algorithm to a new reference level or new configuration settings, or reset the algorithm in case of a situation where a clean start is needed. The rest of the interface is used to update current input values to the algorithm and get a need for a new blood pressure measurement.

Assuming that IR pleth input rate is constantly 109 *Hz*, Smart Trigger is called every 15 seconds when the CBPE input buffer gets full in the On-Demand NIBP system. Ergo, IR pleth signal is controlling Smart Trigger calculations. First, input parameters are updated and then a need for blood pressure measurement is asked. The need for a blood pressure measurement is not returned automatically when input values are updated. This gives the flexibility to keep updating input values and keep Smart Trigger updated on current status but not calculate the need for blood pressure measurement if for some reason it is not currently needed. If Smart Trigger has not been initialized, the output is invalidated. Output returns also acknowledgment status. This tells that if a new blood pressure measurement is needed at some time point, the calling system needs to acknowledge the output status before Smart Trigger starts to determine the need for a blood pressure measurement again. If the output is not acknowledged, an old output status is returned. The idea of the acknowledgment flag is to keep the output of Smart Trigger at state ”Measurement needed” even when conditions are not fulfilled anymore. Because of this, the user is notified that there has been a change even though it went unnoticed by the time the change happened.

Updating the input parameters updates the algorithm internal variables but also updates the time intervals defined in Section 3.6. Every input parameter except SQI has a time window on how long it needs to stay at a certain state before a new blood pressure measurement can be suggested. When the determination of a need for a blood pressure measurement is asked from Smart Trigger, only these time intervals are compared to configured minimum intervals. The checking of all conditions is implemented as a multi-if-else-clause which results in output status of ”Measurement needed” only when all conditions are fulfilled. Otherwise, the output value will be either ”Conditions not fulfilled” or ”Measurement not needed”. Figure 4.6 represents the execution and the output of Smart Trigger’s decision making. Below, the implementation of every condition check is explained in order of checks in if-else-clause.

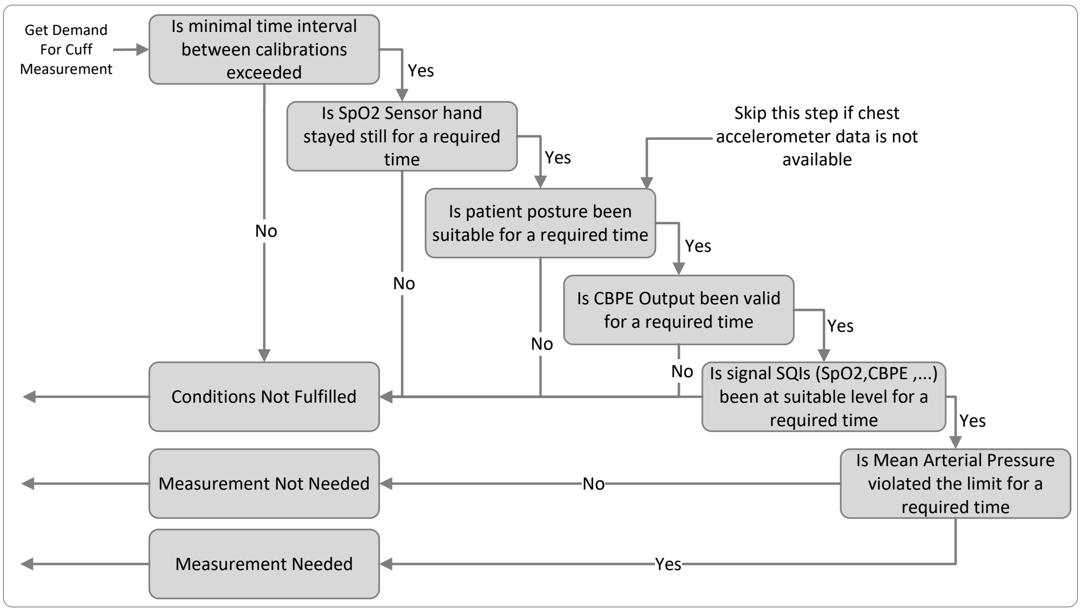

Figure 4.6. *Flow Diagram of how decision for need of new cuff measurement is considered*

Minimal Time Interval Between Measurements

The first check when calculating the need for a blood pressure measurement is to check how long it has taken from the last calibration. The last calibration time is got from the last re-calibration or initialization. The last measurement time point is updated when new input parameters are given to the algorithm. Asking the need for a blood pressure measurement checks the interval. The time between current measurement and calibration being less than the required interval gives the output of ”Conditions not fulfilled” and returns from the calculation. This implementation fulfills check specification of input parameter ’Time from last calibration’ in Table 3.2.

Hand movement detection

The current hand movement status is calculated by an activity classifier outside of Smart Trigger. The activity classification implementation is defined in Section 4.3. The hand movement status is updated when new input values are fed into Smart Trigger. In that phase, the current hand movement is examined. If the activity classifier has determined that the hand has been stationary, the data processing time interval, that is 15 seconds, is appended to the time variable that holds the value of how long time the hand has stayed stationary. If in the other hand, the activity classifier has determined that the hand has been moving the time variable holding stationary time is reset to zero. When the need for a blood pressure measurement is asked from the algorithm, the time variable is checked if it is greater than the required time. If time interval is not fulfilled, output status ”Conditions not fulfilled” is returned. Otherwise, the algorithm moves on to the next check. This implementation fulfills specification for input parameter ’Hand Movement’ defined in Table 3.2.

Suitability of the Patient Posture

Similarly as the hand movement, patient posture is determined in the activity classification algorithm. In the current implementation, usage of the posture status in determining the need for a blood pressure measurement is optional. It is only used in Smart Trigger when an IRR sensor is connected to the system and the activity classifier can classify the posture based on data from an IRR sensor node. Otherwise, it is ignored, and Smart Trigger determines a need for blood pressure measurement based on other parameters only. The checking behavior is the same as with hand movement. First, the time variable of how long the posture has been suitable is updated. If a current posture is not suitable, the variable is set to zero. Otherwise, 15 seconds is summed to the value. The time that a posture has been suitable is compared to a configured minimal time interval and if conditions are not fulfilled, the output of ”Conditions not fulfilled” is returned. This implementation fulfills specification for input parameter ’Patient Posture’ defined in Table 3.2. The design goal for a patient posture defined in Section 3.6 is fulfilled partially. Where the goal defines that posture check is mandatory, in the implemented prototype the posture check is optional. The design choice to ease this mandatory specification to optional in this prototype was done to ensure that On-Demand NIBP system functions and provides development data even when IRR Sensor is not present in the system and posture cannot be classified.

Validity of the CBPE Output

CBPE algorithm outputs a validity flag like defined in Section 3.4. The output validity is used as a condition to determine the need for a blood pressure measurement. The latest CBPE output validity is updated every time input parameters are updated. Like hand movement or patient posture, the time interval how long the output has been continuously valid is updated at this point. When the demand for blood pressure measurement is processed, the validity time interval is compared to the configured value. If the CBPE output has not been valid for a required time, the output is set to ”Conditions not fulfilled” and further processing is not done. This implementation fulfills design goal for input parameter ’CBPE Output Status’ defined in Table 3.2.

SQI at Required Level

Checking signal quality indices is the last pre-condition check before checking the actual mean arterial blood pressure change in determining a need for blood pressure measurement. The design goal for SQIs defined in 3.6 and Table 3.2 is fulfilled only partially in the implemented prototype. Only the CBPE algorithm SQI is validated at this point. However, SpO2 and IRR SQIs are fed to Smart Trigger in case of including these into decision making in the future. SQI check does not have a time interval requirement like other input parameters in the system. Only the latest CBPE SQI is checked when processing the need for a new cuff measurement.

