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Cato Danielsen

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Abstract

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Part I

Introduction and background

Chapter 1

Introduction

A good nights sleep is important in order to stay physically and mentally healthy. Research has shown that the lack of proper sleep can be linked to many health issues.

According to the National Institute of Health (USA) sleep apnea, if left untreated, can lead to different health risks. Among these are increased risk of high blood pressure, heart attack, stroke, obesity, diabetes, heart failure, increased chance of irregular heartbeats and increased chance of having work-related or driving accidents [21]. Other literature has for a long time pointed out the risk of mental health issues related to sleep apnea [23], such as depression.

According to the literature the estimated prevalence of sleep apnea is 2%-4% of the middle aged adult population in USA[67]. One thing we find as a broad consensus in the literature, is that a lot of sleep apnea patients go undiagnosed, as much as 80% to 90%, depending on the criteria for diagnosis.

The clinical term sleep apnea was introduced in 1973 by after the first international symposium on "Hypersomnia with Periodic Breathing" in 1972 [16]. The terms sleep apnea syndrome and obstructive sleep apnea was coined in 1976. Over the last 40 years we have seen an increase in interest and concern over the effects of sleep disorders and it has been discovered to be a more common medical problem than previously assumed.

1.1 Motivation

The most common way and the gold standard of detecting sleep disorders is with a *polysomnography* (PSG) that requires a patient to sleep with monitoring equipment in a sleep lab. A PSG can also be referred to as a sleep study and it monitors a variety of parameters in order to diagnose sleep disorders. These parameters are described further in Section 2.1.

An important question is: if we already have a accurate and precise way of detecting and diagnosing sleep disorders, why are so many occurrences of sleep related disorders undiagnosed? According to the literature there are several key factors as to why these cases go undiagnosed and untreated. Some of the symptoms associated with sleep disorders, such as excessive daytime sleepiness, daytime irritability, difficulty of concentration and waking with headaches, can be ambiguous and it is difficult for a doctor to identify a sleep disorder based only on symptoms observable in a consultation. The symptoms can be vague and ambiguous and the threshold for recommending a costly, overnight procedure without having clear indications that it is a sleep disorder causing the symptoms can be difficult to justify for the clinical staff. As it is not always clear whether symptoms are caused by sleep disorders other more easily diagnosed alternatives are explored first. The overnight PSG requires technology, personnel, dedication and experience.

This is a recognized problem and attempts have been made to create pre-screening tools in order to detect sleep disorders. We will look into some examples of these solutions in **??**. This can be done by either using mobile devices with their built in sensors such as smart phones, or using custom made home usage device such as home PSGs or other sensors that monitor parameters that can indicate sleep disorders, such as respiration rate, blood oxygen levels, heart rate, body movement or other relevant metrics.

Also, a patient with a sleep disorder will not yield the same result for each PSG recording, as a patients sleep pattern can change from night to night. It would be even more costly to have a patient spend multiple nights in a sleep laboratory for several tests

in order to determine the exact extent of the sleep disorder. This also brings us into the problem of sleep quality during the sleep study. A PSG requires multiple electrodes connected to a patient which can cause the patient to not be able to fall asleep or give a false or imprecise impression on the sleeping pattern of the patient.

Even if a PSG is accurate (the current gold standard for sleep related measurements), the threshold for doctors to order a PSG is relatively high due to the cost and effort required to do a complete PSG. This makes the need for non intrusive pre-screening tools in order to clinically diagnose the cases of sleep disorders. If a patient can with minimal effort take a test without the use of intrusive sensors and in their own home, closer to a normal nights sleep it might be easier to justify a more thorough examination.

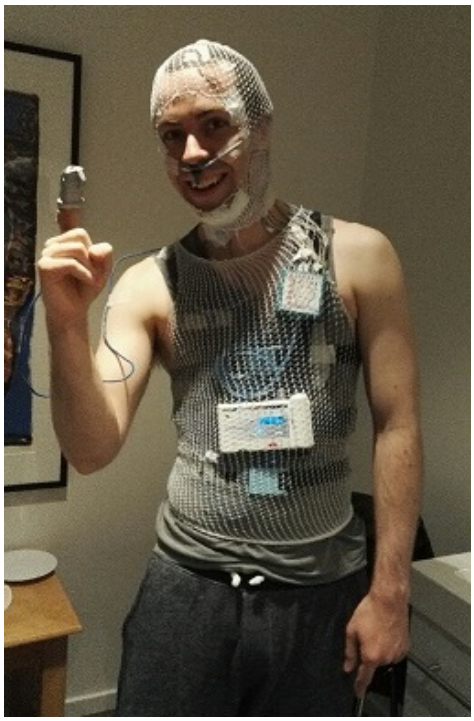


Figure 1.1: Equipment used in a PSG

1.2 Problems caused by sleep disorders

TODO: Why are sleep disorders important to detect...

1.3 Non intrusive senors

In order to create a system that can detect sleep disorders without the need for overnight stay at a sleep laboratory or the presence of clinical personnel, we will look into the use of non intrusive sensors.

By sensor we are talking about a device or multiple devices coupled together, able to detect bio markers, such as respiration stops, in order to indicate sleep disorders. Sensor technology will be described in Section 2.3.

The quality of being non intrusive is that the patient is not hampered of put in physical discomfort by the sensor, as they would have with a sensor that require electrodes or a mask or other probes that might cause discomfort. Whether a sensor is intrusive or not is not well defined, but varies based on different parameters. If we have a sensor that requires the user to sleep with a elastic band around their chest, this might not be seen as an intrusive sensor for a healthy person as they have no problem attaching and wearing the sensor. But for a person with limited mobility, the act of attaching the sensor might prove to be a considerable inconvenience.

1.4 TRIO

This thesis is aimed to become a part of the ongoing project TRIO. The project is a collaboration between the Distributed MultiMedia Systems (DMMS) and Nano Electronics (NANO) research groups, both a part of the Institute of Informatics (IFI) at University of Oslo (UIO), The Intervention Centre at Oslo University Hospital (OUS), and Novelda AS. The project description states that the main goal is to develop systems based on non invasive sensors that can be used in a home environment to identify parameters indicating the need of medical intervention.

One such parameters is respiration. Respiration signals can be used to indicate acute health related problems, but can also

combined with knowledge about the wakeful state of a patient help diagnose sleep disorders.

1.5 Problem statement

If we can obtain a respiratory signal from a non invasive sensor and also detect low level events that describe useful changes in the signal, we can then pass these on to a separate system, such as TRIO, to do analysis in what is called event space.

For this thesis we will attempt to adapt the software and algorithms found in existing work using sensors for deriving respiratory information from physical sensors. From the data generated from the sensors we detect the low level events that is in turn transmitted to a analysis system.

In order to evaluate the real time capabilities of such and adaptation we create a test framework that can give us insights to the limitations and potential challenges.

1.6 Approach

The first step is to identify and analyse existing software to find a solution that have the functionality we need.

- **Find** and **analyse** existing software
- Identify useful **parameters** detected by the software
- **Modify** if necessary
- **Adapt** (convert results into **events**) for *real-time* use and **evaluate** viability

1.7 Structure

TODO:

Chapter 2

Background

The system described in our problem statement will make use of *sensors* in order to detect *sleep disorders*. The *sensors* captures physical phenomena and converts it into *signals*, that we in turn *process* into *events* for TRIO. This chapter explain some of the underlying concepts for such a system.

2.1 Sleep Apnea Syndrome

Sleep Apnea Syndrome (SAS) is sleep disorder characterized by the disruption of airflow during sleep. SAS is often divided into one of three sub diagnosis, Obstructive Sleep Apnea (OSA), Central Sleep Apnea (CSA), and Mixed Sleep Apnea (MSA), also know as Complex Sleep Apnea.

All diagnosis have in common either total stop or a reduction of respiration with a subsequent decrease in blood oxygen levels. The cause of these respiration reductions is what defines the type of SAS. An apnea event is the name for a complete stop of respiration for at least 10 seconds, while a hypopnea event is defined as an at least 10 seconds reduction in ventilation of at least 50% of normal airflow during sleep[33]. When the blood oxygen level is reduced the body is aroused from sleep in order to resume normal breathing. The arousal from normal sleep reduces the sleep

quality.

2.1.1 Obstructive Sleep Apnea

Pathogenesis

OSA is also known as Obstructive Sleep Apnea/Hypopnea Syndrome (OSAHS), due to the occurrence of both apneic and hypopneic events. In OSA the upper airway (UA) passage is either completely or partially blocked. There are multiple structural or anatomic factors that have been discovered to cause UA blockage, and these blockages occur in the pharynx. The pharynx is the area where the nasal and oral cavity meet and it has both the digestive, speech and respiratory functions in human anatomy. The pharynx area consists of muscles and soft tissue and it is necessary to be able to collapse and close the UA for digestive and speech purposes while awake. The negative pressure created by the inspiration process can cause the soft tissue region to collapse, causing blockage.

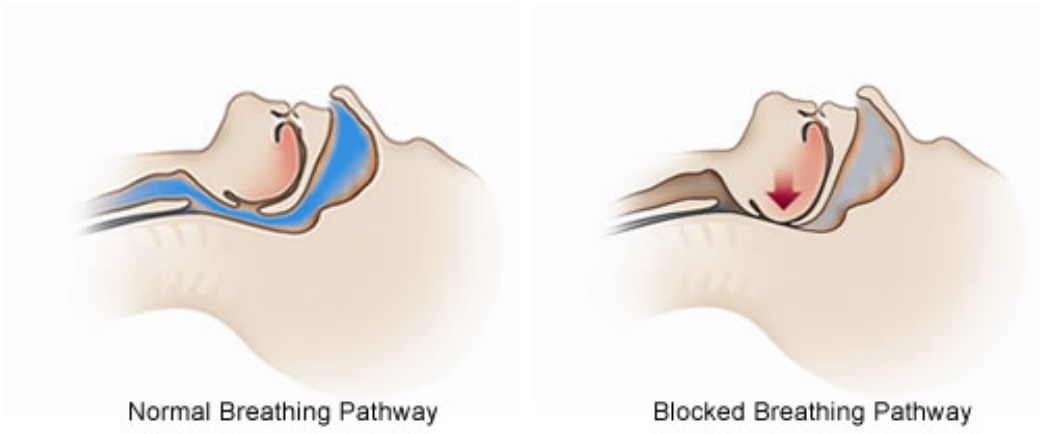


Figure 2.1: Obstructive Sleep Apnea

There are also genetic factors as some have smaller airways that also can contribute to the lack of airflow. Nasal obstruction can lead to mouth breathing, which predisposes to abnormal airway dynamics that favors not only pharyngeal collapse but also what is called backward displacement of the tongue. The soft tissue of the tongue can cause UA blockage.

In addition to the soft tissue risk factors, the bone structure of the jaw region can be positioned in such a way that the tongue is predisposed to be pulled back into the pharynx during sleep during sleep stages with decreased muscle tone.

The factors that can increase the risk of UA blockage makes OSA difficult to predict and diagnose.

Epidemiology

Patients with anatomical vulnerability are considered to be more susceptible to developing OSA[50, 9]. These vulnerabilities can be enlarged tonsils, recessed mandible, small upper airway, impaired retrolingual airway among others. Each of these case is not a clear indication of OSA, but can be a contributing factor. Other factors that increase vulnerability for OSA include age, obesity, menopause, sleep hygiene, and certain health behaviors such as cigarette smoking and alcohol use[49].

Hypertension, also known as high blood pressure, is an often reported co-morbidity of OSA[11]. During the lowered blood oxygen levels experienced during an apnea or hypopnea event results in increased activity in the autonomic nervous system in order to increase the oxygen level. The literature suggests that as much as 50% of OSA patients suffers hypertension even during wakefulness[53, 44].

OSA has also been linked as a risk factor for cardiovascular diseases, stroke, abnormal glucose metabolism, insulin resistance, and diabetes mellitus [49, 59]. Cerebrovascular diseases and OSA have been pointed out to have a bi-directional relationship[16], and as a result of the hypertension and reduced cerebral blood flow the risk for carebrovascular diseases such as stroke is increased.

As Fusetti points out, ”the common association of OSAS with hypertension and obesity in general population makes it difficult to separate their respective independent role in the long-term cardiovascular and metabolic consequences associated with OSAS”[13].

2.1.2 Central Sleep Apnea

Pathogenesis

While obstructive apnea is caused by blockage of the airways, a central apnea is the complete stop of respiratory effort as a consequence of imbalance within the brains control of the respiratory effort, described as a loss of ventilatory control[64]. While instability in the upper airway leads to obstructive sleep apnea, the imbalance of ventilatory control can lead to both obstructive and central sleep apnea.

Epidemiology

CSA can manifest in two broad categories according to the wakefulness CO^2 levels. Hypercapnic and nonhypercapnic. Hypercapnic is defined as elevated CO^2 levels in the blood. Patients often exhibit some degree of daytime hypercapnea and this condition is often worsen during sleep. Two patterns are often used to classify hypercapnic: impaired central drive ("won't breathe") and impaired respiratory motor control ("can't breathe")[8].

Impaired central drive can be caused by physiological factors that diminish ventilatory function, but has also been linked to genetic factors without anatomic pathology. Opioid-based medication have for a long time been pointed out to have a respiratory depressant effect[63].

Impaired respiratory motor control can experience CSA due to abnormalities in the signaling of the respiratory system. It can be caused by a wide range of neuromuscular disorders that causes some stage of the signaling process to not be able work properly.

Cheyne–Stokes breathing is a nonhypercapnic breathing pattern that is most commonly observed in patients with congestive heart failure and left ventricular systolic dysfunction[8]. During Cheyne–Stokes the patient increases the breathing rate gradually in a crescendo/decrescendo pattern broken up by apneic events. Arousal typically occurs mid-cycle at the peak of ventilatory effort

rather than at the cessation of apnea.

2.1.3 Mixed/Complex Sleep Apnea

Pathogenesis

As defined by Guilleminault, Tilkian and Dement in 1976, "mixed apnea is defined by cessation of airflow and an absence of respiratory effort early in the episode, followed by resumption of unsuccessful respiratory effort in the latter part of the episode"[15]. This diagnosis is a combination of central and obstructive sleep apnea. In some cases when the respiration effort stops as a result of CSA, the pharynx region is collapsed due to the lack of pressure, so when the body is aroused into resuming breathing efforts it is still completely or partially blocked.

Epidemiology

These episodes of central apneas followd by airway collapse and obstructive apneas and hypopneas are considered to be multifactorial. Obesity and/or snoring has been linked as a contributing factor for developing mixed apnea in CSA patients as the increased risk of high passive airways which leads to higher susceptibility for airway collapse[7]. The same article also points out mixed apnea in in patients that are administered chronic doses of opioid medications.

As this diagnosis is a combination of Central and Obstructive sleep apnea, many of the same health effects can be found.

2.2 Diagnosis

Hypopneic and apneic events are common symptoms of sleep apnea, and in order to diagnose the different conditions. Respiratory

Disturbance Index (RDI) is often used in sleep studies, but it includes other disturbances other than hypopneic and apneic events. This calls for a more specialized scale to diagnose sleep apnea.

2.2.1 AHI

Apnea–Hypopnea Index (AHI) is a commonly used index for the severity of sleep disturbances during the course of the total sleep time of a patient. The AHI usually refers to the number of events per hour of sleep. The number of events can be used to measure a severity score, where:

0-4	Normal
5-14	Mild
15-29	Moderate
30 or more	Severe

Table 2.1: AHI severity scale

In order to calculate the AHI we use the number of apneic and hypopneic events per hour

$$AHI = (Hypopneas + apneas) * 60/TotalSleepTime(minutes)$$

The AHI combined with daytime symptoms, such as EDS, dry mouth or headaches when waking up, is the basis of diagnosis for sleep apnea.

The first indication that often warrants the sleep study is the daytime symptoms, but according to the literature there are patients without any associated clinical symptoms (asymptomatic apnea). The literature suggests that the effect of these asymptomatic patients still suffer altered heart rate during daytime without symptoms or co-morbidities[3].

As the name implies, AHI counts both apnea and hypopnea events and is very useful for OSA detection, since a patient suffering from OSA can exhibit both apnea and hypopnea events.

There are several different non intrusive ways of indicating a diagnosis of sleep disorders. Questioners such as the Berlin Questioner, STOP BANG and Epworth Sleepiness Scale (ESS) are used in order to screen for and discover the usual symptoms of sleep disorders. One example of a study using the Berlin Questioner (BQ) and Epworth Sleepiness Scale (ESS) is "A Norwegian population-based study on risk and prevalence of obstructive sleep apnea"[18] where it was used to make an estimate on the prevalence of OSA in the Norwegian population. These questioners help researchers to estimate the prevalence of OSA, but for a clinical diagnosis a physical examination such as a sleep study is needed.

2.2.2 PSG

In order to detect sleep disorders in patients, we need to monitor certain physiological parameters of the patient in order to classify the type of As mentioned in Section 1.1 the gold standard for sleep disorder diagnosis is the polysomography (PSG) or sleep study.