Mean Arterial Blood Pressure Change

When all pre-conditions are fulfilled for a required time, meaning patient movement and posture status is suitable, SQIs and CBPE Output is valid, and time from the last calibration is over the limit, the current blood pressure level is checked. The blood pressure estimate is received from the CBPE algorithm's output and inputted to Smart Trigger. When inputted, mean arterial pressure is compared to a reference value which is the latest calibration value of Smart Trigger. In case of a mean arterial pressure being over the set limit, processing time (15 s) is summed to time-variable holding time how long MAP has been over the limit. If MAP falls back within boundaries, the time variable is set to zero. The time of breaking boundaries is compared to limit value and in case of time being longer than the required limit, the output is set "Measurement needed" allowing the On-Demand NIBP system to notify other systems that new measurement is needed. While time being under required time, output is set "Measurement not needed". This implements the design goal for a mean arterial blood pressure change defined in Section 3.6 and Table 3.2.

An Example of the Smart Trigger Working Principle

In Figure 4.7 basic functionality of Smart Trigger is demonstrated over a small period of time. This figure considers only blood pressure change and timings. The movement of a hand, the posture of the patient, signal quality indices, and the CBPE output are considered to fulfill their conditions during the whole artificial measurement. Furthermore, in the next explanation, On-Demand NIBP system is considered to be set to auto-cycle mode with a cycle length of over 70 minutes. Therefore, Smart Trigger output "Measurement needed" would trigger a new cuff measurement. Red circles in the figure demonstrate points where calibration of the Smart Trigger was done. In other words, the output of the Smart Trigger would be set to "Measurement needed" and a new cuff measurement would be performed at those points. The black trend demonstrates a continuous mean arterial pressure over 70 minutes and red dashed lines describe a fictional tube whose edges are limits for blood pressure change. The black dots are significant regarding decision making, thus examined further.

At the first red circle, the Smart Trigger is calibrated and reference means arterial pressure

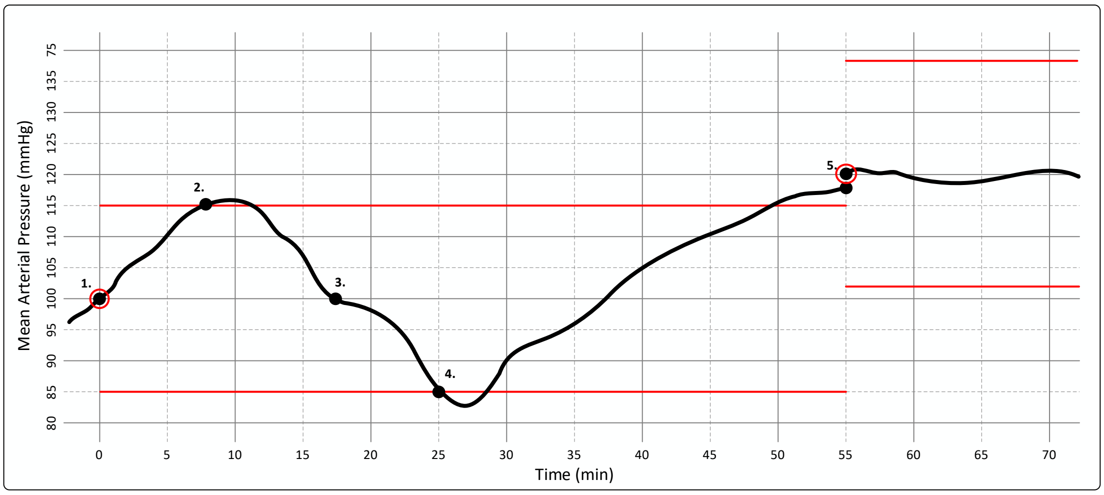

Figure 4.7. *Demonstration of the operation of Smart Trigger algorithm. Only mean arterial pressure is considered in this figure. Red circles are calibration points where the output of Smart Trigger would be set to "Measurement needed". The black points are significant points in time regarding decision making but output is set to "Measurement not needed" or "Conditions not fulfilled" at those points*

is set to 100 *mmHg*. Since MAP at calibration was 100 *mmHg* and specification says that 15 % change in MAP reading should trigger new cuff measurement, limits for blood pressure change are set to 115 *mmHg* and 85 *mmHg*. Between points, one and two, blood pressure raises over 15 % and the change limit is violated. However, the trigger prevention time, which was 15 minutes, is not elapsed yet from the last calibration, thus output is set "Conditions not fulfilled" and no cuff measurements are done. After that blood pressure starts to decline and at point three, the difference of the blood pressure between points two and three are again over 15 %. Also, the trigger prevention time condition is fulfilled at this point. Still, no cuff measurement is triggered since delta blood pressure regarding calibration value is close to zero. Output is set to "Measurement not needed". At point four, the blood pressure change limit is violated once again but because exceeding the limit lasts under the deviation time limit, no cuff measurements are performed. When reaching point five, one can notice that limit is exceeded already five minutes ago. Thus, the deviation time limit is fulfilled, the output is set to "Measurement needed" and a new cuff measurement is performed. The new mean arterial pressure value got from the cuff measurement is 120 *mmHg*, ergo limits are set to 138 *mmHg* and 102 *mmHg*. Note that *tube* width is now bigger since limits are always set as the percentage of the calibration value. Also, pay attention that the calibration value got from the cuff measurement can differ from the value that was continuously trended. Therefore, a small gap takes place in this demonstrated graph. In the implementation of On-Demand NIBP system trends are not shown hence gaps are not visualized.

4.6 Displaying a Need for a New Blood Pressure Measurement

On-Demand NIBP system implements a custom notification prompt. The notification is only used when On-Demand NIBP system is set to operate in the pleth supported notification mode. Also, because of missing dependency on NIBP sensor controls, direct calibration after performed blood pressure measurement was not possible. Therefore, an acknowledgment button is needed to prompt.

In the software architecture user interface (UI) related implementations lie in a different process than a data processing where the functional blocks of On-Demand NIBP system are located. For this purpose, inter-process communication (IPC) is needed. A simple IPC server was created to communicate between processes. The IPC server holds information of need for additional blood pressure measurement as well as acknowledgment status of this information. A Figure 4.8 shows a flow diagram in the event of new blood pressure measurement needed when operating in pleth supported notification mode. In addition, the implemented notification bar is displayed. In normal operation when there is no need for blood pressure measurement, the bar is not displayed at all. This notification could be used also in prompting auto cycled measurements like defined in Section 3.2. However, auto cycling was not implemented in this prototype, and thus, it is only used to notify Smart Trigger-related blood pressure measurement demands.

The first step after On-Demand NIBP system have determined that there is a need for a blood pressure measurement is to update the IPC server status first to a 'Measurement needed'. The server status is observed in the UI process which then prompts the notification to an ambulatory hub's display. At this point, On-Demand NIBP system continues monitoring continuous blood pressure and patient activity but keeps the output status as 'Measurement Needed' until a clinician performs the measurement and acknowledges the event by pressing the acknowledge button. The button press changes the server status to acknowledged and On-Demand NIBP system is calibrated to a current blood pressure level. A correct operation would be to calibrate the system to values received from a spot check measurement. However, since communication with an NIBP sensor was not available, the system is calibrated to the current blood pressure reading provided by continuous blood pressure measurement. After calibration, the server state is changed to 'Measurement not needed' and normal operation is continued.