The function of PSG is monitoring of a patient during sleep using an array of medical equipment that is simultaneously recorded. The types of parameters depend on the type of PSG used. As there are at least `number of sleep disorders` types of sleep disorders diagnosed by sleep studies, variations on what types of signals recorded is classified by different types of PSG. According to AAST (American Association of Sleep Technologists) the standard PSG has the following parameters[41]:

With electrodes:	
EEG	Electroencephalogram monitors the electrical activity in the brain.
EOG	Electrooculogram measures eye movement.
EMG	Chin Electromyogram monitors level of muscle tone around the chin area.
ECG	Electrocardiogram monitors the heart rhythm
Respiration	recorded from the movement of electrodes
Other sensors:	
Audio	Upper Airway Sound Recording
Thermistor or Inductive Respiratory Plethysmograph (RIP)	Respiratory effort and flow
Limb EMG	Limb Movement and Body Position

The EEG documents wakefulness, arousals and sleep stages during the sleep study, which is important in order to know whether symptoms occur while the patient is sleeping and at which sleep stage it occurs. Sleep stages are often classified into five separate stages; 1, 2, 3, 4 and REM (rapid eye movement), or into REM and nonREM stages.

- In stage 1, muscle activity slows down, the eyes move slowly and ?you? drift in and out of sleep.
- In stage 2 the brain waves becomes slower and the eye movement halts.
- In stage 3 the brain waves becomes very slow with occasional smaller, faster waves.
- In stage 4 the brain almost exclusively produces the same slow brain waves as in stage 3.

Stage 3 and 4 are referred to as delta sleep, which is the namesake of the extremely slow brain waves (delta waves) found in these stages. During delta sleep there is no muscle activity or eye movement. During REM sleep breathing becomes more rapid and irregular, eyes move rapidly and limb muscles are temporarily paralyzed. The brainwaves during REM sleep increase to an

activity level which is comparable to an non sleeping person. In order to detect REM sleep, other parameters such as EOG and EMG combined with EEG are usually used. Novel solutions have been proposed in order to be able to monitor all sleep stages with the use of only EEG [19].

Stages

Waking	REM Sleep	NREM Sleep			
Stage 0	Stage R	Light Sleep		Deep Sleep	
		Stage 1	Stage 2	Stage 3	Stage 4
Eyes open, responsive to external stimuli, can hold intelligible conversation	Brain waves similar to waking. Most vivid dreams happen in this stage. Body does not move.	Transition between waking and sleep. If awakened, person will claim was never asleep.	Main body of light sleep. Memory consolidation. Synaptic pruning.	Slow waves on EEG readings.	Slow waves on EEG readings.
16 to 18 hours per day	90 to 120 min/night	4 to 7 hours per night			

Figure 2.2: Sleep stages[57]

The EOG is useful for identifying and studying the REM sleep stages. It uses electrodes positioned near the corner of each eyes to measure the existing resting electrical potential between the cornea and Bruch's membrane in order to determine the position of the eyes.

For sleep studies EMG is used in the metalis, submentalis muscle, and/or messater region[55]. The EMG records the muscle tone and is used as a criterion for staging REM sleep. EMG can also be used on other muscle groups to determine sleep disorders, such as monitoring leg muscles in order to detect restless leg syndrome.

Each time a heart beats it is triggered by an electrical impulse. The ECG (also called EKG) records these impulses as they travel through the heart. The electrical activity is recorded using

electrodes placed on the patients body. Today the standard ECG consists of 12 leads in order to monitor all three dimensions of the heart [60]. Typically there are six limb leads placed on arms and legs and six precordial leads placed across the chest. Each lead has a specific angle from which it observes the heart in order to

TODO: reread book for better explanation.

The limb leads monitor what is called the frontal plane, while the precordial leads monitor the horizontal plane. Each node records the average current flow at any given moment. Each heartbeat is described as an RR interval, also known as a cardiac cycle. Based on which electrode records activity the RR interval can be further segmented into smaller and identifiable intervals of the cardiac cycle and used in diagnosis and evaluation of the heart and breathing of a patient.

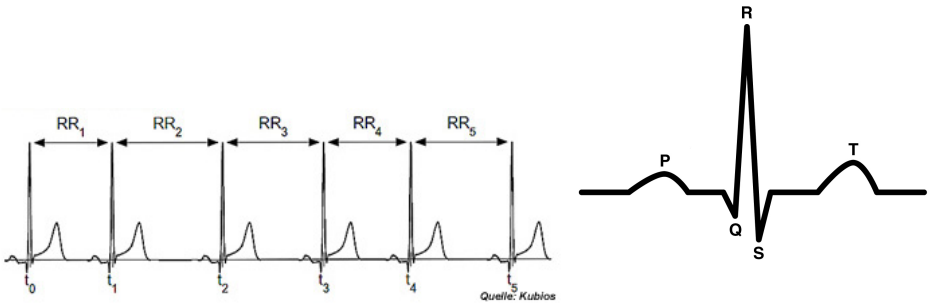
QRS is a pattern seen in an ECG that indicates the pulses in a heart beat and their duration. Each part of a QRS complex shows the activity

TODO: QRS –very brief!

There are multiple ways to record the respiration rate during a PSG. Nasal and oral airflow are often recorded either with nasal *thermistors* or thermocouple, which uses changes in temperature to measure the airflow with prongs or probes placed in or near the mouth or nose. Another way of recording is to measure the physical movement the body during respiration using respiratory inductance plethysmography (*RIP*), which uses elastic bands around the torso and abdomen to record the movement of the body as a patient inhales and exhales. Based on the inflation and deflation of the chest and abdomen area, the respiration rate can be derived. Both of these methods are used as ground truth in assessing the respiratory rate in sleep studies[4, 27].

When none of these respiratory signals are recorded, other techniques can be deployed. One such technique is to use the ECG signals to derive the respiration rate. ECG, or electrocardiography, measures the electrical signals generated by the heart. There are different ways of obtaining the respiration rate from an ECG signal and also from the ECG electrodes themselves. One method

calculates the respiration rate based on beat to beat variation RR intervals (Figure 2.3a). This technique is based on respiratory sinus arrhythmia (RSA) which is a natural variation in the heart rate. TODO: finish



(a) RR Intervals (b) QRS Complex

Figure 2.3: ECG signal illustrated

Another technique is ECG Derived Respiration (EDR). When a patient breaths the ECG electrodes on the chest surface move relative to the heart due to the lungs filling and emptying. The transthoracic impedance varies as a result of the expansion and contraction of the lungs and from the mean cardiac electric axis show variations that correlate with respiration[37]. TODO: finish

Oxygen saturation is a useful parameter for detecting OSA, as the SaO^2 (blood oxygen saturation) drops after the onset of an apneic/hypopneaic event. According to Division of Sleep Medicine at Harvard Medical School[51], the SaO2 is usually around 96% - 97% at sea level. A dip to 90% is generally considered mild, while dips to between 80% to 89% are classified as moderate and saturation below 80% are severe.

2.2.3 Treatment of OSA

In order to effectively treat OSA, physicians have to consider the severity of the disease, co-morbidities and the patients preferences. A non surgical option is lifestyle changes, such as weight loss, avoidance of alcohol and nicotine, position therapy and treatment of co-morbid conditions. Continuous Positive Airway Pressure (CPAP)

or therapy is described as a first-line therapy for moderate to severe OSA[16].

CPAP consist of a air pump, tube, and a mask, which provides pressurized air into the patients throat via the mask. The pressurized air helps avoid negative pressure from the inspiration collapsing the airway.

APAP devices (Autotitrating PAP) detect snoring, airway resistance or impedance in order to only administer positive airway pressure. It also uses diagnostic algorithms in order to adjust the amount of pressure, but are far more complex than a standard CPAP and require calibration by a sleep technician. They do though have the advantage of adapting the pressure to sleep stage and sleep position, reducing the risk of discomfort due to too high pressure during sleep stages with more relaxed muscle tone.

Surgical treatments for OSA is centred around reducing the risk of collapse and removing potential obstructions. Surgical techniques can be to remove some of the soft tissue in the pharynx region, reposition the soft tissue by skeletal mobilization, or bypassing the pharynx region[54]. There is no standard procedure found to eliminate OSA.

Another approach that can be utilized is pharmacological treatment, but the literature suggest that such treatment has not been successful. A review by Hedner, Grote and Zou from 2008 concludes: "Currently, no widely accepted pharmacological treatment alternatives are available for OSA"[17]

2.3 Sensors

The name sensor has according to Webster's New World College Dictionary its roots in classical Latin *sentire*, which means to sense. "A sensor is a device which responds to stimuli, or an input quality, by generating processable outputs"[22]. This is how Kalantarzadeh defines sensors. He also points out that the outputs of a sensor are always functionally linked to input stimuli of the sensor.

The term sensors refers often to two aspects, i.e. the sensor that quantitatively measures an input quality and the component that converts it to a readable signal for the device or person receiving the recordings. The part of a sensor that is responsible of taking the input signal of the sensory apparatus and converting it is referred to as the transducer. A *transducer* converts one type of energy to another and is sometimes used interchangeably with sensors.

An example of a simple sensor is litmus paper, which usually is used for determining whether a solution is basic or acidic. The litmus paper is exposed to the the solution and reacts to the stimuli by changing colour, allowing an observer to read the results.

The output from sensors is a representation of the measured property and this can be described in different ways depending on the property measured. Over time the output can be used to create a sequence of data points called a *time series*.

`TODO: describe transducer?`

There are different ways a sensor can be constructed in order to record some quality of the real world. *Contact* and *non contact* sensors are two broad categories can be used to describe sensors. Sensors that are described as *non invasive* do not necessarily have to be *non contact* sensors, but rather refer to the level of disturbance or discomfort the sensor cause for the monitored patient. A *non contact* sensor can be *invasive* if the operation of the sensor generates noise, while a *contwact* sensor might be very light and not noticeable by the wearer, and hence be considered a *non invasive* sensor.

In general, a *non invasive* sensor can be defined as that it will not interrupt a patients normal sleep. As this criteria is subjective, it makes the grouping of sensors difficult to pin down.

Signal processing is an umbrella term for operations applied to the signal. J. Moura defines processing as ”operations of representing, filtering, coding, transmitting, estimating, detecting, inferring, discovering, recognizing, synthesizing, recording, or reproducing signals”[38].

2.3.1 Sensor characteristics

Ideally a sensor should be able to measure a desired quality (input) of the physical world without any other input being registered. This is referred to as *sensitivity* towards the desired input and an *insensitivity* towards other potential inputs. It is important that a sensor does not affect the input or the environment it is deploy in.

The *accuracy* of a sensors recording is the correctness of the output compared with the actual value of the quality it measures. Deviation from the actual value of the quality can be due to rounding error, inaccurate sensor, calibration error, too low resolution etc. The example Kalantar-zadeh uses is a temperature sensor measuring a real temperature of 20.0°C. If the sensor measures 20.1°C it is more accurate than if it had measured 21.0°C[22]. This is not to be confused with *precision*, which is the capacity to get the same result from repeated measurements of the same quality under the same conditions. The difference between precision and accuracy is illustrated in Figure 2.4.

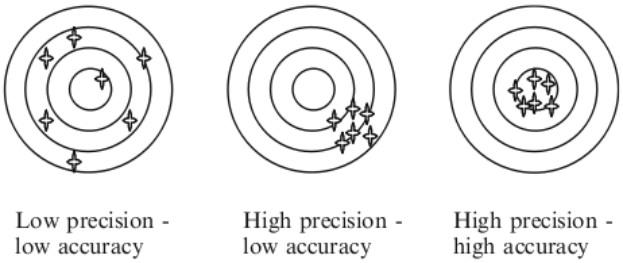


Figure 2.4: Precision and accuracy[22]

McGrath and Scanaill[34] describe "$v1.0$ sensors" as simple measurement of quantity, such as a mechanical thermometer. For the second generation of sensors we add computational power and communication which allows the sensor to process the data it records and transmit it to other devices. An example of this can be a acidity sensor, which is connected to an actuator which controls a valve in order to restore the Ph level to a preset value based on the sensors readings. At this stage the cost of production is still so high that it is not commonplace and highly specialized.

"Sensors $v3.0$" is described as when private consumers adopt the use of sensors. At this point sensors that previously were too expensive for consumers can be found in smart devices and in affordable home-use devices. In addition to the computational power introduced in "$v2.0$", the connectivity to the Internet opens up for new avenues for communication and pervasive sharing of data in real time. The data recorded by smart devices can be used for location tracking, health applications, consumer habits, and other areas.

"$v4.0$" is the stage we are currently stepping into. The capabilities of sensor systems have been increased due to increased computing power, smaller sizes, increased connectivity and more affordable prices.

2.3.2 Sensor networks

As defined by Phoha, LaPorta and Griffin sensors and sensor networks can be described with the following characteristics: "they monitor changes in the operational environment and collaborate to actuate distributed tasks in dynamic and uncertain environments"[46]. Each sensor has a task, a measurement of the physical world to perform and converts it into a signal. There are two primary approaches to how to process the data recorded: either distributed or centralized.

A human body can be compared to a centralized sensor network. We have different sensing devices such as eyes, touch, smell and hearing among others. The signals from these sensors are processed and coordinated by the central nervous system and the combined information provided from the different sensors gives us information about the world and gives us the ability to detect events around us based on the combined data recorded from the surrounding environment.

A distributed sensor network uses the sensor-nodes themselves to do processing. As the name implies, the sensors do not relay all the information gathered to one centralised storage/processing unit. Each sensor works autonomously but collaboration

can be achieved by letting each node share and request information from the network as a whole.

2.3.3 Data Stream Management Systems

Data Stream Management Systems (DSMS) are used in order to process the information gathered continuously by sensors or sensor networks. A database management system (DBMS) is concerned with persistent storage of data, and is often used in conjuncture with DSMS. Instead of sporadic writes and frequent reads, as found in most traditional DBMS, DSMS have to filter out relevant events as data arrives. Access to the data is done as it arrives, thus the system has to continuously read and write data to memory.

A DSMS can not make use of a traditional query language, but instead uses what can be described as a *Continuous Query Language* (CQL). It can also be referred to as StreamSQL, as it shares the declarative nature of of SQL-like language. There is no standard language, but several prototypes has been created. A common trait is that all queries has to be one-pass queries, due to the stream-centric nature of a DSMS. An *event* is a *match* to a Continuous Query (CQ) on transient data. Results of a CQ is then passed on to *sinks* who consume the resulting matches, while the data in the stream can be passed forward to a different system, discarded or stored in a persistent database system.

It is important to note that a source does not have to be a physical sensor, but can just as easily be another DSMS or similar system running different queries. This way we can multiplex and demultiplex any given data stream.

As a data stream can be potentially infinite, the DSMS cannot do aggregation or analysis of data when it has gathered a ”complete” set. Many DSMS uses a windowing technique to look at portions of the data as it arrives. These windows can be time or tick-based. Tick-based windows waits for N number of entries to arrive, while time-based windows aggregate on certain intervals. Aggregations can be averages, sum, count for time-based windows etc.

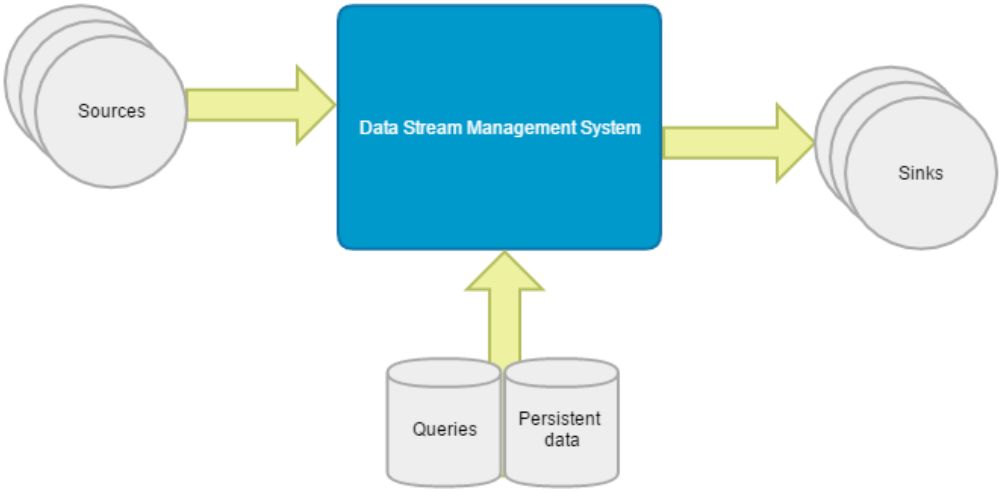


Figure 2.5: A simplified Data Stream Management System

Each arriving tuple has to be marked with a time stamp. There are different strategies, all with different pros and cons. The main issue when dealing with time in a distributed systems is synchronization. If the sender attaches the time stamp we need mechanism in order to make sure their timing mechanisms are synchronized precisely. This approach, when the time stamp is injected by the data sources is called **explicit** time stamp, while **implicit** introduces the time stamp when the data arrives at the DSMS. This introduces an extra workload on the system, especially if we have multiple inputs. Depending on the domain the application is created for we also have to consider what is more important. The time when the data was created or the time the data arrived at the DSMS.

2.3.4 Complex Event Processing

While a DSMS detects changes in state, an isolated event that signifies things that happen in a stream of data, *Complex Event Processing* (CEP) combines data from multiple sources to infer events or patterns for complicated situations. TRIO makes use of a CEP called *Esper*, developed by *EsperTech*[58].

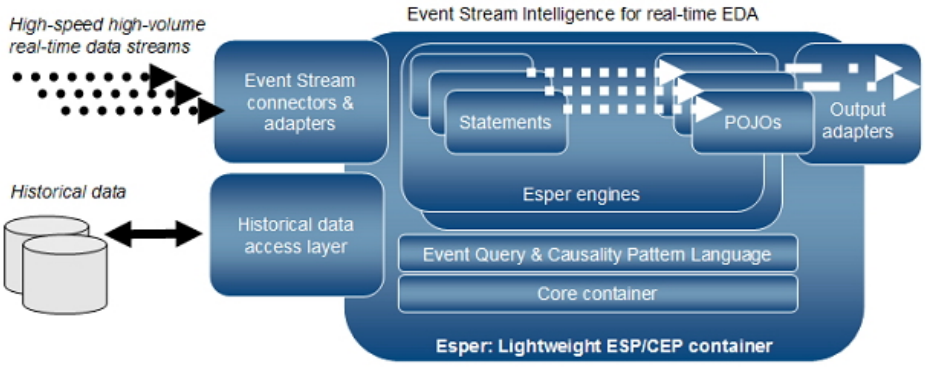


Figure 2.6: Esper components[56]

In order to make sense of data recorded by multiple sensors or a sensor network, they can be grouped together into what is called a *logical sensor*. By multiplexing signals from multiple sources, be it sensors or external sources, a logical sensor can learn new information and detect complex events based on multiple inputs.

An trivial example of a complex event can be a system utilizing a temperature sensor and a smoke detector. The logical sensor created from these two physical sensors can use both signals to detect a fire by combining, and decrease the chance of a false positive from a kitchen appliance or other device that generates heat.

Part II

Respiration analysis application

Chapter 3

Existing applications/Basis for analysis

Because of the estimated high number of undiagnosed cases of OSA and the high cost of sleep studies, there has been a lot of research into non intrusive methods of detecting and diagnosis of sleep disorders.

There are many existing solutions on the market with different capabilities. Some of these solutions come with software which delivers high level physiological data such as heart rate, respiration per minute, temperature etc. Similar techniques to what is used by existing systems can be used to detect other low level respiratory events, such as onset of pauses in respiration and peak and trough detection.

BioRadio[20] has created software for their sensors that promises real-time visualization of data-streams, which suggests that there is potential for real-time analysis as well. But as with other projects, the software is propitiatory, which turns out to be the most common problem when trying to find an existing solution. We need to, based on the goal defined in the problem statement (Section 1.5), find existing solutions that allows us to define the low level events we want to detect.

To create a new respiration analysis system from scratch would allow us to have full control over the definition of the events,

but will require considerably more work than using an existing solution. The quality assurance of the results will also require a much deeper understanding of the analysis, rather than working with existing and testes software. In order to reduce the work load of such an undertaking libraries such as *The BioSig Project*, which is an open source library for biomedical signal processing[40]. This library can help us considerably, but will still require more effort than using an existing solution.

3.1 puka

The application we use for the respiration analysis is called *puka*. The decision to use this particular solution is based on the fact that even though a lot of other more recent and novel approaches exist, none of their implementations can be found. Since puka is not only implemented, but also open source we are able to tailor it to our needs and make modifications where we see fit. The source code for the application can be found on PhysioNets websites[47].

PhysioNet Resource is a public service funded by funded by the National Institute of Biomedical Imaging and Bioengineering (NIBIB) and the National Institute of General Medical Sciences (NIGMS) at the National Institutes of Health. The service PhysioNet can be divided in three parts:

1. **PhysioBank**: a collection of digital recordings of physiologic signals, time series, and related data
2. **PhysioToolkit**: a library of software for physiologic signal processing and analysis2
3. **PhysioNetWorks**: a virtual laboratory for collaboration

3.1.1 Key functionalities

To generate events for the Esper engine in TRIO (see Subsection 2.3.3) we need a system that can analyse signals from respiratory sen-

sors. Based on time series generated by sensors such as RIP or thermistor based respiration monitoring we must be able to derive events that are significant to the detection of sleep disorders.

In the analysis system of the signal gathered from sensors we look for two main functionalities:

1. detect stops in respiration (effort)
2. detect these in as close to real time as possible

The first one is found in puka, assuming we can make the application run on modern systems. For the second functionality we have to make modifications to the existing application as the original application was created to analyse pre recorded signals.

The signals analysed are discrete-time signals or time series which can be represented as waveforms. This representation makes it easy to illustrate the signal and visually detect events such as inspiration and expiration start and stop. The design of puka is such that it takes a time series as input, finds respiration peaks and troughs and then, based on a threshold, calculates the pauses between each breath. These types of events can in turn be used for a real time analysis in order to fulfil the second quality.

One advantage of using an existing implementation is that it has been created by programmers with a through domain knowledge. Not only does an implementation of a respiration analysis require knowledge of signal processing, but also a great understanding the underlying algorithms. By basing the system on an existing implementation we can more easily get started on creating a system that can integrate with TRIO as a whole. Since the application is open source we can also make changes as we see fit if necessary.

3.1.2 Terminology

To avoid confusion about the terms used in puka and terms used in both the modernization and real-time implementation, we briefly will go through key terminology used by puka.

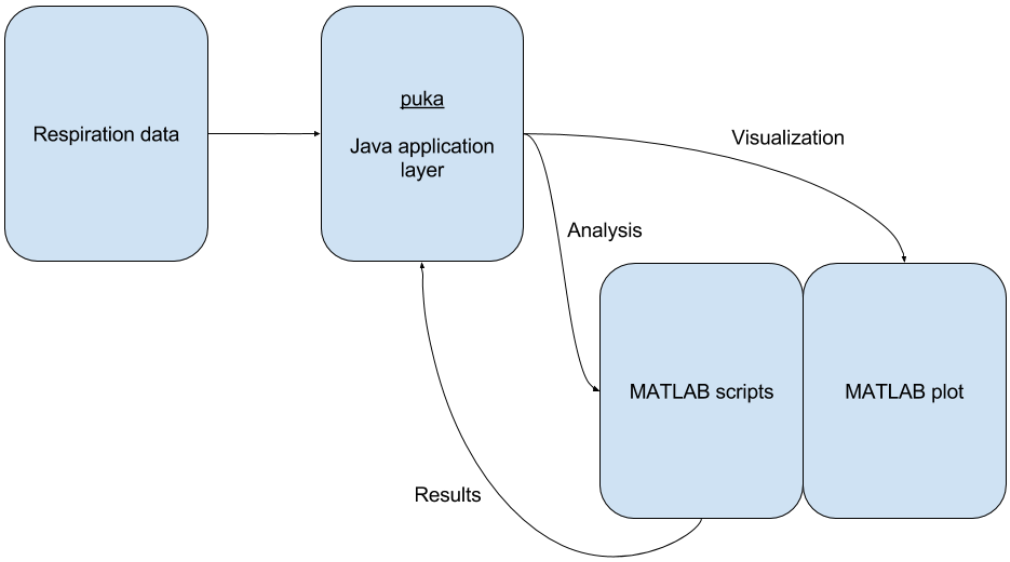


Figure 3.1: The main flow of puka (generalized)

When puka refers to a *record*, it is referring to a time series persistently stored, either in a *file* or *database*. The record is read into memory.

The section of the *record* puka analyses is called a *clip* in puka.

3.1.3 History

Puka was written by Joset A. Etzel, Erica L. Johnsen, Julie A. Dickerson and Ralph Adolphs in 2004 to analyse pre recorded data collected from equipment and software from BIOPAC Systems, INC. BIOPAC is a company founded in 1985 that makes physiological measurement tools. The authors of the software found that puka was able to analyse other physiological signals as well. The latest implementation (2004) contains ECG and respiration analysis

tools. The respiration signal it uses for the analysis are gathered from strain gauge sensors that measure the circumference of the chest and/or abdomen as it expands and contracts during respiration. The strain gauge respiration data are time series that show the conductivity of the strain gauges signal which reflect inhalation and exhalation as the chest and/or abdomen. The respiratory analysis was designed to use signals collected with a TSD201 Respiratory Effort Transducer, a single strain gauge recorder.

Puka uses MATLAB to calculate descriptive statistics such as heart rate variability, peak-trough respiration sinus arrhythmia and respiratory variables from ECG and the strain gauge respiration data[48].

The same analysis can also be applied to other signals that share the same characteristics as strain gauge respiration data, such as thermistor sensors and RIP (described in Subsection 2.2.2). These types of signals fluctuate around a base value, and give us a respiratory waveform when plotted against time. The rise and fall in amplitude is representing different physical attributes, such as conductivity in the case of RIP, or temperature in the case of respiratory thermistor.

3.1.4 Program structure

The main control and structural code of puka is written in Java. This part of the code is responsible for I/O operation, interactions with the user and data persistence. Interactions with MATLAB are synchronous operations, originally via the library JMatLink, initiated by the user using a GUI. The GUI has been created using the Netbeans module Form, but since the intent is finally to strip away the GUI, no modification or upgrades are necessary for this project, and any description of the GUI code is therefore skipped.

The application is initialized via the *frmMain* main class which instantiates the GUI and prompts the user as to what data input to use. Data can either be read from a database or from a file that adheres to the format allowed, described in Subsection 3.1.7. A simple program must be written to change the raw text output of

the PhysioNet data to the format specified by puka. Physionet has a program library which contain programs that allow us to easily convert the signal files into a more suitable text format.

TODO: illustration of the application, diagram?

The calls to the MATLAB engine are done via the JMatLink library. The MATLAB scripts that are executed is located in the folder *Matlabscripts*, found in the puka source code. The instance of the JMatLink proxy which all classes communicate with MATLAB through is instantiated in the *frmLoadData*-class and used throughout the lifetime of the application.

3.1.5 Runtime requirements

In this thesis a 64-bit Windows 7 machine is used to compile and run all software. As stated in the user manual[48], operating systems other than Windows XP and 2000 has not been tested. The manual also list six main external dependencies that have to be installed in order to run puka.

Dependency	**Comment**
Java	Minimum v1.4 according to documentation
MATLAB	R13 was released in 2002
Cygwin	No version specified
WFDB	Installed within Cygwin
JMatLink	Latest version (V1.3.0) released in 2005
~~MySQL~~	Ignored since puka supports file storage

Table 3.1: External dependencies for puka

On the machine used for this thesis the Java code has been compiled with *Java JDK 1.8.0*, with the exception of the attempt to compile JMatLink when *Java 1.4* was used (see Subsection 4.1.1). *MATLABR2012b* has been used to run all scripts. This is version of MATLAB available to students at UiO, making it a natural choice for this thesis.

Puka depends on parts of the WaveForm DataBase (WFDB) Software Package. The WFDB Software Package is a curated list of specialized software for usage with PhysioBank data. The bulk of the necessary software is found in the WFDB library which is an API for access to PhysioBank.

The WFDB library is available both for command line usage and as a library for MATLAB. puka makes use of a small subset of the package (Table 3.2), but other components can be useful for reading, retrieving and manipulating the recordings found in Physiobank. The package requires Cygwin and certain libraries within the environment. Cygwin replicates significant parts of the POSIX system call API for a Windows environment, which WFDB package applications depend on.

ecgpuwave.exe and *convertecg.exe* are separate from the WFDB library, but can be compiled using the compilers *gfortran* and *gcc* respectively. Both of these programs are used in the ECG analysis.

Cygwin allows us to utilize the *gcc* and *gfortran* compilers in a Windows environment, which are necessary to compile the support applications *convertECG* and *ecgpuwave* respectively. *rdann* is used to read the file format used by Physiobank. It can read both local files or download the files from Physiobank web service containing signals.

ann2rr, *ihr*, *ECGPUWave* and *convertECG* are all used by the ECG analysis, and therefore not described in much detail.

ann2rr reads a WFDB record and an accompanying annotation file and returns the the RR interval in number of samples, and a vector of sample numbers representing the onset of these RR intervals. *ihr* reads an annotation file (specified by the annotator and record arguments) and produces an instantaneous heart rate signal.

The standalone tool *ECGPUWave* analyses an ECG signal and detects the QRS complexes and locating the beginning, peak, and end of the different stages of the QRS complex. Another standalone tool is *convertECG* converts ascii text files into the binary WFDB data format.

rdann	move annotation created by ecgpuwave to external file
ann2rr	create an RR interval series
ihr	create a instantaneous heart rate series
ECGPUWave	marks ECG waveforms
convertECG	converts ecg.txt into wfdb .dat format

Table 3.2: WFDB programs used by puka

The JMatLink library is used for communicating with the MATLAB engine from Java runtime. JMatLink was created by Stefan Müller in 1999 [29] to allow users to interact with MATLAB via a web server, running a Java program. The last iteration of the library ($v1.3.0$) was released in 2005 and the source code can still be found on Sourceforge[31].

3.1.6 Preferences

In the startup process puka looks for the *preferences.txt* file in the working directory which is the directory in which the program was launched. The preferences consist of the absolute path to helper programs such as the WFDB applications and *convertECG*. In addition to keeping a track of helper application the preferences also keeps track of certain meta-data about signal clips to be analysed by puka.

The preferences window contains five tabs with different values (Figure 3.2). These preferences has to be set for each system.

3.1.7 Data format

The program can either read data from a database or from a raw text file. Each line in a text file represents a sample and if we have multiple channels they are separated by a white space character. The column number of the signal used by ECG and respiratory analysis is indicated in pukas preferences file which can be edited in the GUI or directly in the text file.

Paths
WFDB tools
Installation directory (eccgpuwave.exe and puka.jar)
WFDB data file directory (download and signals)
ConvertECG.exe directory
ECG
Signal Frequency (hz) (even though under ecg spec, used in resp)
Signal unit (mV)
Signal Gain (adu/mv)
ADC resolution (bit)
Zero-level (adu)
Length of Record H:M:S
Data columns
Column for ECG and respiratory signal
Onset trigger
Clips
Clip name and length (num samples)
Database
List of database connections

Figure 3.2: Preferences stored in preferences.txt

TODO

Figure 3.3: PE pause, PI pause, peaks and troughs

3.1.8 Respiration analysis algorithm

The algorithm that is used in puka for respiration analysis is implemented in MATLAB. The scripts that contain the algorithm are found in the *matlabscripts* folder, and is split up into several *m*-file containing the logical components of the algorithm based on the steps in the algorithm.

The project site describes puka in the following terms: ”puka incorporates a new method of identifying the breaths and pauses in strain gauge belt recordings. This technique locates the points of maximum inspiration and expiration for each breath as well as post-inspiratory and post-expiratory pauses”[48].

The algorithms used in the respiration analysis identifies critical parts of a recording. The critical parts are peak, trough, post-inspiratory (*PI*) and post-expiratory (*PE*) pause. These four parts are useful events for detecting sleep apnea, and will have to be converted into events for the TRIO system. PI and PE pauses are the length of the section in a time series after the signal has flattened, as shown in Figure 3.3.

The program uses an algorithm which the puka manual splits up into five steps

1. Load and prepare signal,
2. identify breath (peaks and troughs),
3. check validity of peaks and troughs,
4. mark pauses at each peak and trough and finally
5. statistical computation

3.1.9 Item 1

The application reads a *record* which is the signal file into memory and stores it within the MATLAB engine as the *data1* variable. This is then split up using the *onsetTime* and *endTime* variables to create what puka calls a *clip*.

The *onset time* and *end time* which is passed to the peak detection algorithm (Item 2) is used to make sure that the found peaks and troughs are within the clip defined in the application. According to the puka manual, certain signals contain an *onset time*, and if not puka will use MATLAB to detect the first trigger point and use this as the stimulus onset time.

This is done by rounding the entire signal into a binary time-series. All values within the series that are below 0.5 is considered *false*, while the rest are *true*. The onset is set to the midpoint in the first *false* range.

Item 2

Firstly, the algorithm makes a pass over the whole clip, marking peaks and troughs using a *peak detection algorithm* based on Todd and Andrews' peak detection algorithm published in 1998[61]. When we use the term peak in this section, we refer to both peak and troughs as both are in principle the same. "A peak elements is any element that dominates both a preceding element and subsequent element. Correspondingly, a trough element is any element

that is dominated both by a preceding element and by a subsequent element"[61]. By dominating the surrounding elements the authors refers to the amplitude being greater in the element. Element does not necessarily mean a single point in a time-series, but can also refer to a range of points.

The suggested algorithm goes through a given signal Q. Each index in Q contains the amplitude of a sample in the time-series. Within the loop a variable d indicates the direction of the signal on the *y-axis*, that is the trend in the amplitude of the signal. The variable a records the index of a *maximal* element since the last *trough* while b contains the index of the *minimal* element since the last *peak*. A variable S records all indices of the maximal elements since the last peak *if* the signal is rising, minimal in the case of troughs.

`usikker på denne, men slike jeg forstår skriptet er det slik:` The direction d is in the puka implementation initially set to *unknown* to be able to start the algorithm and is arbitrary set to either up or down. The *onsetTime* in not allowed to be set to zero by the application code, resulting in a small window where the algorithm can correct the d. After the peak detection is completed the implementation removes peaks and troughs found before the *onsetTime*.