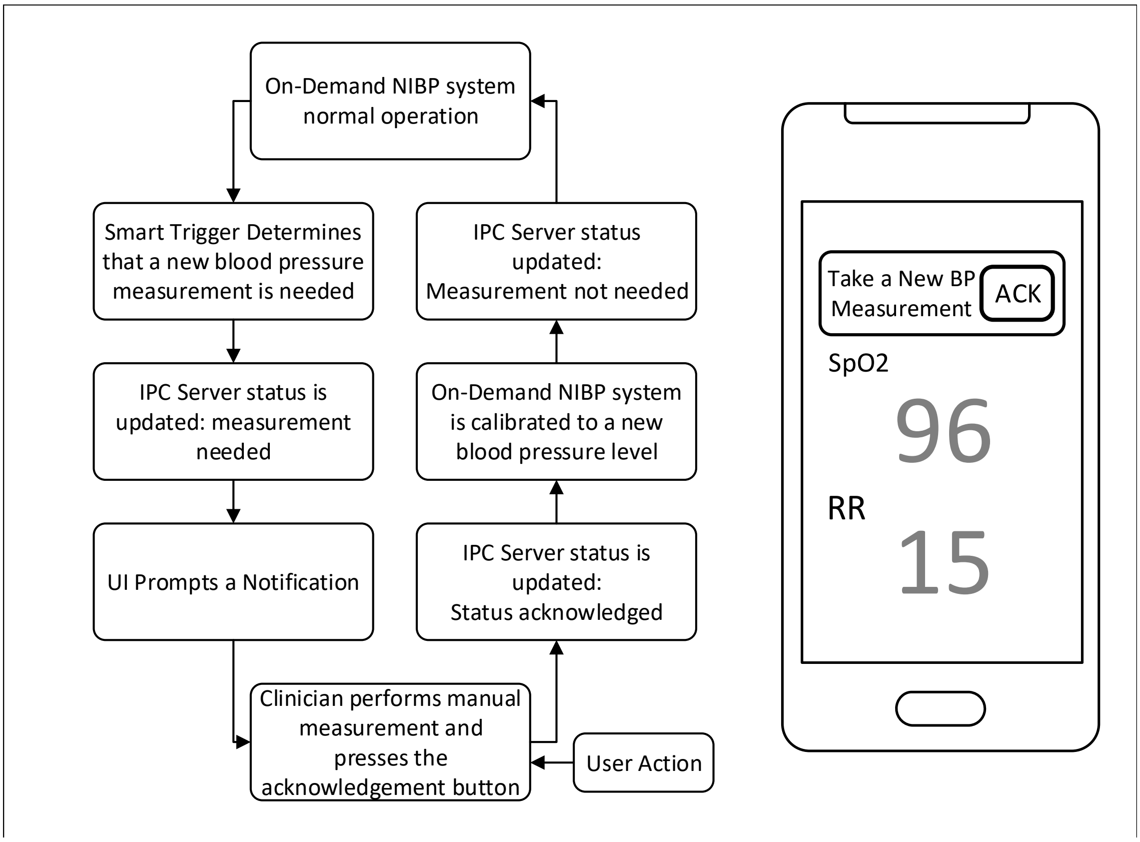

Figure 4.8. *A flow diagram of the functionality of notification prompt. When a decision to need for a blood pressure measurement is made, a notification is prompted and user action is waited. After user acknowledgment, the system is re-calibrated and the operation of On-Demand NIBP system is continued. In addition, a sketch of the notification displayed in an ambulatory hub's display is shown. It consists of a text and an acknowledge button. The notification is placed at a screen in a manner that scales other parameters and does not cover anything underneath.*

5. SYSTEM EVALUATION

On-Demand NIBP system was evaluated from two different perspectives: from the software performance point of view and the system performance point of view. The software performance assessment included CPU and memory consumption analysis. The system performance analysis included a small overnight test set which was then visually analyzed and used to assess the system's operation.

5.1 CPU Utilization and Memory Usage Assessment

CPU usage of the whole system was assessed. A comparison of CPU usage between two versions of the Ambulatory Hub application was done. The released software that did not include On-Demand NIBP system was used for comparison. The process of the ambulatory hub to which the system was implemented was under inspection. For this purpose, a simple shell script was implemented. The shell script reads from the Linux Kernel statistics the amount of CPU utilization. The statistics can be read from the Linux file system under process information and statistics. This is usually found from '/proc/stat' for the whole system CPU utilization and from '/proc/[PID]/stat' for a specific process where *PID* is is the process ID. This statistic gives information on how much time the Linux system or specific process has spent in various states [54]. The shell script calculated the percentage CPU usage for the process by first reading CPU utilization for the Linux system and the process, then waiting for a second and then reading them again. After that percentage CPU utilization of the process was extracted by using equation

$$CPU\_util_p = \frac{t_{p2} - t_{p1}}{t_{s2} - t_{s1}} * 100\%, \tag{5.1}$$

where CPU_util_p is the percentage CPU utilization of a process during the last second, t_{p1} is CPU time spent by a process at the first time point, t_{p2} is CPU time spend by a process at the second time point, t_{s1} is CPU time spend by the Linux system at the first time point and t_{s2} is CPU time spend by the Linux system at second time point. All times are referring to CPU time from the system start-up. All various states were taken into account when calculating the CPU time of the system. For the process, included states were user time, kernel time, waiting for children in user mode, and waiting for children in

Table 5.1. *Minimum, maximum, and mean CPU utilization of the process with and without On Demand NIBP system. Also, CPU idle percentages are shown. In addition, the memory used by the process and the percentage of the total used memory used is shown.*

	App without OD NIBP	App with OD NIBP
CPU Min ($\%$)	2.30	2.33
CPU Max ($\%$)	4.52	13.07
CPU Mean ($\%$)	2.75	3.38
CPU Median ($\%$)	2.90	2.91
CPU Idle Min ($\%$)	51.70	69.65
CPU Idle Max ($\%$)	98.42	97.40
CPU Idle Mean ($\%$)	90.76	90.38
Process Mem Mean (kB)	46180	51340
Total Mem Used ($\%$)	1.13	1.13

kernel mode.

The CPU utilization was captured for a specific period of time from both software versions. Minimum, maximum, mean and median CPU utilization were calculated from the recordings for both software version using Equation 5.1 and the results are shown in Table 5.1. From the table, one can see that enabling On-Demand NIBP system software increases maximum CPU utilization for almost 10 percentage points whereas to minimum value the effect is close to zero. In addition, 0.63 percentage point increase is observed in the mean CPU utilization. Nevertheless, a median of CPU utilization shows no increase at all, showing that CPU utilization is still at low levels most of the time. The total CPU idle time gives an illustration of the full CPU load during software execution. The CPU idle time is also proportional to the heating of the device because the more the CPU is in an active state and is not able to sleep, the more heat will be generated. Temperature considerations are important in wearable devices and therefore should be inspected. Table 5.1 shows only 0.38 percentage point drop in mean idle percentage. Therefore, no significant effect on the system's ability to sleep is observed. Notice that the CPU idle percentage for the application without On-Demand NIBP system is lower than the system with On-Demand NIBP. A more precise inspection of data shows that there was one moment where the system's CPU usage was higher than during normal execution. This high usage was not produced by the process running the On-Demand NIBP system. Excluding this point from results, the minimum CPU idle time percentage for the system without the On-Demand NIBP system rose to 79.91 %. Mean in this case for the idle percentage was 91.07 %. The difference between software versions is then 0.69 percentage points which is still considered not a meaningful change.