Using detecting a peak as an example and letting i as the current index during the loop, a is only updated when $Q[i]$ is higher than $Q[a]$. When $Q[i] == Q[a]$, we add $Q[i]$ to S. When $Q[i]$ is significantly smaller than the last maxima ($Q[a]$), the direction (d) is changed, S is stored and the algorithm looks for troughs by using $Q[b]$ now that d is changes. The significance of a change is determined by the *threshold*, which is a global value which is added to $Q[i]$ when comparing whether the value is significantly larger or smaller than the last maximum or minimum. The implementation of the algorithm that is used in puka can be found in Section 8.1.1.

The function returns two arrays, one containing the index of all peaks and the other containing troughs.

Item 3

After the peak detection is completed, puka classifies the peaks with three classifications:

1. valid,
2. invalid and
3. questionable.

The arrays returned from this function are of the same length as the result from the peak detection with classifiers for each entry. The classification is based on analysing each side of a peak within a certain window size. The size of the *classification window* is hard coded into the script and defines the length (number of samples) in each direction of a given peak or trough the script will look to validate the peak or trough.

The classification window is *only* used for this script when evaluating the validity of a given peak or trough. As stated in the source code (*classifyPeaks.m*): "try 1 second windows around each peak/trough, centered on found peak 1000 Hz signal decimated by 5, so now 200 Hz; 200 data pt window either side". More on this implementation detail in Subsection 5.2.1.

The application classifies the found peaks and troughs using the *classifyPeaks* script. The classification is based on the total negative and positive difference of the amplitudes of all neighbouring indexes on both side of a peak. It calculates the difference between each point within the *classification window* and finds all indices where the difference is either negative or positive and sorts them in based on whether they are before or after the peak or trough.

The resulting arrays are

Listing 3.1: Classification of window surrounding a peak

```
diffWB4 = diff(windowB4); % difference between all
   adjacent pts in the window
```

```
diffWAf = diff(windowAf);
[indNegB4] = find(diffWB4 < 0); % neg diff = curve going
   down
[indPosB4] = find(diffWB4 > 0); % pos diff = curve going up
[indNegAf] = find(diffWAf < 0); % neg diff = curve going
   down
[indPosAf] = find(diffWAf > 0); % pos diff = curve going up
```

If the *classification window* start or end of window higher than the peak (or lower in the case of troughs), the point is labelled as *invalid*. The difference calculated in Listing 3.1 is used to check whether (in the case of peaks) the difference is negative in front of the peak and positive after by summarizing the difference.

Item 4

After the classification the user is prompted to evaluate the marked peaks and make the final call on which peaks to accept and which to discard based on the plots of the signals. When the peaks and troughs are identified and validated, the algorithm calculates the pause, if any, surrounding the peak or trough.

Check for same-height indexes around each peak and trough found in the validated points. This is done checking both direction on the y-axis from the current peak or trough location, and based on the threshold the algorithm looks at the total difference between values until it reaches a slope higher than the threshold. The index when the threshold is reached is the end or beginning of a pause.

Item 5

After the four steps of the respiratory analysis, puka conducts a statistical computation consisting of: number of breaths, shortest breath, longest breath, average breath length, standard deviation of breath length. For *PI* and *PE* pause calculations the system calculates the average *PI* and *PE* pause by adding the length of all respiration pauses and dividing by the total number of pauses. In

the process of calculating the average puka also reports the longest and shortest respiration pause found in the clip.

Chapter 4

Modernizing

The best case scenario is if we can launch the application to verify and test it and then begin the adaptation for integrating it with TRIO. In this chapter we look at the process of making the standard version of puka usable on modern systems. In order to do this we firstly map the dependencies that require updating and consider different solutions for making updating or circumventing the dependency.

The first natural step in this process is to attempt to execute the system as described in the accompanying installation manual, but when doing so we get an error message (Listing 4.1) which can be used to identify why the application won't work out of the box. When the hindrance is identified we can take steps to mend it.

4.1 Identifying decrepit parts of puka

To execute puka it has to have some way of communicating with MATLAB from the executing Java code. It is, as described in chapter 3, written to use JMatLink in order to achieve this. The JMatLink library is distributed as a *dll* (Dynamic-link library), but the source code is freely available as well. The library is implemented in C and Java.

The JMatLink-manual has instructions for installation on Windows 98 and Windows 2000 only. The installation described in the manual is to copy the *dll* into the Windows *System32*-folder, but running puka after this operation results in the error message shown in Listing 4.1.

Since we are running on a Windows 7 operating system we have to find how to load the *dll*. According to the official documentation[35] there is an official tool, *regsvr32.exe*, in the Windows OS for registering libraries.

Listing 4.1: Trying to launch puka after adding JMatLink

```
ERROR: Could not load the JMatLink library
     This error occures, if the path to
     matlab's <matlab>\bin directory is
     not set properly.
     Or if JMatLink.dll is not found.
Exception in thread "main" java.lang.UnsatisfiedLinkError:
   C:\Windows\System32\JMatLink.dll: %1 is not a valid
   Win32 application
```

Both the 32 bit and 64 bit versions of *regsvr32.exe* result in the same error message (Figure 4.1), suggesting the *dll* is incompatible with our OS.

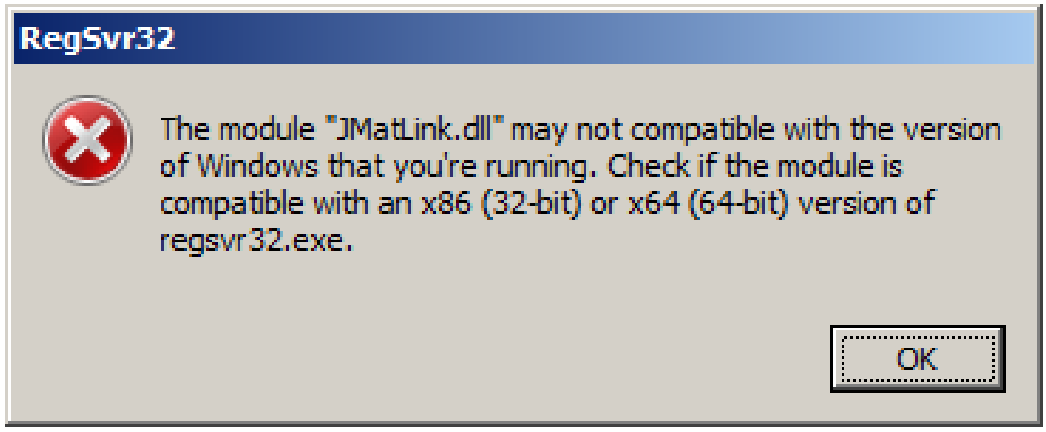


Figure 4.1: Resulting error message from regsvr32

By running the *jmatlink.dll* through "Dependency Walker"[36], we are able to map the dependencies of the library. It seems that

some of the 32-bit Windows native libraries JMatLink is dependent upon are only found as 64-bit versions on our version of Windows, and others are not found at all.

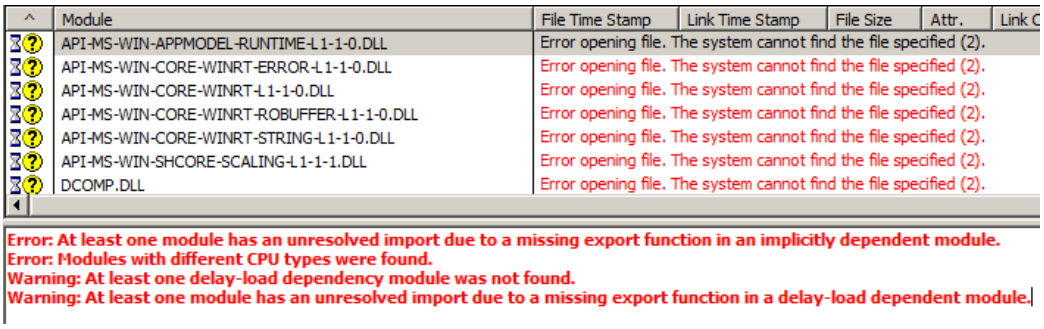


Figure 4.2: Missing Windows libraries and error message from Dependency Walker

TODO: conclusion?

4.1.1 Recompiling JMatLink

The latest version of the library was released in 2005 (*v1.3.0*), but according to the change log it has not seen much development since then. Since the library is, at the time of writing, over 15 years old it is difficult to make it run on a modern systems. It can be described as legacy software, in the sense that it can not be easily installed and executed on a modern system. We therefore need to make modifications to be able to test puka for use in TRIO. The source code for both puka and JMatLink is publicly available meaning one or both can be altered in order to make puka compatible with modern system and modern versions of MATLAB.

The *jmatlink.dll* file that is found pre-compiled by the author cannot be used so we attempt to compile a new version. The source code of the library is accompanied by a build file for Ant, a Java-based build tool [12].

The *build.xml* file used to compile the project contains hard coded values that has to be changed in order to compile the library locally. These includes the path to *Java Development Kit* (JDK), *Borland C++ Compiler*[10] and MATLAB compiler support libraries

(Listing 4.2). These components need to be installed on the host machine in order to attempt a recompilation of the library.

Listing 4.2: Hardcoded paths in build script

```
-Ic:\j2sdk1.4.2_06\include
-Ic:\j2sdk1.4.2_06\include\Win32
-Ic:\bcc\INCLUDE
-IC:\MATLAB6p5\extern\include
-IC:\MATLAB6p5\simulink\include
```

The installation paths has to be updated to match the host system on which we are building on. As evident from the same parameters, we need to update the arguments passed to the compiler based on the system we are using. We also have to make sure the targets within the different parameters actually exist.

Listing 4.3: From JMatLink build file

```
<target name="compile" depends="env">
<!-- compile object file -->
   <exec executable="bcc32" dir="${build.src}/jmatlink/" >
      <arg line="-Ic:\j2sdk1.4.2_06\include
         -Ic:\j2sdk1.4.2_06\include\Win32 -c -3 -a8 -w- -b
         -g30 -Ic:\bcc\INCLUDE -oJMatLink.obj
         -IC:\MATLAB6p5\extern\include
         -IC:\MATLAB6p5\simulink\include -O1 -DNDEBUG
         JMatLink.c"/>
   </exec>
<!-- link object file to DLL -->
   <exec executable="bcc32" dir="${build.src}/jmatlink/" >
      <arg line="-DLL -eJMatLink.dll -tWD
         -Lc:\bcc\lib\32bit -Lc:\bcc\lib
         -LC:\MATLAB6p5\extern\lib\win32\borland\bc50
         libmx.lib libmat.lib libeng.lib JMatLink.obj" />
   </exec>
  <move file="${build.src}/jmatlink/JMatLink.dll"
     todir="${build.dir}" />
  <delete file="${build.src}/jmatlink/JMatLink.obj" />
  <delete file="${build.src}/jmatlink/JMatLink.tds" />
</target>
```

When trying to build JMatLink with Java 1.4 JDK, Borland

5.x using ant 1.8.2 we get the self describing errors in Listing 4.4. This is not surprising considering the *include.cpp* file is not found in the indicated folder in our installation of MATLAB. There is no support for the Borland compiler in the version of MATLAB we have available (2012b). It is also more relevant to find a solution that can support modern versions of MATLAB instead of relying on an older and specific version.

Listing 4.4: Errors when attempting to compile

```
[exec] Error E2194: Could not find file
   'Files\MATLAB\R2012b\extern\include.cpp'
[exec] Error E2194: Could not find file
   'Files\MATLAB\R2012b\simulink\include.cpp'
```

The MATLAB documentation[32], states that the compiler support needed to build the JMatLink library is not present in MATLAB 2012b (the version available to UiO students). In the original build-file we can see it includes a references to MATLAB6.5 specifically, which did have support for the $Borland5.x$ compiler, but has not been present in subsequent releases.

Without any documentation as to what the missing components do, the compilation of the library is difficult to complete. Based on the error messages from the compiler, we can deduce what components found in *MATLAB 6.5*, the *bc50.cpp*, will have to be included in the project. A dependency on an obsolete version of MATLAB is not desirable, so other approaches to running puka might decouple dependencies to the MATLAB implementation.

According to MathWorks, MATLAB had support for the Borland compiler up until Release 2007b. The versions of MATLAB that have support for the Borland compiler are 32 bit versions, so the necessary libraries for compiling for MATLAB 2012b 64-bit does not exist. So even if the JMatLink source code is available, the hurdles of compiling and linking the library are far greater than writing a wrapper to reproduce the functionality of the library.

The process of compiling the original version of JMatLink is extra convoluted because of the lack of documentation and the fact that the dependencies are deprecated and no longer maintained. The necessity for a system library and specific MATLAB versions

to run puka is not ideal. A more portable solution will make it more useful. Therefore the focus will be shifted to a strategy to modernize the software.

4.2 Modernization of puka

If we are to make a version where we won't have to recompile the JMatLink library for each target, it might be of interest to look at different approaches than the use of JMatLink. We take a look at relevant options that can be considered for such a process.

Seacord, Plakosh and Lewis[52] describe four reasons for changing software:

1. **Perfective** - improvements to the software. Adding new functionality, enhance performance, improve usability.
2. **Corrective** - repairing defects in the software.
3. **Adaptive** - changes made to changes in the environment, such as changes to operating systems, language compiler or tools, database management system etc.
4. **Preventive** - these changes are mode to improve the future maintainability of the software.

The changes we make to the software is primarily adaptive, since the main issue is making the software run with a newer version of MATLAB and Windows. During the modernization we attempt to include preventive changes as well in order to be able to adapt to future changes in the environment by making the dependencies loosely coupled by avoiding interdependencies where possible.

4.2.1 Approaches

Virtual machine

By running an old version of MATLAB and an operating system such as Windows 98, 2000 or Windows XP 32-bit, we should be able to run JMatLab library without having to recompiling the library. These are the platform and software puka was designed to run with, so this will allow us to start testing the application quickly.

Update JMatLink or write a new library

As the source code for JMatLink is hosted on *sourceforge.net* [31], and the source code for puka is available on PhysioNet[47] we can potentially update JMatLink to make it compatible with modern systems and software.

Writing a MATLAB wrapper

By removing the Java code, we strip away the need for the decrepit library. We can utilize the MATLAB scripts containing the algorithms by calling them from a new *controller* scrip, removing the need for calls from Java to the MATLAB engine.

Create Adapter for JMatLink

We can modernize the calls to the MATLAB engine by utilizing a modern Java - MATLAB interface and wrapping the calls that are intended for JMatLink in the new interface. This allows us to avoid much changes to the original source code.

Instead of using JMatLink we look at the potential of using MatLabControl[24] as a wrapper around the JMatLink interface to intercept and reroute calls to MATLAB to the new interface, that

has none of the tightly coupled dependencies on specific system libraries and also supports calls to a 64 bit version of MATLAB. The adapter is based on pukas usage of the methods in JMatLink.

4.2.2 Evaluation of modernization approaches

Each approach has its pros and cons that has to be weighted up against the intention for the planned changes to puka. Ideally we want to make a version of the application that can

- run on modern operating system,
- no version restriction on MATLAB,
- demanding as few dependencies as possible and
- allowing changes and optimizations to be easily implemented and tested.

Based on these criteria we can out of the gate exclude running the application on a virtual machine, as this solution is only for running the unaltered version of puka. This is also not in line with the overall goal of modernizing and utilizing puka in new ways such as real time analysis. Practical consideration for this approach will also be how get a hold of licenses for discontinued software such as Windows 98 and older versions of MATLAB. This solution is only considered as a last resort or for experimenting with the original source code and library if necessary.

Updating or writing a brand new library for Java to MATLAB interaction will require a lot more work than other solutions. As described in Subsection 4.1.1, the library depends on decrepit systems, and a modernization of the library will require deep understanding of MATLAB internals, which is not within the scope of this thesis.

By creating a new control layer in MATLAB we get to remove parts of the software that is redundant to the respiration analysis. For a real time implementation of the respiration analysis

this approach has to be considered, as the control layer has to be redesigned. The steps that are manual in the original version of puka will be altered into automatic versions or ignore the steps altogether. This option will be considered in chapter 8, as the process of rewriting the control code is easier to verify when translating within the same language.

As it stands the control code is written in Java, which makes the option of writing an adapter for JMatLink a strong candidate. The flow of the respiration analysis is easier to comprehend and replicate when using the same programming language, and it is easier to verify that the same procedure is executed.

The first iteration of the modernized puka makes use of an adapter for the calls to JMatLink, and relays them to an existing and more modern library for the Java to MATLAB communication.

4.3 Adapter for JMatLink

The adapter has to capture calls that are intended for JMatLink, and execute the same operation as the library would have. Based on the JavaDocs for the library we can map what types and methods we need for the adapter.

There are a few existing solutions for executing MATLAB scripts from a running Java application. There is support for calling Java classes from MATLAB, but no official way for the other way around. The solutions range from corporate [6] to hobby projects[26].

A promising project is *matlabcontrol*[24], as it seems to be frequently cited on MathWorks forums, it had an active development and has been forked and continued after the closing of the *google code* service where the project was initially hosted.

4.3.1 JMatLink analysis

We need to assess what types are being set and used Java, in order to make sure the conversion of these types is done properly. We know the return type of all the methods used in JMatLink[30] and will have to make sure the conversion between system is correct.

JMatLink method	return type and description
engGetArray	double[][], Used for both 1 and 2 dim array
engGetScalar	double

Table 4.1: JMatLink methods used by puka

For our implementation of the adapter we have to prioritize the methods that have been used in the implementation of puka. The software adheres to a strict naming convention which allows us to find all instances of the JMatLink class and what methods are called via text searches in the source code.

These searches show that all *get* calls to MATLAB returns a scalar, single dimensional array, or two dimensional array of Java primitive double.

(TODO: expand about the analysis)

4.3.2 The matlabcontrol library

matlabcontrol was originally created as a *Remote Method Invocation* (RMI) wrapper around an existing Java to MATLAB library made by Kamin Whitehouse at University of Virginia[66]. MATLAB have had the ability to make use of Java code since version 5.3 (R11) with the Java MATLAB Interface(JMI). Whitehouse sought to provide techniques[65] to call MATLAB commands from Java with a program written in 2001 using undocumented parts of the JMI library. The work on this Java class has been continued by Joshua Kaplan and the project *matlabcontrol*[24].

There are a few projects that have kept the *matlabcontrol* project available even though the Google Code-service has been

shut down. The source code has been hosted on github and been made available through the Maven project management software and comprehension tool[1] allowing us to easily set up puka and a version of *matlabcontrol* together.

The two versions that we found to be interesting are:

- **matlabcontrol**[45] (fork on Github) and
- **MatConsoleCtl**[62]

Both projects are based on the code hosted on Google code, and now hosted on GitHub. They have both also been published as Maven artefacts. The project called *matlabcontrol* contains the pre packaged jar file of the original *matlabcontrol 4.1.0*, while *MatConsoleCtl* has seen changes made to it since it was forked from the original repository.

Since MatConsoleCtl contains the source code and has been maintained since the last release in 2013, this seems like a good candidate for this thesis. The changes since 4.1.0 seem to be mostly minor bug-fixes such as error handling and a demo project for tutorial purposes.

4.4 Creating the adapter

We have identified what parts of the application that does the respiration analysis and focuses the changes to the source code on this part.

4.4.1 Replacing references to JMatLink

Once the application is adapted for modern system we use the existing GUI in puka while testing, but ultimately we only make use of the respiration analysis part of the application. To create the adapter for *JMatLink* we configure the project up as a Maven

project to handle build and dependencies. We create a package called *JMatLinkAdapter* which we then import into the puka source code-project.

The source code changes to be made to puka in order to swap out the original *JMatLink* library can be found by a text search through the source code for instances of the *JMatLink*. The instances of the *JMatLink*-class are renamed *JMatLinkAdapter* to make it clear that we are no longer using the actual JMatLink library.

The instances of *JMatLink* have been given the same name throughout the entire project, meaning we only replace the initialization of the class, since we keep the method names as described in the JavaDoc. The *JMatLinkAdapter* implements an interface based on the JavaDoc to make sure we maintain the same return types and arguments as expected by the existing code.

4.4.2 Interface

Based on the javadoc and the source code, we can create a list of methods that the application makes use of. Ideally we want to create an adapter that replicates the entire functionality of the JMatLink library. But the prioritized methods are the ones in use by puka. These methods are shown in Listing 4.5

The following methods are the complete list of methods found in the JMatLink library, but only the ones used by puka will be described further.

Listing 4.5: Methods used in puka from JMatLink

```
//matlab session:
engOpen() : void
engClose() : void
setDebug(boolean debugB) : void
kill() : void

//matlab commands:
engEvalString(String evalS) : void
```

```
engGetScalar(String arrayS) : double
engGetVariable(String arrayS) : double
engGetArray(String arrayS) : double[][]

engPutVariable(String arrayS, double[][] valuesDD) : void

engPutArray(String arrayS, double valueD) : void
engPutArray(String arrayS, double[] valuesD) : void
engPutArray(String arrayS, double[][] valuesDD) : void
```

4.4.3 Unit testing

When writing the adapter we first write the unit tests to validate the communication between Java and MATLAB. Matlabcontrol has been fairly well documented, but we implement unit tests to validate that the results are as expected. The type conversion between the two systems (Java and MATLAB) has to be correct, and the return types has to match the expected types found in puka.

Even though the API is similar there are certain differences we needed to take into account when writing the adapter. The major concern is to make sure we convert types and arrays correctly. As the analysis of the puka source code in Section 4.3, we have the following Java types to convert between Java and MATLAB, and back again:

Java Type	MATLAB Type
double	double scalar
double[]	Numeric array
double[][]	Numeric array

All of the Java types passed to MATLAB can and should be represented as a *numeric array*. This allows the MATLAB scripts to do calculations without the risk of receiving a non numeric type which will be incompatible with the scripts that implement the peak detection.

Before we implement the adapter we create unit tests for all

calls puka does through the MATLAB interface (Listing 4.5). We control that values passed between each system is appropriately converted and retain the correct value. We must also make sure that operations and conversions return the expected result and type.

The interface does type conversion between MATLAB and Java for primitive types, but there are certain differences to be aware of. As stated in the documentation for the library[25], it is not possible to send Java primitives directly to MATLAB. All variables are treated as arrays in MATLAB, even scalar variables. This means the programmer has to keep track of the types used in the MATLAB scripts and decide what method to use when retrieving the variable. When getting scalar variables we need to cast the first (and only) member of the array to a *Java double primitive*. We also make sure that MATLAB considers it a scalar by using the built in function *isscalar()* after setting a scalar.

For conversion of single dimensional arrays *matlabcontrol* automatically converts between Java and MATLAB arrays. Most Java primitives have a corresponding MATLAB array type, with two exceptions. These two are `char[]` and `long[]` and will cause a MATLAB to throw an exception if used in MATLAB version R2009b or higher.

When converting multi dimensional arrays, we need to make use of the *MatlabTypeConverter* class, which can be found in *extensions*. This class converts between Java array to the type MatlabNumericArray. If the conversion is not done, the resulting array in MATLAB will be a cell array. A cell array is data type with indexed data containers cells that can contain any data type. These containers are called *cells*. The scripts used in puka expect arrays of the type *double*, and will throw an exception if they receive cell arrays due to the inability to do double precision mathematical operations on cell arrays.

To test that arrays are imported correctly we perform matrix addition and multiplication to verify that both Java and MATLAB gives us the same result.

Java uses zero-indexing for the arrays. The first element in

a given array is given position zero, as opposed to MATLAB whose index starts with *one*. The conversion of indexing is handled by the matlabcontrol library, so no consideration has to be made to this potential problem, but it can be important to make note note of the difference. To prove that this is handles correctly, we write a unit test to verify that values at the first and last position of an array are the same.

JUnit is used for testing the methods in JMatLinkAdapter. The tests has to cover each method used by puka (Listing 4.5). They also have to verify that results are as expected in order to be certain that the type conversion works as expected.

Some of these tests has to rely on other parts of the interface to be able to automatically assert the result. In addition we add print-statements to both the MATLAB window and the standard output. The only test for which we can not find a JUnit assert solution for is the debug print from matlabcontrol.

In order to be able to test for exceptions we let all methods throw exceptions. This leads to changes in the puka source code. For example for *engGetScalar* we need to add *throws MatlabInvocationException* statements to the methods that makes use of the method and surround the callee with a try/catch statement.

Chapter 5

Re-purposing for real time analysis

The algorithm used for respiration analysis in puka was originally implemented to be run on a pre recorded signal and with user input to verify and adjust the parameters during the analysis. We take a look into what changes to be done in order to automate the analysis and also provide a capbaility to analyse data streams instead of pre recorded signals.

The intention is to create low level events that TRIO can use to derive useful information about the sleep quality and detect deviations from normal sleep in real-time. The achieve this goal goals for the application is to

1. make puka work without user input and
2. detect and report low level events in real-time.

By doing the analysis in real-time TRIO will be able to detect sleep disorder symptoms and report it to other actors that can actuate based on this information. puka has algorithms for finding peaks and troughs based upon the surrounding signal, so we can not classify a peak the instant it occurs due to the definition of a peak. A peak is the highest point in a given section of a signal, surrounded by increasing and decreasing amplitude.

The resulting application can be described as a *test framework* or a *proof of concept* that demonstrates and evaluates the validity of using puka as a basis for a real-time system. It has to be designed with modularity in mind as we want to be able to easily make changes to the analysis and evaluation functionality as well as the data input. By separating the logic for *communication*, *analysis* and *evaluation* each module can be swapped out or modified.

5.1 Initial approach

Looking into what makes the algorithm work, we have identified the parts that must be removed, modified and added in order to be able to supply TRIO with useful events in close to real-time without any intervention from a human user.

The way puka is designed to analyse a *clip* within a signal record, then discard the rest of the remainder of the record requires us to implement a *window* that moves along the whole record. We have to change the flow of the controlling Java application from a file centric to a stream centric paradigm, allowing it to analyse data as it arrives. The record will in our real-time implementation be a *data stream* from a sensor simulator and we will analyse *windows* within this data stream.

The basis for the real-time version (*pukaRT*) is a reduced version of the modernized implementation of puka without the user interaction to adjust threshold and validity of peaks and troughs. Ideally these interactions can be automated for a more accurate analysis, but in the first iteration we use the default values. These interactions are the *peak detection* and *classification* which both uses a threshold to determine what constitutes a peak or through.

For our purposes we create a program that feeds data into the stripped down version of puka which only contains the respiration analysis. We need to create a Java controller class which will control the execution of the puka respiration analysis. This controller handles communication with simulated sensor(s) and initiates the analysis. This controller also contains the historical data needed to be able to make sense of the current window.

1. Isolate and extract the respiration analysis, remove GUI and user interaction from analysis runtime,
2. create sensor simulator for serving data,
3. initiate analysis from controller that reads sensor data,
4. adjust parameters used by the analysis,
5. read and evaluate the results

Figure 5.1: Steps for converting to a real-time application

5.2 Implementation

Both the algorithm for detecting peaks and troughs and the algorithm for calculating pauses in respiration can be modified in order to improve the real-time capability of such a system, but as stated in the previous section, the first iteration focuses on the surrounding Java controller implementation. There are 5 parts of the implementation described in Figure 5.1.

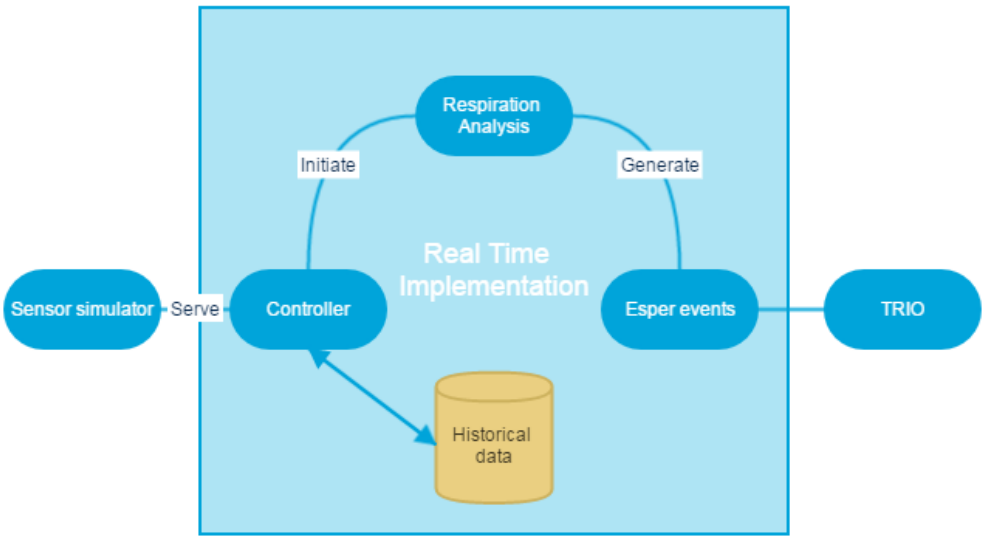


Figure 5.2: General flow of the real-time system

5.2.1 puka reduced

This application controls the user-application interaction. A user can initiate the respiration analysis either from a local file or from a data serving service from a shell. This application is the basis for the testing framework and is designed to easily accept new types of signal or analysis.

The first iteration of the real-time implementation does not make any significant changes to the MATLAB implementation of the respiration analysis, but instead focuses on the Java control structure around the script. The part we want to isolate is the respiration analysis (as shown in Figure 5.3) and automate it.

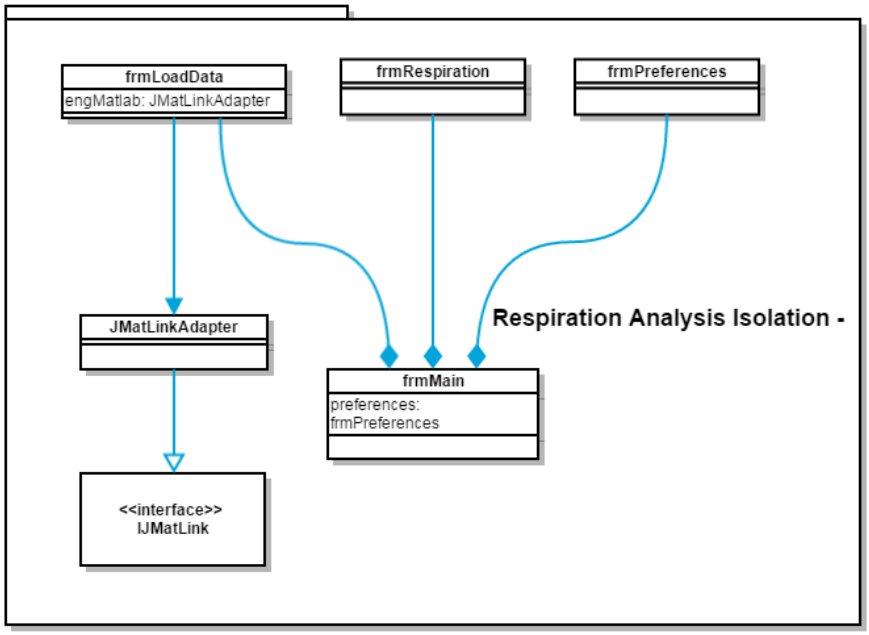


Figure 5.3: UML of the respiration analysis aspect of puka

The option to run puka on a local signal file is intended to mimic the original puka, and to test the now isolated respiration analysis. This option is initiated from a text shell and without the GUI and the user input during the analysis. When analysing data

from the data serving service the application uses an adapted version, attempting to analyse the signals in real-time. Both options must be able to store the results in order to evaluate the results.

What is called a *clip* in puka is the same as a *window* in the sense that it is the size of the selection of a given time series we want to analyse. The smaller the windows are the less theoretical latency we get. In Section 6.5 we look into different window sizes and evaluate the limits to these parameters.

The main consideration when choosing window size is the *responsiveness* of the application. The smaller the window, the closer to real-time, but the number of false positives and negatives will necessarily increase as each pass of the algorithm will have less data to base its analysis on.

There are limits to how small a given window can be and still being able to derive useful information. The signal sample rate plays a crucial role in mandating how small a window can theoretically be. Since we are looking at trends within a signal, we need to compare data points. If the sample rate is very low, for example 5 samples per second, we do not have enough data within a window size of 10 ms to derive any meaningful trends.

The *RespirationAnalysis* class is charge of the analysis and contains the control of the MATLAB code found in puka. We create a minimal and non interactive version of the respiration analysis found in puka and let the *RespirationAnalysis* class execute this code. Here we can easily introduce new implementations by adding new classes with minimal changes to the code.

The main procedures used to analyse the signal is extracted from the main application and reduced to a few calls to the MATLAB scripts with a minimal amount of the control code. These consist mainly of loading data to the right variables and setting other variables. It is at this step we can define the window sizes, based both on the size of the recording and also the onset time.

Listing 5.1: Interactions with MATLAB scripts from the Java application

```
frmLoadData.engMatLab.engEvalString("[P,T,th,Qd] =
   newPT(y, threshold, onsetTime,
```

```
 endTime)");
...
frmLoadData.engMatLab.engEvalString("[peakLabels,troughLabels]
   = classifyPeaks(Qd,P,T,th);");
...
frmLoadData.engMatLab.engEvalString("[validPeaks,
   validTroughs] = makeValidArrays(P,T,peakLabels,
   troughLabels);");
frmLoadData.engMatLab.engEvalString("[newP] =
   markPeakPauses(Qd, validPeaks, validTroughs, th);");
frmLoadData.engMatLab.engEvalString("[newT] =
   markTroughPauses(Qd, validPeaks, validTroughs, th);");
frmLoadData.engMatLab.engEvalString("plotPauses(Qd,
   validPeaks, validTroughs,
  th, newP, newT);"); // only used for visual verification
...
CalculateResp(); // statistical computation, not used by
   pukaRT
```

As seen in Listing 5.1, the *newPT* function, which detects peaks and troughs, takes a parameter with the threshold. This is also manually set and adjusted by the user. Ideally we implement functionality that keeps track of the average amplitude of the signal in order to dynamically adjust this parameter to fit the signal and avoid errors.

An important feature of the test framework, is that it should be straight forward for an application developer to make changes to the respiration analysis.

TODO: table with parts and parameters

Due to the implementation of the respiration analysis, we need to store data that might contain events from the previous window. We what parts of the preceding window based on the location of the last found peak/trough. The simplest solution is to indiscriminately keep the remaining signal from the last peak or trough, or we can simply check to see if there is an onset point within the remaining time series. The signal is prepended to the next window before analysis. If this is not done the application has no way of detecting peaks and troughs at the very beginning or end

of signals.