Further inspection of the CPU utilization over time shows that triggering On-Demand NIBP

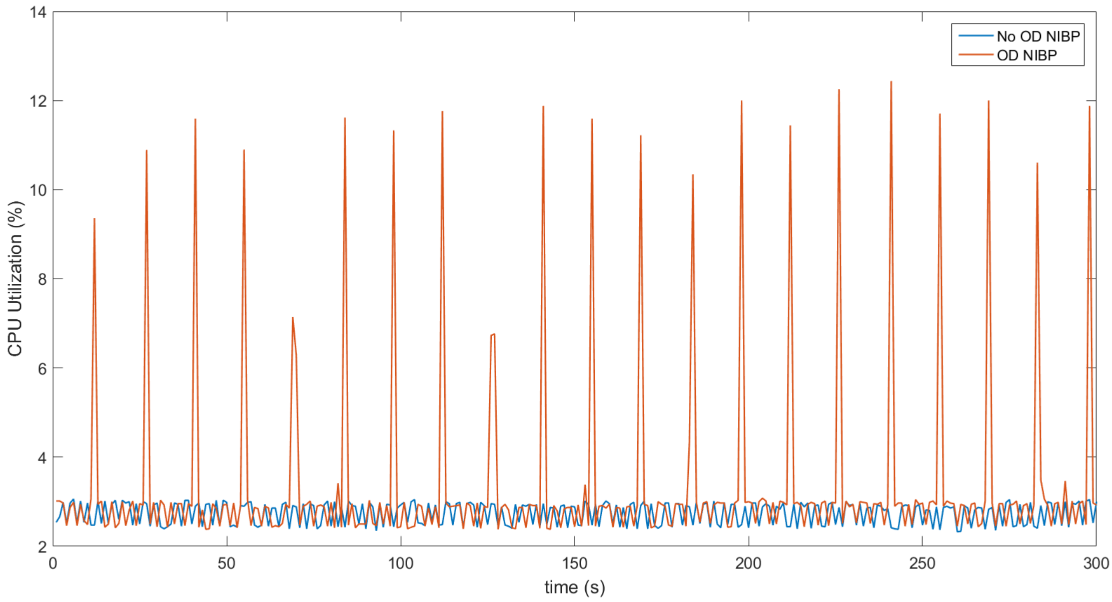

Figure 5.1. *Percentage CPU utilization of two different software versions during 5 minutes. The orange line is software version with On-Demand NIBP system. The blue line is the same software but without the On-Demand NIBP system.*

system's algorithms (patient activity classification, CBPE, and Smart Trigger) causes high spikes in the CPU load. Like defined in Section 4, every 15 seconds algorithms gets triggered. This causes a spike in the CPU load with a magnitude of 7 to 13 percent. Figure 5.1 illustrates the CPU utilization of the same process with and without the On-Demand NIBP system for 5 minutes. The spikes every 15 seconds can be seen. Otherwise, there is no visible increase in CPU utilization between software versions indicating that On-Demand NIBP system's input data parsing and buffering does not cause additional load for the CPU.

In addition to process' CPU utilization, CPU usages of two On-Demand NIBP system subsystems were compared. The two most demanding components of the system regarding CPU utilization were considered to be the activity classification which includes feature calculation, and estimation of blood pressure changes i.e. CBPE algorithm. These algorithms are run every 15 seconds and the increase of CPU utilization could be detected in the analysis of process' CPU utilization. Thus, the CPU usage of these algorithms is inspected. The CPU usage is calculated using C++ time library's 'clock_gettime' function. The 'clock_gettime' function returns a per-process high-resolution timer when used with ID 'CLOCK_PROCESS_CPUTIME_ID'. This returns time spend in nanoseconds since the epoch at the same process where the function was evoked. Activity Classifier and CBPE processing time were extracted by taking calling 'clock_gettime' before and after blood pressure estimate and activity classification processing and then saving the value to a log file. Also, the same kind of time measurement was used for all algorithms in the

Table 5.2. *Minimum, maximum, mean and median time spend by single processing cycle in Activity Classification, CBPE and all algorithms of On-Demand NIBP system. In addition minimum processing time with valid input buffers is shown*

	Min (ms)	Max (ms)	Mean (ms)	Median (ms)
CBPE	133.96	219.12	163.54	161.58
AC	1.81	4.20	1.88	1.83
Full OD NIBP	139.60	224.90	169.07	167.12

processing pipe.

It can be seen in Table 5.2 that CBPE algorithm processing takes visibly most of the processing time when On-Demand NIBP system's processing is triggered. All the values are calculated after the CBPE algorithm and the activity classifier's input buffers are fulfilled with valid samples so algorithms are not returning invalid values before covering the whole processing pipe. Over 96 % of all the processing time of algorithms is used in CBPE, which was expected at some level. Fairly surprising, activity classification and calculating all 17 features takes only around 1 % of the processing time in On-Demand NIBP system. Therefore, it can be concluded that most of the heavy processing of On-Demand NIBP system is within the CBPE algorithm.

The memory consumption of the On-Demand NIBP system was also assessed. This was done by reading process information and statistics to fetch memory usage of the process. Memory consumption can be read from file '/proc/[PID]/status' where fields under interest are total virtual memory allocated, resident memory, shared libraries, data, stack and text segments (VMSize, VMRSS, VmLib, VmData, VmStack, VmExe). A kernel-internal scalability optimization causes an error on some of these readings [54], but for our use case inaccuracy is not essential because absolute values are used for comparison the software with and without On-Demand NIBP system. A comparison between software versions was made by recording memory usage of the process over time with a shell script. The results are shown in Table 5.1. The percentage of total memory used and memory used by the process is shown.

VmSize which corresponds to the total virtual memory reserved by a process was used to assess memory usage of On-Demand NIBP system. In addition, effect of including On-Demand NIBP system was evaluated. It can be seen from Table 5.1 values that including the On-Demand NIBP system increases the total memory reserved by the process by 5160 kilobytes. There is no effect observed in the total memory used percentage. The used memory stays at 1.13 % regardless of On-Demand NIBP system.

5.2 On-Demand NIBP System Qualitative Assessment

To evaluate On-Demand NIBP system operation, a small test set was executed. The intention of the set was not to validate the system performance but to test the prototype software's correct functioning and hence prove the potential of the system for further development. Thereby, this work can be considered as a proof of concept. In addition, this evaluation does not try to prove the performance of the CNIBP method in use, because the algorithm is provided by an external company, hence the accuracy of continuous blood pressure measurement is not in the scope of this work.

In the test set, three different test subjects were measured with a total of five separate measurement cases. Test subjects were healthy adult males. One overnight measurement refers to one measurement case. Duration test cases were between nine to sixteen hours. A precise test procedure was not defined but a "normal living" of test subjects during the evening, night, and the morning was recorded. The test system recorded IR PPG signal, accelerometer signals from hand and chest, the intermediate result of continuous blood pressure, and Smart Trigger algorithm's intermediate parameters. Test instrumentation included an oxygen saturation sensor and impedance respiration sensor. A hand movement and an IR PPG signal were received from a SpO2 sensor and an IRR sensor provided a posture status of subjects. In addition, test subjects were instructed to measure blood pressure for an appropriate number of times, however, so that absolute blood pressure values were obtained from the evening and the morning. GE Carescape B650 patient monitor was used to record reference blood pressure readings.

The system was operating in auto-acknowledge mode, thus, automatically calibrating to the current continuous blood pressure value when a new blood pressure measurement would have been needed. In this manner, the system was continuously operating during the night regardless of user actions. The parameters MAP, trigger events, hand movement, and patient posture were examined to evaluate On-Demand NIBP system operation. An intrusion limit for MAP was set to 15 % of calibration value. At the start, On-Demand NIBP system was calibrated to an artificial MAP value of 100 *mmHg*. The limit for the hand movement was set to 50 (unitless), meaning if standard deviation of the acceleration signal acquired from the SpO2 sensor increases over 50, activity is determined as moving. The patient's posture was classified based on the pitch angle of the IRR sensor. An angle being over -45° was determined as lying, otherwise unsuitable posture.

Data collected from the test sets is show in Appendix A. The collected data were visually analyzed. From the collected data, a total of 11 intrusions of trigger limits were examined from where two actual trigger events were observed. Both trigger events happened during the same measurement (Test subject #1, Measurement 1). In the two trigger events, one can see that all set conditions are fulfilled. A mean arterial pressure violates the set limit for over 5 minutes, a pitch angle is over -45°, thus the subject's posture is lying, and hand movement stays under the limit. Therefore, it can be determined that the trigger events were expected operations. In the 9 remaining intrusions where a trigger event did not happen, other conditions were not fulfilled. From the Appendix A can be seen that during intrusions one or more of the following conditions were not fulfilled. Either posture was not determined as lying, hand movement was not low enough, or the MAP value violated the limits only over a short period. Therefore in these intrusion points, the system was working as expected.

A couple of notes can be drawn from an independent inspection of hand movement and patient posture. From the posture point of view, a limit of -45° seems to work fairly well. During the evening when subjects were active, posture status was mostly reported not suitable, which is the desirable outcome. Abnormality to this is the test subject #1 measurement 1 where posture is reported suitable during the evening. The subject reported being sitting on a sofa in a fairly low pose, which most probably lead to posture classification lying. After subjects lie down for the night, a posture is constantly reported lying except for time points where subjects got up to perform blood pressure measurement. Even rolling from one side to another, which could be seen from an IRR sensor roll angle, did not affect the reported posture status. Roll angles were recorded and analyzed but they were not shown in the appendix because it was not determined as a parameter that affects to triggering of a blood pressure measurement. This was expected since only the lying of the subject was examined. A divergence during the night is noticed in a test subject #2 measurement 2 where the pitch angle stays just under the limit for an hour, thus classifying posture not suitable. Possible posture change in bed could have caused the pitch angle to fall under the limit. A more careful determination of the limit could be needed. In addition, it was noticed that in the test subject #2 measurement 1 sensor reported a constant value of 0 for pitch angle after a couple of hours in the measurement and a posture status cannot be trusted. This is not eligible for the system and the root cause of the failure needs to be accounted for. One possible reason is a failure of an accelerometer unit to work correctly. Regarding of the goals in this test, the failure did not have an effect. A zero value is determined as a suitable posture and the rest of the data could be analyzed without taking to account the posture of the subject. Furthermore, even without the correct posture status, the system seemed to behave correctly meaning no unnecessary measurements would not have been triggered or blood pressure level changes did not go unnoticed.

The same kind of pattern that was seen on posture can be seen on a hand movement. During evenings and mornings, a SpO2 sensor acceleration SD spikes constantly over-limit determining the subject is moving and active. This points out that these moments are not suitable for blood pressure measurement and no measurements were triggered during hand movement. During the nights, on the other hand, SD values stayed low, close to zero, indicating that subject is rather still and inactive. Numerous spikes can also be seen during the nights but much less frequently. These are most probably caused by posture changes or similar activities. The posture changes were expected to be detected by the system because movement could cause false positives or negatives to the blood pressure reading. During movement, the system should not trigger new blood pressure measurements and this seems to be the case in all measurement cases. Based on visual analysis of movement detection, the system performed quite well. Movement of the hand could be detected presumably reliably and the system's response to no trigger measurement during movement was correct.

Overall, the implemented On-Demand NIBP system appears to behave as defined. A couple of abnormalities were detected in the test sets which are described above. The test set demonstrates the system's ability to track blood pressure changes, detect sustainable and significant changes, and act on them under desirable conditions.

6. DISCUSSION

The purpose of this thesis was to design and implement a prototype software system that estimates blood pressure changes continuously and reacts to significant and sustained changes when a patient's state is suitable. In addition to prototyping, the main goal was to investigate the possibility to integrate the system into a patient monitoring system. Continuous blood pressure measurement is growing technology in healthcare, especially in research, but it has not been able to exploit its full potential in patient monitoring yet. Certain characteristics of CNIBP like the accuracy of measurements and sensitivity to interference have been complicating the process of taking the technology in use in patient monitoring. However, other characteristics like non-invasiveness and continuous tracking of blood pressure makes the technology a promising and intriguing measurement technique and therefore worthy of a study. The prototype developed in this thesis was aimed to assess the problem areas of CNIBP measurement methods and to study possible practicalities to overcome the problems.

The prototype system uses an externally developed algorithm to track continuously blood pressure. The algorithm is based on pulse wave analysis technology using a photoplethysmogram signal as an input source. PWA analysis was introduced in Section 2.1.1. It is characteristic for CNIBP methods that they do not measure absolute blood pressure values but are tracking changes. Also, verifying accuracy and validity of the CNIBP measurement have been observed to be cumbersome. The lack of absolute measurement gives rise to possible drifting and therefore error. Also, interference in the input signal tends to cause errors in the blood pressure reading which may recur in the long run. These problems are taken into consideration in the design of the prototype software. The prototype handles CNIBP measurement only as an intermediate result. The CNIBP measurement values are not presented to the user, and thus, the accuracy or validity of the measurement is not a direct problem because clinicians cannot take action based on the CNIBP measurement values. When a change is detected, a verified blood pressure measurement method is used to measure the actual blood pressure. Therefore, CNIBP is only used to detect possible changes in the patient's state of health where otherwise, a change could have gone unnoticed. Moreover, the prototype implements error detection methods to detect false readings in the input signals. SQIs of inputs are examined to detect possible interference and hence incorrect measurement results. Moreover, PPG is prone to movement artifacts, and therefore, patient activity is essential to detect. The system implements a patient activity and posture detection that is used to validate CNIBP measurement but also detects suitable moments to do cuff-based blood pressure measurements.

A working prototype of the system was implemented during this work. The system can track blood pressure changes using a PPG signal from a oxygen saturation sensor. Also, the system collects accelerometer signals from the patient's chest and hand to track patient posture and activity. Blood pressure change, patient posture, and activity are used to detect significant and sustained blood pressure change events. For this, a detection algorithm was implemented based on the definition. The prototype system was implemented as part of Ambulatory Hub's software, which means that system could be directly used to gather crucial research data in a real patient environment for future development activities. The prototype developed during this work creates a good basis for On-Demand NIBP development and provides tools to research CNIBP methods and their use cases in a clinical environment.

Design

A few essential changes were needed to the originally designed system. The pleth-supported auto-cycling mode defined in Section 3.2 could not be implemented during this work. Control of the NIBP sensor in the ambulatory hub's software would have been needed for auto-cycling behavior, but it was not available when implementing this system. Implementing NIBP sensor control during this work would have been too big effort, and would have delayed the implementation process of this system. Therefore, it was scoped out so that the system implements only the pleth-supported notification mode. Nonetheless, a placeholder for auto-cycling behavior was implemented inside the system. This simplifies the process of integrating auto-cycling mode into the system in the future. Integrating auto-cycling after the NIBP sensor control is implemented to the Ambulatory Hub's software should be minimal work. In its simplicity, it should only send the right commands for the controller to trigger a new cuff measurement with the sensor.

Moreover, auto-acknowledge mode explained in Section 4 was implemented for development purposes. This mode is valuable when investigating the amount of blood pressure change events the system would have provided for example during nights without the need of any user actions after starting measurement. This mode was also used in the evaluation process of the system. Also, the development data collector was implemented, which was proven to be useful when the analyzing data. The collector records a continuous blood pressure trend as an intermediate result, accelerometer signal features, Smart Trigger algorithm status, and other development-related parameters. These were used already to trend the collected data and analyze the behavior of the On-Demand NIBP system in Section 5.

Implementation

The system can be divided into four major parts that all have their main responsibilities. This makes the software architecture quite clear. However, there are still a couple of matters in the implementation that have room for improvement. These are discussed next.