5.2.2 Data serving

We create an application which reads the data files and serves them to the *puka reduced* application, simulating a sensor. We also add the option to insert an explicit time stamp.

A very simple text based protocol is implemented in order to control the flow of data. The connection phase consist of a simple handshake between the client and the server, where the client sends the server the name of the signal. The server then reads the signal file and stores it in memory to reduce the number of disk IO operations. The size of a given signal file will vary based on the *length* and *sampling rate* of the time series.

Table 5.1 contains the first iteration of the protocol. To keep the protocol extensible and easy to read we reserve a range for different types of communication. $2xx$ is acknowledgements, $3xx$ is modifications and commands, and $4xx$ is reserved for errors.

Function	**Parameters**	**Status code**
Request file list	<empty>	REQ
Request file	<file name>,<num>	REQ
Acknowledge OK	<human readable message>	200
Request new rate	<requested rate>	300
Abort	<empty>	400

Table 5.1: Calls from client to Data Feeder service protocol

The software that serves the data is implemented in Java and uses Java NIO socket channels to send data to a connecting application. We also need to make sure that the program is implemented efficiently enough as to be able to send at a realistic rate.

Since both the data serving application and the data consuming application is running on the same system, use Java *System.currentTimeMillis*. By using milliseconds we can send data at a

rate up to $1000hz$, or 1 per millisecond. To serve the data in a timely fashion we look at two libraries found in the Java language.

The class *java.util.Timer* contains functionality to schedule execution of execution of task in a background thread, either one of execution or repeated executions at regular intervals. According to the documentation[43], the class does not offer real-time guarantees.

ScheduledThreadPoolExecutor inherits from *ExecutorService* class which is found in the concurrent library. "An Executor that provides methods to manage termination and methods that can produce a Future for tracking progress of one or more asynchronous tasks"[42]. *ScheduledThreadPoolExecutor* build upon this and pre-allocates n number of threads to execute the task which is being set up, thereby reducing the overhead of creating and starting new threads.

To allow the recipient to determine the boundaries of each data point, we wrap each discrete piece in greater than and less than brackets as such: <*data*>. This is due to the fact that there is no guaranty that each data point will be sent in its entirety. This way the client can reconstruct the data if it broken up and we avoid errors such as the one shown in Listing 5.2.

Listing 5.2: Received data entries with parse error

```
x: '-0.911736'
x: '-0.'
x: '911056'
x: '-0.910373'
```

Item 3 ... ?? TODO

5.2.3 Reading data and initiating analysis

The receiving application stores the data in a buffer until we have enough data to fill a window, and then applies the algorithms that have been adapted from the ones found in puka. The analysis method will have to be timed in order to discover how much time

we can expect to use on the analysis itself, which in turn puts restrictions on the theoretical window sizes.

Timing is important for the application to work in real time. We have to make sure the analysis does not blocks for the data arriving. We time each module to be able to evaluate how an alteration to either the control structure or the analysis affects the execution time. We also extract both the communication and analysis into separate threads so that neither blocks the execution of the other.

Running in a separate thread is the part of the application which connects to and reads from the server described in Subsection 5.2.2, and checks the integrity of the data. It also keeps track of the current size of the buffer and notifies the analyser when we have enough data for a window. The data is then copied to the the analyser thread and the buffer is cleared and we keep reading data from the simulated sensor while the analysis is conducted in the *RespirationAnalyser* thread.

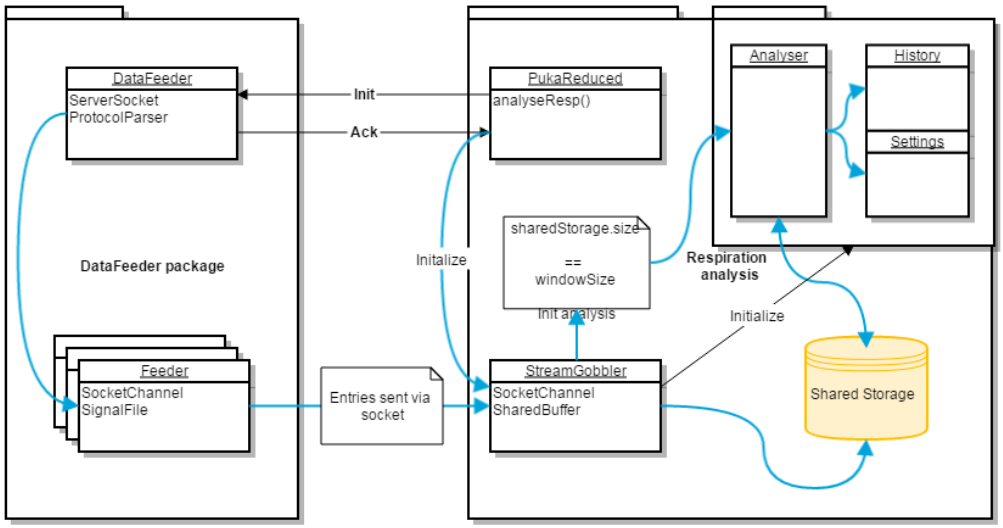


Figure 5.4: Details for the implementation

Part III

Results

Chapter 6

Evaluation

In this chapter we will present the evaluation of the original implementation of puka as well as testing whether it is suited for usage in a real-time environment. The chapter will discuss both the metrics used to evaluate the functional and non functional aspects of the implementations. We want the real-time version of puka to have the same functional qualities, such as accurately be able to pinpoint the onset of respiration start and end, but we introduce the requirement of being able to process arriving data in a timely fashion. This requirement has to be tested by timing the different components and identifying the parameters that can be tweaked in order to speed up and maintain or improve the accuracy of the analysis.

We have three versions of the respiration analysis to evaluate:

1. Modernized vanilla puka (reference),
2. puka reduced offline (verify), and
3. puka reduced online (compare).

The original but modernized implementation of puka is used as a reference for the other tests. We compare the automated offline version and the real-time version with the metrics described in Section 6.1.

Before this is done the modernized application has to be tested and shown to work as described in the documentation. This application will function as the reference for testing Item 2 and Item 3 in this chapter. For Item 2 we only need to verify that the results from the analysis on different types of signals correspond the reference, while for Item 3 we need to experiment with different clip/window sizes to see how close to real-time the application can detect an event with the existing implementation.

6.1 Metrics

In this section we will look at the methods used to evaluate the results from the real-time implementation compared with a reference result created with the original implementation of puka. By running the same signal through the different implementations we can do a comparative evaluation based on different metrics.

6.1.1 Timing

Since the design of the real-time implementation implies the need for previous windows to be analysed before the subsequent window can be analysed, we need to make sure the execution is able to execute within the limits set by the window size.

In order to evaluate the real-time implementation we look at the *execution time* of each component. The execution time is dependent on the hardware of the environment the application is running on. The specifications of the test platform are described in Table 6.1.

Determining the *average application response time* can be achieved by creating an application that runs the analysis steps n times, timing the each execution and calculating the average execution time. The size of the signal will also have to be taken into consideration.

OS	Windows 7 Enterprise (64bit) SP 1
CPU	Intel Core i7 2.9GHz
RAM	8GB DDR3
HDD	80GB 7200rpm SATA

Table 6.1: System specification for experiment environment

6.1.2 Precision and Recall

The method *Precision and Recall* (PR) is often used in information retrieval with binary classification of the results. When used in information retrieval

This method suits our needs and data well, as a result is either correct or false based on the reference results.

Our reference analysis gives us the True Positives (TP). Any results from an analysis that are not in the TP set are grouped together as False Positives (FP). If a value that is in the set of TP, but not discovered by our system is called a False Negative (FN). A value that is not a TP in the reference analysis is classified as a True Negative (TN). These are the basic building blocks for PR.

This can be represented as a *confusion matrix* as shown in Table 6.2. In the table *Reference* is defined as verified by the reference analysis, while *Result* are values that are found in the tested analysis implementation.

		Result	
		Yes	No
Reference	Yes	TP	FN
	No	FP	TN

Table 6.2: Confusion Matrix

Based on the building blocks that are TP, FP, FN and TN we can calculate the metrics *precision* and *recall*.

- $Precision = \frac{TP}{TP+FP}$

- $Recall = \frac{TP}{TP+FN}$

The *evaluation* class is a utility class which calculates these values based on what it calls *result* and *reference*. The method for calculating the precision and recall takes two arrays containing indexes of the events and the size of the original signal. It creates a new list of all potential hits, i.e. every index within the size of the original signal and assigns all of them to TN. Then we iterate through the *result* marking each index value as a FN as these have not been verified yet. To verify a index from the result we iterate through the *reference* array. If a given index is marked FN, this is verified, and every TN is changed to a FP as it is only found in the reference array.

NOTES:

wiki: Recall in this context is also referred to as the true positive or sensitivity, and precision is also referred to as positive predictive value PPV.

True Negative Rate: $\frac{TN}{TN+FP}$ Accuracy: $\frac{TP+TN}{TP+TN+FP+FN}$

Recall is described as the fraction of all correct (TP) events that were found.

TODO: report precision and recall together to avoid being given a false impression. presenting just one of the metrics can easily be manipulative...

6.1.3 TODO: distance/accuracy IN FUTURE WORK INSTEAD?

One downside to the Precision/Recall method is the binary nature of the metric. We have no indication whether the result of the analysis is far off from the reference or whether it is similar.

We need a method that is suited for comparing the results of the peak detection and the pause detection. The resulting data from the analysis is stored in arrays which contain the indexes of

Newborns	44 RPM
Infants	20-40 RPM
Children (1-7 years)	18-30 RPM
Adults	**12-20 RPM**

Figure 6.1: Normal Respiration Rate[28]

the events within the time series. These results can also be considered time series, and allows us to expand upon the PR method.

6.2 Test data

In order to evaluate the algorithms used for detecting respiration in puka, we use both real world recordings from PhysioNet to derive respiration events from different types of sensors as well as simulated data. The respiration events derived with puka can then be used as input for the logical sensors found in the TRIO project. Ultimately we want to compare the real world data and the results from the manual analysis found in the apnea annotations in the PhysioNet data with the result from the automated analysis.

6.2.1 Simulated data

In the initial testing of puka we use a smaller sample sizes of the recordings representing different challenges as well as using simulated signals in order to reproduce different potential errors that can occur in recordings. The experiments conducted to map potential weak points and errors will be described in Section 6.4 and Section 6.5.

A normal respiration rate, *eupnea*, varies with age, activity, illness, emotion and pharmaceutical influence[28]. In ”Delmar’s Comprehensive Medical Assisting”, normal respiration rates are defined in Figure 6.1.

In order to evaluate the correctness of the algorithms used

in puka it will be reasonable to run some experiments using simulated data. Not only will we more easily detect errors and deviations when we have generated the data ourself, but we can also create different types of signals in order to verify that the system can analyse the various signal types.

The simulated signals can be generated based on a sine function. The sine of an angle ω in a right triangle is as the artio of the lengths of the side of the triangle opposite the angle of the hypotenuse[2].

"The sine function sin(x) is one of the basic functions encountered in trigonometry (the others being the cosecant, cosine, cotangent, secant, and tangent). Let θ (Figure 6.2) be an angle measured counterclockwise from the x-axis along an arc of the unit circle. Then sintheta is the vertical coordinate of the arc endpoint, as illustrated in the left figure above"[2].

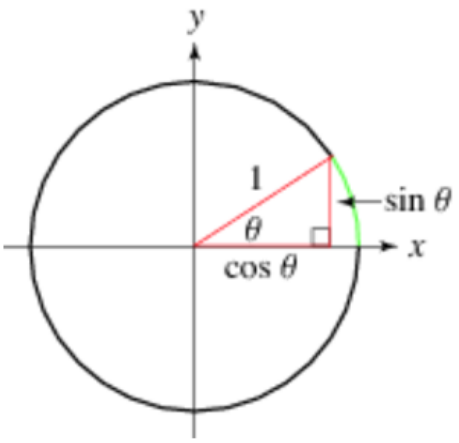


Figure 6.2: Sine definition

A simple implementation of a sine function in MATLAB gives us a smooth sine curve and a time series that can be used as an ideal respiratory signal.

Listing 6.1: Test data generation in MATLAB

```
ns = 0:2999; % number of samples
am = 1;      % amplitude
base = 0;    % offset
dur = 500;   % duration of each "respiration" as
             % number of samples
             % dur:500/hz (samples per sec) = 5 second
hz = 100;    % samples per second

sinewave = base + am * sin(2*pi*ns/dur);
```

With the basis in the formula that gives us a smooth sine curve we can create a time series that is more akin to actual respiratory signals. Actual respiratory waveforms for signals such as RIP are not smooth, and the during recording several types of noise are introduced. We create a function for adding both random and deliberate noise to a generated signal.

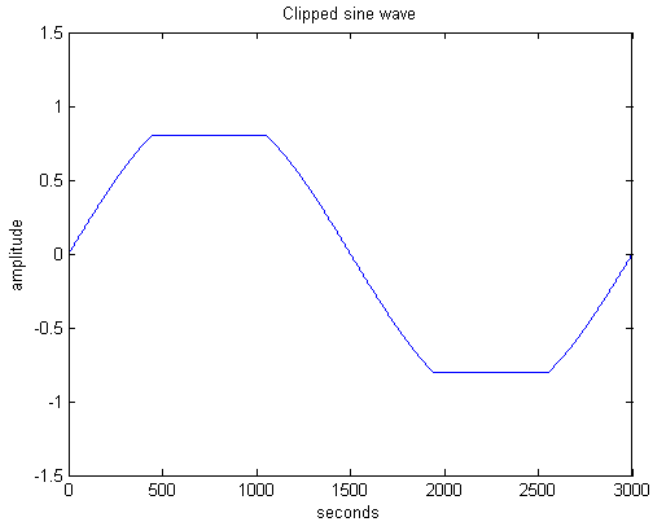


Figure 6.3: Clipped signal

Since the normal respiration of a human being is not the same as a perfect sinusoid curve, we create a couple of functions to generate more lifelike signals. One such approach is to clip the signal both on inspiration and expiration end. When the amplitude of a signal is set to 1 we can slice the signal at anything above 0.8 to create this effect. The resulting signal is depicted in Figure 6.3. Ideally we want to create a signal that is close to the ones found in the PhysioBank database (Figure 6.6), we explore a different approach to simulating signals.

As described in "Evaluation of respiratory inductive plethysmography"[5], waveforms from respiratory sensors such as RIP tend to have pauses, especially at the end of expiration.

By manipulating these simulated signals we can create dif-

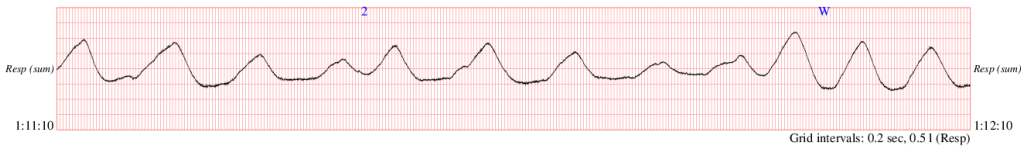


Figure 6.4: Respiration signal from 1 minute of stage 2 sleep [14]

Listing 6.2: Respiration simulation

```
ns = 0:2999;   % number of samples total in each clip
am = 1;         % amplitude
base = 0;       % offset y axis
offsetStartP = 0.5; % offset x axis
dur = 3000;     % duration of each "respiration"

respTest = base + cos(am * sin(pi*ns/dur +
   offsetStartP) * pi);
```

Figure 6.5: The MATLAB script for generating respiration like time series

ferent scenarios such as respiration stops, errors in sensors and so on. Some of the potential scenarios we want to control for are listed in Figure 6.7. Using simulated data allows us to more easily test different challenges and aspects before moving on to more complex signals. We can also experiment to detect weakness in the puka implementation by adding and removing the different scenario.

For each scenario we can implement a script that generates that specific signal. By combining these scripts we can compose the signals we need to preform the experiments to test pukas ability to handle the different scenarios creating signals that are similar to the real world examples such as Figure 6.6.

The data has to be converted into a format described in Subsection 3.1.7. These are trivial IO operations that require us to manipulate raw text files, delimiting the signal values with newlines, as is the delimiter puka uses when reading data.

The noise added to the signal is created by adding random

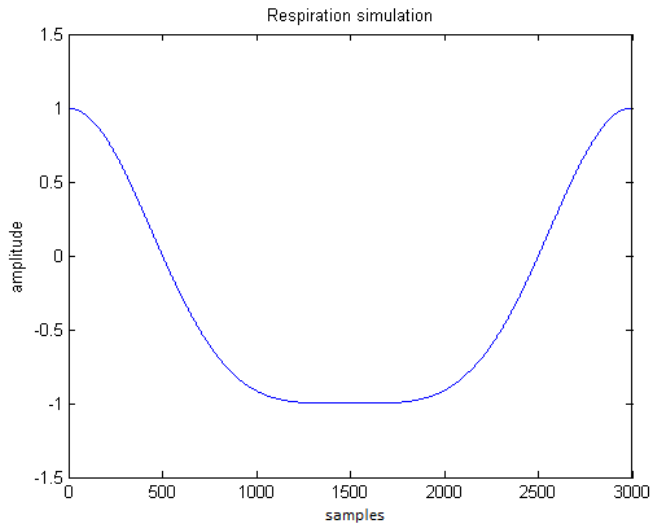


Figure 6.6: A 3000 samples long simulated signal

- amplitude fluctuation (threshold variability due to signal strength),
- noise (unexpected fluctuations),
- offset (we know puka relies on a baseline amplitude of 0) and
- baseline shift.