On-Demand NIBP system has four sub-systems shown in Figure 4.1. In the optimal case, all these four sub-systems are independent of each other and they do not directly share any objects excluding IPC communication objects. Instead, communication between the sub-systems happens through callbacks or IPC messaging. However, this is not entirely the case in the implemented system, since 'Blood pressure estimation' -sub-system and 'Blood pressure measurement need' -sub-system share the same data processing block. In fact, the latter mentioned sub-system is much more like a sub-sub-system for the first mentioned sub-system. One design option could be to separate these two, and design a communication interface between them. The sub-system that estimates blood pressure would only have an IR PPG signal as an input because it is the only input needed to estimate blood pressure. The sub-system that decides if there is need for a blood pressure measurement would then get patient activity, BP estimation, and SQIs as inputs. This makes the sub-systems interfaces more distinct and tell directly which sub-systems requires which input signals. From a software architecture point of view, more specifically defined sub-systems are better.

There is also another architectural consideration related to the same data processor. On-Demand NIBP system has its own input data processor and controller. The main factor leading to implementing an own data processor for the On-Demand NIBP was the lack of an NIBP sensor control system in Ambulatory Hub's software. If the NIBP control system had been present in the software, one option would have been to embed On-Demand NIBP with the rest of the NIBP related system. This architecture can be considered from two perspectives. Firstly, it makes sense to have a common data processor for NIBP sensor data and On-Demand NIBP related data because these two are closely related to each other, and because On-Demand NIBP system needs for example absolute blood pressure measurement result for calibration from NIBP sensor to work as defined in the auto-cycling mode. Also, presence of the NIBP sensor is an essential input parameter for On-Demand NIBP. Therefore, an own data processor for On-Demand NIBP is not an ideal system architecture. This intersects with the earlier point that highlighted the independence of individual sub-systems.

Therefore, from another perspective, On-Demand NIBP system can be considered as an individual software component that could be disabled or enabled if a user wants so. The user could decide to not use On-Demand NIBP features at all, and therefore, the regular NIBP system does not need the features of On-Demand NIBP. Thus, implementing On-Demand NIBP as an own component could be beneficial. In that case, On-Demand NIBP system has no relation to the NIBP sensor system, and the needed data is transferred using IPC-messaging or callbacks. Furthermore, the independent implementation of the whole system reduces dependencies to other parts of the software and makes the system more transferable. This makes the system more reusable in other software designs. Without direct dependencies on other systems, On-Demand NIBP system could be written as own library that could be reused in other products. The current implementation does not directly support making its own library because it has other dependencies inside Ambulatory Hub's software, but with its own input data processing, it will at least ease the separation process. In addition, unit testing for the system is much simpler when there are no direct dependencies. In the end, it seems to be a beneficial that there was no readily implemented data processing for NIBP, and fusion of On-Demand NIBP was not possible. In the next development steps, the pros and cons of the two approaches should be considered.

Another implementation design that may require more work is patient posture and activity recognition. The current design of patient activity classification is explained in Section 4.3. There were three different architectural proposals for patient activity classification: as part of On-Demand NIBP system, an individual system that classifies the activity when a calling software asks the classification, and an individual system that classifies activity in fixed intervals. The individual implementation that can be asked to do classification based on the latest data was best for our use case. The design increases the portability of this sub-system and allows any other system outside On-Demand NIBP to use the same activity recognition system for its purposes. In addition, this design was considered to be a good solution to synchronize data sources inside On-Demand NIBP. However, the current implementation has room for improvement and it could be considered as the most unfinished sub-system inside On-Demand NIBP system.

The initial proposal to classify activities was to use algorithms developed in earlier work [3, 4] directly. However, these algorithms could not be utilized fully in this work because they were not fully compatible with our use case, and some extra research would have been needed to integrate them into the On-Demand NIBP system. Therefore, the ready-made classification library was modified to meet the purpose in the system. The classification of the activity and posture was amended to a very unsophisticated level where only SD and pitch angle are taken into account from acceleration data. This served its purpose in this prototype sufficiently, and it can be considered to be a good decision in this work. Nonetheless, the decision reduced the possibility to detect different postures and activities dramatically, and thus, more activity categories should be detected in later development phases. As an example, sitting and standing cannot be differentiated with current implementation, which is beneficial in detecting suitable postures for performing a cuff-based blood pressure measurement. Therefore on the side of activity classification, there is more work to be done to make the On-Demand NIBP system fulfill its design goals. Especially benefits and integration possibilities of the machine learning algorithm developed in [4] should be further investigated.

In addition to the simplified classification algorithm, the interface of the activity classification is a work in progress. The classification library itself was divided into three parts: pre-processor, feature extraction, and classifier. This was a suitable solution during the development phase because changing one sub-part to another is much simpler when they are not existing in the same library. Also, the division eases the collection of debugging information. On the other hand, it makes the interface fragmented and complicates the usage of the algorithm. A developer needs a deeper understanding of the relationships between the parts of the algorithm. In addition, the current library parts does not support multiple input sources. Because of that, each input source needs an individual instance of each library. Therefore, in a case where two sensors are providing acceleration data, there would be six instances of activity classification libraries at run time: two pre-processors, two feature extractors and two activity classifiers. Individual instances also lead to multiple output classifications based on each input data. A better approach is to have one instance of the library that could handle all input sources and return the current activity based on all provided input signals. The proposal is to support multiple input sources inside one library in the future, so only one instance is needed. Also, pre-processor, feature extraction, and classifier should be combined again to one library which creates a complete patient activity classification library.

Testing and Performance

Testing of the On-Demand NIBP system was limited during this work. Developing a fully functional software that is ready to be integrated into development branch was not in the scope of this thesis. Therefore, formal software testing was not implemented although it would have had many advantages already during early prototyping. Nonetheless, some testing and evaluations of the operation of the system was performed. Firstly, exploratory testing for the system were performed during development. This consisted of investigation of the system's behaviour with different inputs and attempts to create erroneous situations. Secondly, test set, which was defined in Section 5.2, was run for the final implementation. Visual inspection and analysis of the output signals were performed in the test set. Finally, software performance analysis for memory and CPU usage was carried out.

A testing plan was not defined for the system nor were any test cases written for the system. Therefore, race conditions or unexpected situations might not be handled correctly, and the system is expected to misbehave. Also, programming and logical errors are expected to exist even though the system was working as expected with the assumed operation conditions. In the next developing steps, a testing plan, unit testing, and static code analysis should be utilized for On-Demand NIBP system.

It would be good to define a test plan for the system. A good starting point for testing is to test different operation modes of the system as well as the behavior and output of the system under various and changing input signals. Moreover, commonly known fault conditions like sensor disconnection, re-connection, and input data gaps are important aspects to test. With testing that covers the cases mentioned above, most of the system's normal operation is covered.

It is worth mentioning that system outputs under varying blood pressure can be troublesome to test directly. Estimating blood pressure change is done with the CBPE algorithm which uses PPG signal as an input. Testing the variation blood pressure change can be difficult to utilize in a test setup because it would need correct variations to the features of the PPG signal. Since the CBPE algorithm is provided by an external company, and there is no knowledge about algorithms operation, it is close to an impossibility to create an artificial PPG signal that would result in an eligible outcome. Therefore, covering the system's behavior during blood pressure changes could be done offline with PPG signals collected from a clinical environment where blood pressure levels are collected with other verified blood pressure measurements. A clinical study or a set of recorded cases could be an appropriate approach to test this feature.

In addition, unit tests for software blocks were not written during the development process. This fairly common development process was scoped out because only an early prototype was implemented in this work. In the next development processes, unit testing should still be included because it is a sensible way to catch programming and logical errors inside the code. Unit testing helps to verify that individual functionalities of the system are operating as expected.

Lastly, static code analysis should be performed for the code. Static code analysis can catch hazardous programming styles and provide feedback to produce more trustworthy, cleaner, and readable code. Understandable code and good coding style decrease undetected erroneous situations and ease future development.

One test set for the system was performed. The test set included operation of the system in real operating environment and the evaluation was described in Section 5.2. The system was operating as defined during the test. The analysis was based on a visual inspection of the measurement data. The system detected significant and sustained blood pressure changes reliably. Moreover, the system was able to detect and ignore false-positive blood pressure changes as well as blood pressure changes caused by patient activity. Only when there was no movement detected, a posture of the subject was suitable, and the quality of input signals was at a suitable level, a new blood pressure measurement would have been triggered.

One point from the analyzed data raised concerns. In Subject #2 measurement 1, acceleration data from the chest sensor was incorrect, and it went unnoticed by the On-Demand NIBP system. In this case, the outcome could be that there is a change of blood pressure caused by posture shift which would be qualified as a true-positive change by Smart Trigger because activity of the subject was classified wrong. The situation does not cause a hazardous situation for the subject but can for example distract sleep by triggering multiple cuff measurements which are irritating at a minimum. This is not expected behavior because the posture of the subject is directly derived from that sensor and posture is used to detect suitable conditions for the cuff measurement. This kind of a failure is hard to detect because either the sensor was sending zero values for acceleration during that time, or the acceleration data processing system has an issue to use old data for analysis if new data is not provided. The system considered this data as valid. Nevertheless, faulty sensor conditions or lack of input signal should be detected by the system and it should be verified that activity classification is done with valid data only.

Software performance evaluation results were presented in Section 5.1. Overall, adding On-Demand NIBP system did not induce a huge effect on the Ambulatory Hub's software performance. Especially overall memory consumption was not changed at all. Considering CPU utilization, a small increase of 0.63 percentage points in mean CPU utilization was noticed. This is considered as a small change in CPU utilization and overall CPU utilization is not affected by On-Demand NIBP system. A more interesting observation from the evaluation was the spiking of the CPU utilization during program execution. Every time, the CBPE algorithm executed an analysis, a roughly 10 % increase in CPU utilization was noticed. More closer analysis revealed that each CBPE analysis took around 170 *ms* to be completed, and therefore, CPU was under heavy load during this time. 170 *ms* execution time is not harmful during development of the software, but however, it has side effects. The whole software process that executes the CBPE algorithm is blocked during the algorithms execution which means other operations are not processed. This same process has also many other responsibilities which are time-constrained. Therefore, this blocking operation should be addressed and a possible fix provided.

Two approaches were discussed to overcome the blocking problem: refactoring of CBPE algorithm and threading. The refactoring would need more work and collaboration with the company providing the algorithm. An idea here is to not buffer data for 2 minutes for CBPE and feed it in the algorithm at once but constantly feed samples inside the algorithm when they arrive. CBPE would do as much pre-analysis for the input samples as possible before doing the final analysis for the whole input buffer and providing the output. With this kind of approach mathematical operations would be decentralized to the whole data collection period and CPU utilization spike would be decreased. Also, processing time when running the CBPE algorithm would be decreased. Threading solution would run the CBPE algorithm in an another thread which would allow context switching from the algorithm's thread back to the main thread to serve other time-constrained events. This approach would need small refactoring of the code in Ambulatory Hub's software and handling of shared resources between the threads so that data is not malformed when different threads access it.

Conclusions

The aim of this thesis was to design and implement a prototype software system that estimates blood pressure changes continuously and provides either notification for clinicians or auto-triggered oscillometric blood pressure measurements when a significant and sustained blood pressure change is detected. As part of the thesis, a working prototype was implemented and integrated into Ambulatory Hub's software.

Most of the set design goals were fulfilled by the prototype system. The prototype was able to estimate blood pressure continuously using a PWA-based algorithm and assess the activity and posture of the subject using two accelerometer data sources. Based on the given inputs, the prototype was able to detect significant and sustained blood pressure changes. However, some design goals were not fulfilled during this thesis work. The pleth-supported auto-cycling mode was one major design goal that was not fulfilled. The reason for lacking implementation for certain goals was the unavailability of software dependencies in the used software stack.

Performance evaluation for the system was carried out. It included a software performance analysis and a qualitative assessment of the system. The software performance was at a suitable level. Only a small performance decrease was detected when comparing the performance of Ambulatory Hub's software with the implemented system and without the system. Alternative design options were discussed to optimize the software performance, but they were not implemented. The qualitative assessment demonstrated the system's ability to operate as expected. The prototype was able to detect significant and sustained blood pressure events reliably, but also discard false changes in CNIBP measurement as well as blood pressure changes caused by the subject's activity.

Overall, the implemented prototype was a success, and it met the goals set for the thesis. The prototype sets a good groundwork for the development and facilitates the next development steps in the field of using CNIBP in ambulatory blood pressure monitoring.

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APPENDIX A: OVERNIGHT MEASUREMENTS

In total five overnight measurements were performed with On-Demand NIBP system. Measurement data is shown in Figures A.1, A.2, A.3, A.4, and A.5. The system was operated in the auto-acknowledge mode where every trigger event is automatically acknowledged, and the system is recalibrated to the current blood pressure value obtained from a continuous blood pressure reading.

There were two trigger events recorded during the five measurements: “Subject 1 Measurement 1” at 01:10 and “Subject 1 Measurement 1” at 07:50. At these points, all Smart Trigger conditions were fulfilled which led to a decision that a new blood pressure measurement is needed. In the auto-acknowledge mode, a recalibration was performed which can be seen as a change in blood pressure trigger levels. In other events where continuous blood pressure estimation exceeds the trigger limits, other Smart Trigger conditions like the subject’s activity were not fulfilled. Therefore, the system is not recalibrated, and trigger limit changes are not seen in measurement data.

In other operation modes, the time points mentioned above (“Subject 1 Measurement 1” at 01:10 and “Subject 1 Measurement 1” at 07:50) would have triggered a new cuff measurement automatically (Auto-Trigger mode) or prompted a notification to the hub’s screen (Notification mode).

Figure A.1. *Test Subject 1 Measurement 1: Mean arterial pressure, pitch angle measured from the subject's chest, and standard deviation of the acceleration signal of the SpO2 Sensor are shown. Also, the trigger limits for Smart Trigger are displayed. MAP displayed is an interim result calculated by the On-Demand NIBP system*