Figure 6.7: Scenarios to replicate with the simulated signal

deviations from the mean value of the signal, but maintaining the normal distribution. Ideally, based on the sample rate found in the RIP recordings in the CINC data set, we would use 100 samples per second. Due to quirks in the source code we start out using 1000 samples per second and change the scripts to not assume sample frequency. This is described in detail in Section 6.6.

The different implementations can all be found in *sineGenerator.m* found in the source code.

6.2.2 Real world data

PhysioNet is a collections of recorded physiologic signals and related open-source software for signal processing and analysis. The data available is from different institutions around the world and it contains a variety of digital recordings of physiologic signals and related data for use by the biomedical research community[39].

The data found in PhysioNet is stored as *.dat* files and has to be converted in order to be used in puka. The PhysioNet toolbox offers tools for converting signals into text. The *rdsamp* program is used to read a specified record, either from a local .dat file or from the on-line database. The output is the decimal number on standard output. If a record contains more than one channel it will write output from each channel on the same line separated by tabs. The function also takes parameters allowing us to for example create CSV (comma separated value) files, read certain intervals, add time data based on the information found in the header file for the record.

To identify suitable datasets we look for two main criteria: ground truth (AHI and apnea annotations) in order to evaluate the results, and signal types allowing us to use puka to calculate respiration events in a format equivalent to the supported types.

An ideal dataset contains different types of signals to enable us to compare the result on different sources. Annotations of respiratory events would be ideal and annotations for apneic events facilitates verification of the logical sensor using the events generated by puka.

MIT-BIH Polysomnographic Database contains both a respiratory signal from a nasal thermistor and a respiratory effort signal from inductance plethysmography in some cases both chest and abdomen and others either one of them. Each record includes a header (.hea) file, a short text file that contains information about the types of signals, calibration constants, the length of the recording. It also contains AHI and sleep stage and apnea annotations which makes it a good candidate for usage in our tests.

The St. Vincent's University Hospital / University College Dublin Sleep Apnea Database also has oro-nasal airflow (thermistor), ribcage movements, abdomen movements (uncalibrated strain gauges). As with the MIT-BIH database we have sleep stage and apnea annotations. In this database the annotation distinguishes between types of apnea, meaning we can control for the different types of apnea. It also contains annotations for other types of respiratory disturbance, meaning it can be a good candidate for future work. The database has both ribcage and abdomen movement recorded with uncalibrated strain gauges

Another good candidate for our purpose is the apnea test database "Data for development and evaluation of ECG-based apnea detectors" which was used in the CINC challenge in 2000. Some of the recordings contains thermistor and or RIP signals in addition to the ECG signal. In the cases where we have all three signals, we be able to compare the results from the different respiration rate estimation techniques allowing for comparative studies of the techniques. These records also contain the necessary AHI in order to determine the accuracy and precision of TRIOs logical sensors. The database also contains annotations for apneic events, which will allow us to see if there is correspondence between the same type of events found by the logical sensor and the data in the database.

6.3 Testing the modernized implementation

TODO: teste med andre signaler også?

In order to run puka using the "JMatLinkAdapter" we have to change the instantiations of JMatLink in the source code to the the adapter class (Listing 6.3). Calls to the loading of the JMatLink library can be removed, as it is no longer a system library we are dependent upon. The creation of a new instance of the library is done in *frmLoadData*. The library is also loaded in *frmConvert.java*, but this class is only instantiated by itself, and is probably separate from puka and can safely be ignored.

```
// Old implementation:
engMatLab = new JMatLink(); //initiate connection
try {
   System.loadLibrary("JMatlink"); // load system library
   engMatLab.setDebug( true );
   int intC = engMatLab.engOpen(); //open connection to
      MATLAB
} catch (Exception e) { e.printStackTrace(); }
//============================================================
// Replaced with:
engMatLab = new JMatLinkAdapter();
```

Calls to JMatLink are now intercepted by the JMatLinkAdapter class which replicates the expected behaviour by using matlabcontrol.

In *preferences.txt* or via the *Program Preferences* in the GUI we define which column in a raw text file we will find the signal used in the respiration analysis, as described in Subsection 3.1.6. When creating the simulated data we only have one column, meaning this parameter will be set to 1. As we do not simulate ECG signals the ECG column will be set to -1, as stated in the documentation. The onset trigger will be set to 1 as well. This value will be updated by the execution of the respiration analysis.

When the application is launched it starts an instance of MATLAB, where we can observe the values being added to the current workspace. The application changes the working directory of the MATLAB instance to the MATLAB-scripts folder set in the *preferences*.

Based on the sampling rate we set the length of a clip. The

clip has to be created prior to loading the data and initiation of the respiration analysis. At $1000hz$ we set the "clip length" to $1000 * 10 = 10000$ to make a 10 second clip. The recording we use in this example is 30 seconds of simulated data, and should therefore give us ample room for the clip size to fit within the recording.

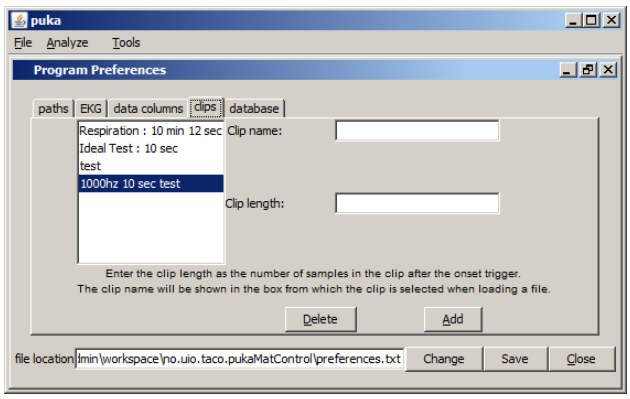


Figure 6.8: The clips tab in preferences

Since we are not using a database for the data, we instead choose the file drop down menu and choose *Load File*. The button *Select File* prompts a file selection window allowing us to choose the wanted signal file. When a file has been chose we must also select one of the pre-configured clip sizes. The *Load File* button initiates the actual reading of the file and preparation of the data by copying it to MATLAB as well as reading it into memory.

When loading the data the application looks for an *onset time*. *Onset time* is the first point in the recording where the signal crosses 0 on the Y-axis. The suggested onset time is shown in the input field but this can be changed by the by the user. The waveform is plotted using MATLAB to indicate where in the record the onset time is, and what the signal look like.

Now that the data is loaded and the clip aligned with the recording we can begin the respiration analysis itself. When it is initiated the user is presented with the window shown in Figure 6.11. The steps presented in Subsection 3.1.8 (identify, validate, mark pause and centre peaks and troughs) are represented by the steps in the GUI. In addition we have a fifth step which is the statistical computations (also described in Subsection 3.1.8).

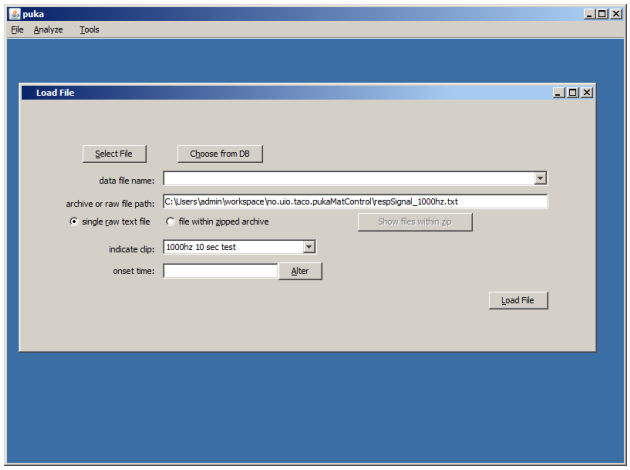


Figure 6.9: Load file dialogue

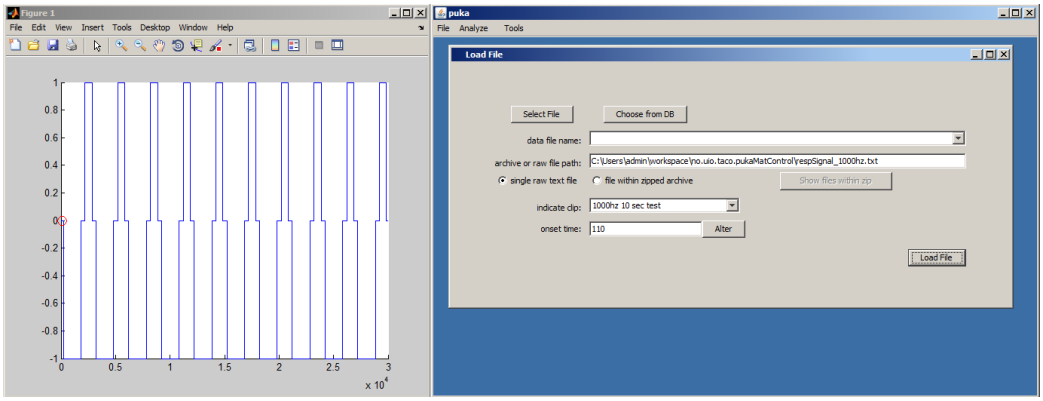


Figure 6.10: Onset time marked both in the input field and on plot

The signal in Figure 6.10 looks different from the one in Figure 6.12. This is because of the MATLAB script *findOnset.m* uses approximations by rounding the raw signal in order find points close to 0. This was probably done for efficiency, but is not documented why this approach was chosen.

After having run the *calculate pauses*-scrip has completed we have two new arrays that are based on the previous P and T; *newP* and *newT*. For each peak and trough we have twin tuples marking the beginning and end of the pause around a peak.

puka then visualises the pauses for the user and gives them

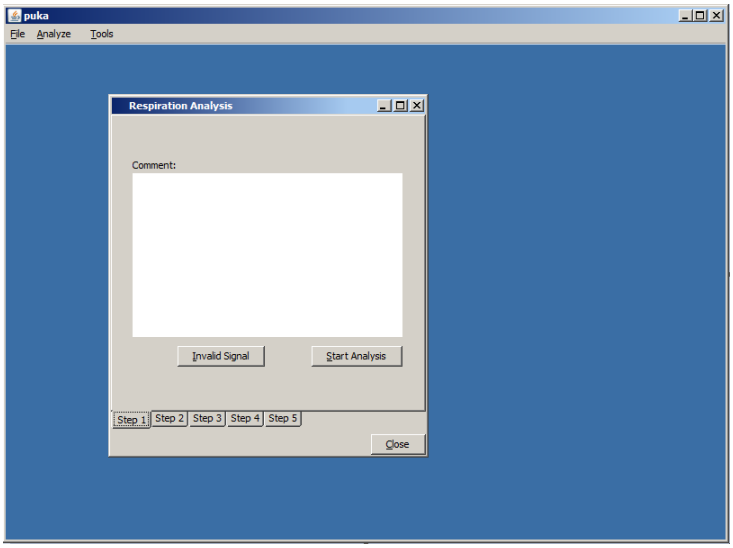


Figure 6.11: Initial screen for respiration analysis

the option to recentre the points or not use the pause information when calculating the statistical information, as shown in Figure 6.13.

Finally the statistical computations are display for the user. This demonstrates the application now working on a simulated recording of 30 seconds with a 10 second clip. The signal was constructed with each respiration lasting 3 seconds from start to finish. For this initial experiment, puka seems to agree (Figure 6.14).

6.4 Experiments: Testing offline puka

In the automated modernized version we have removed the manual verification of certain steps. ...

The vanilla version is tested with the scenarios presented in Subsection 6.2.1 as well as signals from PhysioBank. To verify we compare the results from the vanilla puka with the results from the offline and reduced version we describe in chapter 4. The result of each execution is in the original version the statistical computations at the end of an execution. The statistical computation can be

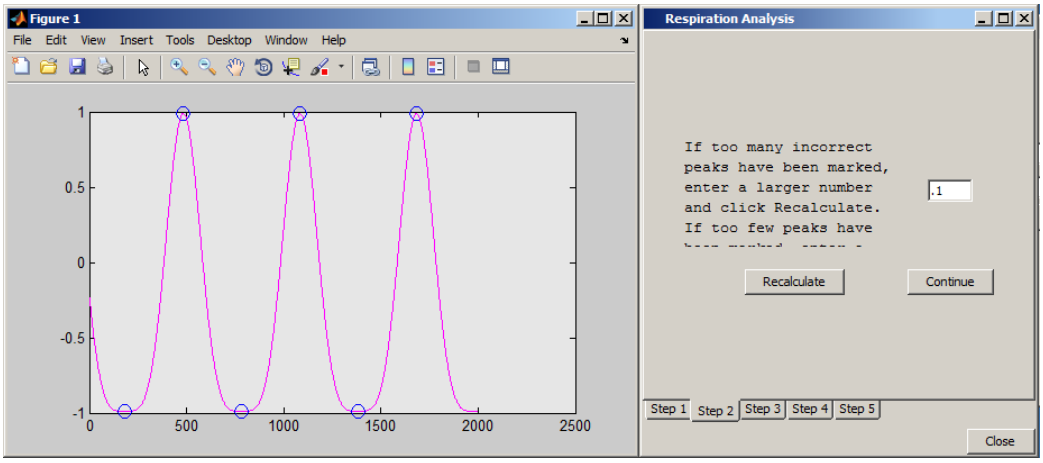


Figure 6.12: Visual feedback to the user when checking validity of peaks and troughs

replicated by removing the GUI related parts of the *CalculateResp* method found in the *frmRespiration* class. These results will then be stored and compared with the results of the vanilla puka execution, which also has to be modified to store the results after the analysis.

Each step of the respiration analysis scripts stores data in numeric arrays within the MATLAB workspace, which we can retrieve and store persistently for comparison. We can achieve this by manually storing the workspace variables in the MATLAB instance, or automatically extract them via the Java controller class and write them to files. The variables containing results that are relevant for the evaluation we use are described in Figure 6.15 with a brief look at what they contain.

Note that all indexes stored in these arrays must me multiplied with 5 to give the correct index in the original signal, since the *newPT* script decimates the signal. This is described in more detail in Subsection 6.6.2.

Now that we have the result from the analysis in a format we can look at what metrics to use for evaluating them. When having run both the vanilla and the *puka reduced* offline component we compare the results and make sure they match using precision and recall. The results contain the indexes, or sample number in

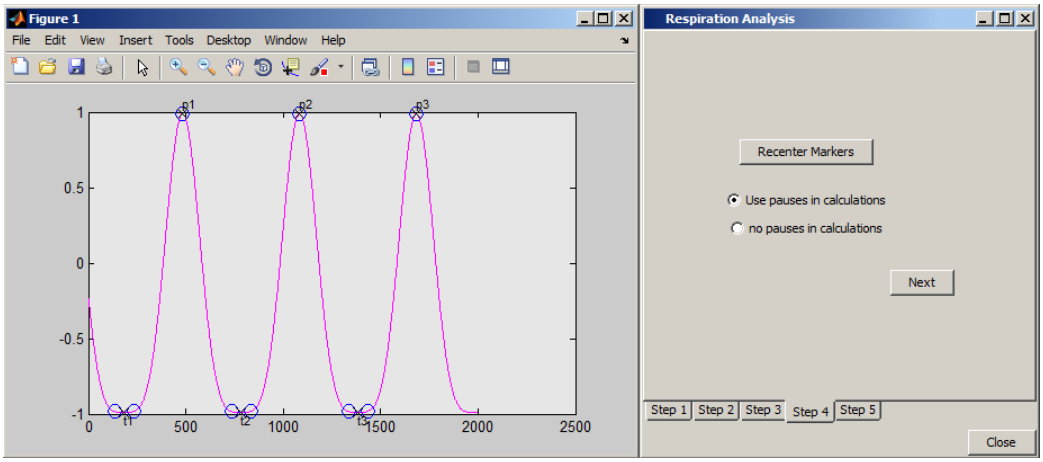


Figure 6.13: Pauses identified in the troughs

the original time series.

We create a 45 second respiration like signal using the script described in Subsection 6.2.1. Based on this premise we create 4 variations:

1. ”normal” second 3 respiration cycles[28],
2. 2 x 6 second respiration stop at end of expiration,
3. 2 x 6 second respiration stop at end of inspiration, and
4. 2 x 6 second respiration in the middle of expiration or inspiration.

For each of these we signals we introduce the scenarios presented in Figure 6.7.