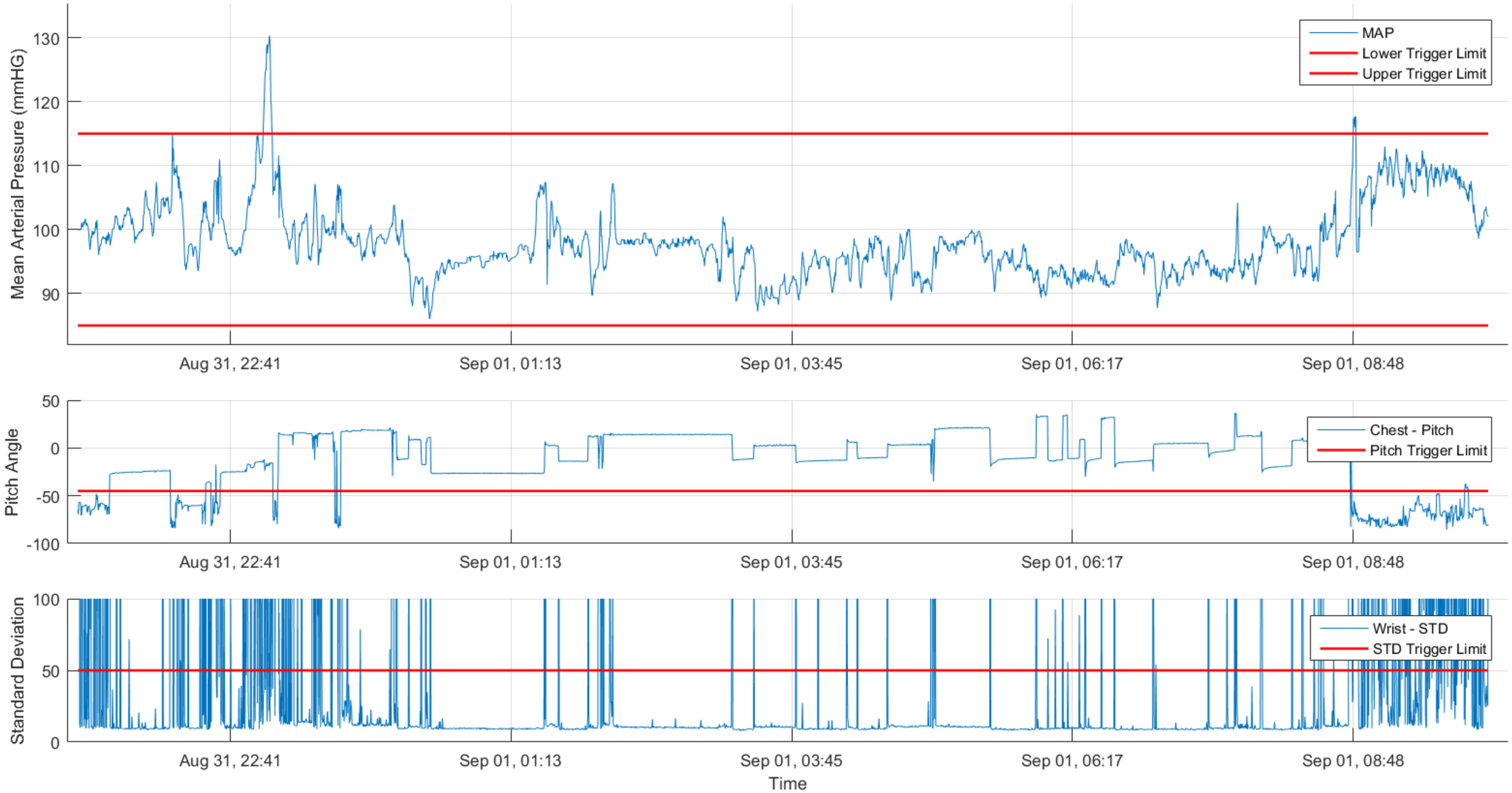

Figure A.2. *Test Subject 1 Measurement 2: Mean arterial pressure, pitch angle measured from the subject's chest, and standard deviation of the acceleration signal from the subject's hand are shown. Also, the trigger limits for Smart Trigger are displayed. MAP displayed is an interim result calculated by the On-Demand NIBP system*

Figure A.3. *Test Subject 2 Measurement 1: Mean arterial pressure, pitch angle measured from the subject's chest, and standard deviation of the acceleration signal from the subject's hand are shown. Also, the trigger limits for Smart Trigger are displayed. MAP displayed is an interim result calculated by the On-Demand NIBP system*

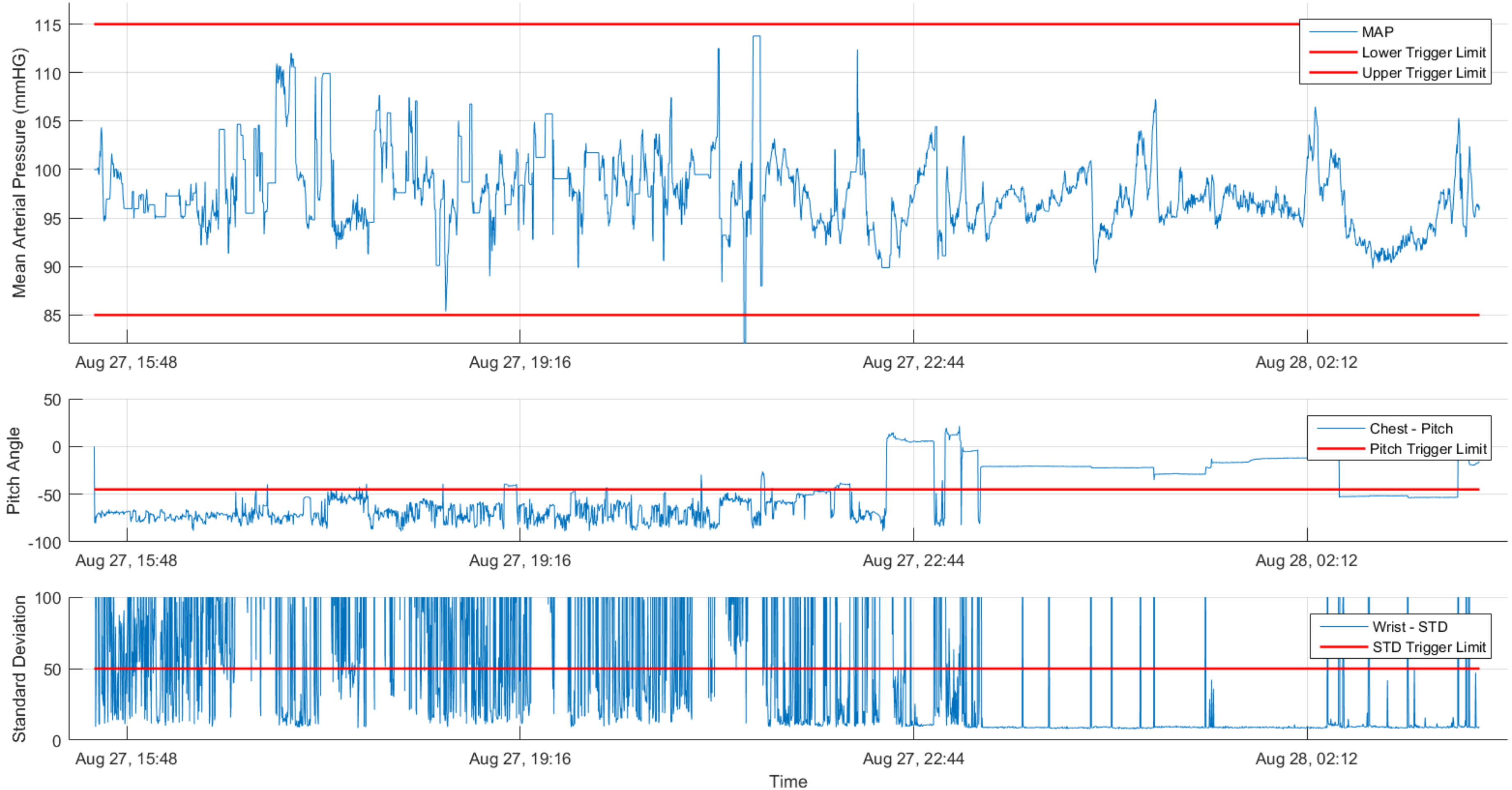

Figure A.4. *Test Subject 2 Measurement 2: Mean arterial pressure, pitch angle measured from the subject's chest, and standard deviation of the acceleration signal from the subject's hand are shown. Also, the trigger limits for Smart Trigger are displayed. MAP displayed is an interim result calculated by the On-Demand NIBP system*

Figure A.5. *Test Subject 3 Measurement 1: Mean arterial pressure, pitch angle measured from the subject's chest, and standard deviation of the acceleration signal from the subject's hand are shown. Also, the trigger limits for Smart Trigger are displayed. MAP displayed is an interim result calculated by the On-Demand NIBP system*