	Base signal	**Variations**
	45 second normal respiration	double

Table 6.3: Signals used

- **notat:** How do we know that puka’s algorithm work?
- **Using simulated signals:**

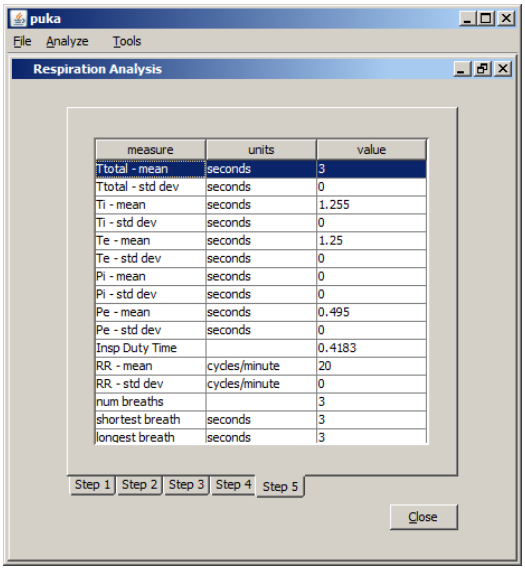


Figure 6.14: Statistical computations from a 10 second clip. Signal with 3 second respiration loops

Variable	Content
P & T	Contains the result from *newPT* script. Initial indexes are stored here before validated
TODO: next var	The text that goes here, where does it end up? Who knows
newP & newT	The final index tuples which include pause duration.

Figure 6.15: Results

  - Analysis: that the generated peaks and pauses correspond to the parameters of the signal generation

- **Using real world data:**
  - Visual inspection (store results persistent, plot results)
  - Statistical computation correspond to manual evaluation
- **More enlightening metrics:** This can be done by introducing distance between FP and TP to calculate a *accuracy metric*.

6.5 Experiments: Testing online puka

How do we measure how the real-time version performs.

- **What do we compare** – precision and recall + timing the execution of the analysis
- **Parameters we can tweak**
  - Timing (latency, analysis execution optimization/ parallelificaiton)
  - Window size
  - sample rate
- Design: table with windows sizes and implementation specs, signals used etc

6.5.1 Timing

Create table with different windows sizes and results

6.5.2 Precision and Recall

execution and results

6.6 Errors and Adjustments in puka

When we run pukas respiration analysis on the simulated data found in Section 6.2 we get different errors and exceptions based on what signal is used and the clip length.

`TODO: table with results for different clips` We need to look for

- missing peaks/troughs
- false positives

based on the simulated signal content. Our gold standard is the fact that we generate the signal to contain a certain number of respiratory cycles

6.6.1 Results

Based on the different signals in **??**

6.6.2 Decimate

This is very relevant for all the implementation due to the fact that the indexes stored in the results uses the decimated signal as a reference. All of the evaluation software has to take this into account. This will also be addressed in **??**

The first MATLAB script to be called by the respiration analysis (TODO er dette sant?) is *newPT.m*. In this script, which is based on *The Identification of Peaks in Physiological Signals*[61], the programmer has assumed a fixed sampling rate, based on the fact that the raw signal (*Qraw*) is down sampled with a factor of 5 using the MATLAB toolbox decimate function.

Listing 6.3: Downsample code in newPT.m line 7

```
Qd = decimate(Qraw, 5); % downsample the signal
```

A more explicit mention of an assumed sample rate by the script creator is found in the comments of *classifyPeaks.m*: "go across entire signal, looking at narrow window around each peak try 1 second windows around each peak/trough, centred on found peak 1000 Hz signal decimated by 5, so now 200 Hz; 200 data pt window either side". Here it is stated that the sample rate has been decimated by five, and that the assumed sample rate is 1000 Hz,

which is not consistent with how the user is prompted to register the sampling rate for a given record.

This has to at least be considered when creating sample data, but should ideally rewritten into using the parameter in *preferences*, and only down sample if it is needed based on performance. The Java code can pass the registered sampling rate to the MATLAB engine and use this to decimate the signal with a dynamic factor in order to make the window size consistent.

This error was discovered when trying to analyse signal with an early onset time and a peak close to the start of the clip. This results in invalid indexes for the peak classification.

s

6.6.3 Mark pause peak and trough location

When running *markPeakPauses.m* with a 10 second clip on a 30 second record using the clipped sine generated signal we end up with a deadlock in the MATLAB script. The amplitude of the initial clipped sine signal was 0.8.

It checks the number of valid peaks created *classifyPeaks.m*

”newP” and ”newT” are variables in the script that both contain the new, centred peak or trough based on the pause one each side. During the execution of this script we run into a problem when checking each side of the original peak/trough. The signal passed to the script is called ”Qd” and is the signal in which the peaks and troughs have been found.

When peaks or troughs are too close to the beginning or end of the clip, the MATLAB script freezes during *markPeakPauses* or *markTroughPauses*. These functions iterates through the peaks and troughs analysing a windows around each event. There is no fail safe implemented, but in puka a user can choose what peaks to analyse. Here we can de-select detected events that border too close to the beginning or end at the cost of the accuracy of the analysis.

This can also be avoided by adding an automatic discarding of these events by checking the index (sample number) of the peak/trough, making sure it is not positioned as to make the window move outside the clip array.

6.6.4 Peak and trough classification

Notes:

- As it stands, the code does not contain any reference to questionable peaks
- A further analysis of the classification code can be found in **??**. `TODO: describe potential errors in this one, the decimation, assumed frequency etc`
- `http://www.ee.ktu.lt/journal/2008/8/11_ISSN_1392-1215_The%20Respiration%20Rate%20Estimation%20Method%20.pdf`

6.7 Result/Analysis online

Meta about the testing done with the vanilla puka version...

`Her kommer resultat av eksperimenter?`

Chapter 7

Analysis and Discussion

...

- zero-crossing algorithm not suitable for baseline shift!!

- **NOTE:** onset description in Subsection 3.1.8 shown us that signals should be 0-centeres or normalized and with a minimum average amplitude around 1, otherwise we need to adjust threshold.

- Dette betyr at onset-time ikke kan regnes ut på signaler som ikke er normaliserte, altså null-sentererte og tydelig favoriserer signaler med -1 –> 1 amplitude. Dette må nevnes (men ikke krise, siden vi ikke bruker onsettime scriptet i RT), men siden denne seksjonen bare inneholder beskrivelse tar jeg det heller... hvor?

Chapter 8

Future Work

Other non invasive approaches

- gather respiration signal using Novelda radar
- wake/sleep state?

- Calculate respiratory flow and bpm in addition to events
- http://www.aastweb.org/resources/focusgroups/rip_intro.pdf p 6

- other bio markers?
- oxygen saturation?
- Other sensors, so^2 sco^2,

In order to make the platform that has been created more descriptive and useful for validating respiration analysis done by puka (or potentially other applications), the following points can be explored.

- http://se.mathworks.com/help/distcomp/introduction-to-parallel-sc
html

1. Adaptive threshold has to be implemented if we want to be able to accurately identify useful events in real time signals, as these have amplitude variability. The threshold is currently set to 0.1 in ...
2. Sample rate is currently locked to 1000hz due to the nature of the respiration analysis scripts.
3. Change the history, we need to change findOnset?
4. No changes has been made to classify peaks! This should be looked into, as there is no reference to be found to it actually working as described

Figure 8.1: Things to do with puka reduced

- http://se.mathworks.com/matlabcentral/answers/52423-run-scripts-i
- http://se.mathworks.com/products/parallel-computing/

8.0.1 Signal processing

The real world data that is found in the different Physionet databases prepares us for what kind of challenges can be found when using these types of sensors. Certain signal processing has to be done to prepare the signal for usage in puka.

Post/pre processing real world data:

- fft? high pass/low pass filter?
- smooth signal:
  - moving average -really slow, removes more noise
  - SG - much faster, keeps more of the features
  - initial
- normalization?

1. Combine the events generated by pukaReduced with other sensors.
2. Recreate the respiration analysis as an CQL or some other stream favourable system.
3. Now that we have a framework for applying algorithms to a respiratory signal, novel algorithms can be implemented in order to detect new types of events or improvements to the existing ones.
4. Test on flow as well as respiration effort. Focus here have been on RIP, but this should be applicable to other sensors such as thermistors, which are able to detect changes in flow, not only respiration effort.
5. Use the system for detecting other respiratory abnormalities, such as tachypnea, bradypnea, Cheyne-Stokes, hypoventialtion, hyperpnea or hyperventialtion[28].
6. Consider swapping out matlabcontrol in favor for `http://preprints.ians.uni-stuttgart.de/downloads/2003/2003-005.pdf`.
7. Create an application that contains the ”answer” we want to validate against that consumes the Esper events and creates a report.
8. standard deviation for peak detection?
9. Deviation detection: Expect changes, but how to define baseline, threshold?
10. Modify the peak detection and pause detection to work on smaller window/clip sizes.
11. MATLAB parallel work, this way we can analyse without blocking? Non blocking processes in MATLAB:

Figure 8.2: Caption

8.0.2 beyond puka

After having implemented a close to real time version of pukas respiration analysis we have some insight as to possible paths ahead.

- Add threshold adaptation in order to classify and adjust for changes in amplitude.
-

8.1 Other approaches to puka

8.1.1 Recompiling puka

The project uses Java's *System.loadLibrary(String libName)* to load JMatLink. One unexplored avenue is to recompile puka even though there is no documentation describing the linking process of the JMatLink classes. When compiling the project we need to find a way of linking the JMatLink classes. A discrepancy discovered when looking into this potential solution is that the puka source code expects an integer returned when calling *engOpen()*, but the source code for JMatLink (both the latest v1.3.0 and v1.1.0) has *engOpen()* implemented as a *void* method.

Apendix

Software

Software delivered:

- JMatLinkAdapter: an adapter for usage in puka to replace JMatLink
- SignalGenerator: lager simulerte greier. Sinegenerator.m lager ideelle og problematiske signaler
- DataFeeder: leser inn og sender sender data til en klient via socket
- pukaReduced: mottar signaler fra dataFeeder og gjennomfører respirasjons analyse.
- SignalPatcher: Rydde opp i signaler fra physionet ettersom de mangler enkeltmålinger. Se Cleaner.java for enkel løsning.

Code snippets

Listing 8.1: Respiration analysis programatical flow

```
// :745 prepare and clear data
frmLoadData.engMatLab.engEvalString("[P,T,th,Qd] =
   newPT(y, .1, onsetTime, endTime)"); //run the matlab
   script

// :536 peak analysis
frmLoadData.engMatLab.engEvalString("[peakLabels,troughLabels]
   = classifyPeaks(Qd,P,T,th);");

//get the peaks/troughs and labels back into the table
dblP = frmLoadData.engMatLab.engGetArray("P");
dblT = frmLoadData.engMatLab.engGetArray("T");
dblPlabels =
   frmLoadData.engMatLab.engGetArray("peakLabels");
```

```
dblTlabels =
   frmLoadData.engMatLab.engGetArray("troughLabels");
FillPeaksTable(0); FillTroughsTable(0); //fill both with
   all peaks/troughs

// :575 Do apply has to be described later...
DoApply(); //call cmdApply first
frmLoadData.engMatLab.engEvalString("[validPeaks,
   validTroughs] = makeValidArrays(P,T,peakLabels,
   troughLabels);");
frmLoadData.engMatLab.engEvalString("[newP] =
   markPeakPauses(Qd, validPeaks, validTroughs, th);");
frmLoadData.engMatLab.engEvalString("[newT] =
   markTroughPauses(Qd, validPeaks, validTroughs, th);");
frmLoadData.engMatLab.engEvalString("plotPauses(Qd,
   validPeaks, validTroughs, th, newP, newT);");

// :481
//control the computation of breathing statistics
ArrayList jcTempList = new ArrayList(); double[][]
   dblTemp; int intTemp = 0; int intC = 0;
double[][] dblTroughs; double[][] dblNewP; double[][]
   dblNewT;

//need the peaks and troughs array regardless of using
   pauses or not
frmLoadData.engMatLab.engEvalString("[peaks,troughs] =
   generatePT(P,T,peakLabels, troughLabels);");
//Ttotal is calculated off of the troughs array - pauses
   don't matter
frmLoadData.engMatLab.engEvalString("[avgTtot,stdTtot] =
   calculateTtotal(troughs);");


//call the matlab scripts to do the calculations either
   with or without pauses
if (rdoUsePauses1.isSelected() == true) { //calculations
   include pauses
   frmLoadData.engMatLab.engEvalString("[avgPI,stdPI,avgPE,stdPE]
      = calculatePauses(newP,newT);");
   frmLoadData.engMatLab.engEvalString("[avgTI,stdTI,avgTE,stdTE]
      = calculateInsExp(newP,newT);");
} else { //pauses ignored; all assumed to be zero
```

```
    frmLoadData.engMatLab.engEvalString("avgPI = 0;");
       //set all of these variables to zero
    frmLoadData.engMatLab.engEvalString("stdPI = 0;"); //so
       that CalculateResp() can retrieve
    frmLoadData.engMatLab.engEvalString("avgPE = 0;");
       //the values to show in the table
    frmLoadData.engMatLab.engEvalString("stdPE = 0;");
    frmLoadData.engMatLab.engEvalString("[avgTI,stdTI,avgTE,stdTE]
       = calculateInsExpNoPauses(peaks,troughs);");
}

try {
    CalculateResp();
} catch (MatlabInvocationException e) {
    // TODO Auto-generated catch block
    e.printStackTrace();
} //shows results in the table and sets in rmData
```

Listing 8.2: The implementation of the peak detection algorithm in puka

```
for ind = 1:n
   if d == 1
      if Qd(a) >= Qd(ind) + th
         d = 3;
      elseif Qd(ind) >= Qd(b) + th
         d = 2;
      end;
      if Qd(a) < Qd(ind)
         a = ind;
      elseif Qd(ind) < Qd(b)
         b = ind;
      end;
      S = ind;
   elseif d == 2 % signal rising, trough-to-peak
      if Qd(a) < Qd(ind) % still rising
         S = ind;
         a = ind;
      elseif Qd(a) == Qd(ind)
         S = [S,ind];
      elseif Qd(a) >= Qd(ind) + th
         P = [P,S]; S = ind;
         b = ind; d = 3;
```

```
      end;
   elseif d == 3 % signal falling, peak-to-trough
      if Qd(ind) <= Qd(b)
         S = ind;
         b = ind;
      elseif Qd(b) == Qd(ind)
        S = [S,ind];
      elseif Qd(ind) >= Qd(b) + th
         T = [T,S]; S = ind;
         a = ind; d = 2;
      end;
   end;
end;
```

Listing 8.3: Some voodoo going on

```
%This is done checking each direction from the current
   peak location, and based
%%%%%%%%%%%%%%%%%%%%%% find the pause to the LEFT of this
   trough %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
sth = abs((Qd(prevPeak) - Qd(thisTrough)) * .30); % small
   threshold = 15% of slope height
mth = abs((Qd(prevPeak) - Qd(thisTrough)) * .08); % medium
   threshold
ssth = abs(Qd(prevPeak) - Qd(thisTrough)) * .0005; %
   super-small threshold
m = -1; littles = 0; negatives = 0; stop = 0; % set markers

% loop until end of window is sth HIGHER than the trough
while (Qd(thisTrough + m) - Qd(thisTrough)) < sth
      if (thisTrough + m) == 2
            m = m + 1
            break;
      else
       m = m - 1; % back up one more step
      end;
end;

if thisTrough == 11499
      s = ['m = ', int2str(m), ' before looping back']
end;

while stop == 0 % now loop back towards the trough until a
```

```
stopping condition is met
   if abs(Qd(thisTrough + m) - Qd(thisTrough + m - 1))
      < ssth % slope of last point less than ssth
         littles = littles + 1; % zero or not too steep
            slope
   else
         littles = 0; % other - medium or steep slope
   end;
   if (Qd(thisTrough + m - 1) - Qd(thisTrough + m) < 0)
         negatives = negatives + 1; % this point lower
            than last - should be higher
   else
         negatives = 0;
   end;

   if thisTrough == 11499
          s = ['m = ', int2str(m), ' looping back']
   end;

   if m == -1
         m = 0;
         stop = 1; % back to trough point - stop
         s = ['m == -1 - LT', int2str(i), '
            thisTrough=', int2str(thisTrough), '
            mark=', int2str(thisTrough + m)]
   elseif Qd(thisTrough + m) <= Qd(thisTrough)
         stop = 1; % height is lower or equal to the
            trough - stop
         s = ['back to start level - LT', int2str(i), '
            thisTrough=', int2str(thisTrough), '
            mark=', int2str(thisTrough + m)]
   elseif littles > 30 & ((Qd(thisTrough + m) -
      Qd(thisTrough)) < mth)
         stop = 1; % slope not changing much anymore
         m = m - 15; % move back to middle of the 3
            littles
         s = ['littles > 30 - LT', int2str(i), '
            thisTrough=', int2str(thisTrough), '
            mark=', int2str(thisTrough + m)]
   elseif negatives > 10 & ((Qd(thisTrough + m) -
      Qd(thisTrough)) < mth)
         stop = 1; % went the wrong direction for 10
            points in a row
```

```
            m = m - 10;
            s = ['negatives > 10 - LT', int2str(i), '
               thisTrough=', int2str(thisTrough), '
               mark=', int2str(thisTrough + m)]
      else
            m = m + 1; % move one point more towards the
               trough
      end;
end;
newT = [newT, (thisTrough + m)]; % add in new point
```

NOTES to be removed

Two main approaches:

Either create events for each PI/PE start and stop, or calculate the pause (most similar to the existing implementation) by increasing the size of the clip! (makes more sense?)

WIP:

- Windows - timed, find useful timeframe
- types of events, trough, peak, respiration stops...
- what is required from TRIO?
- update frequency?
- increase decrease in frequency = sacrifice precision?

- main experiments
- window size
- results compared to manual reading
- results compared to ECG algorithm???

```
other events that are noteworthy?

/NOTES
```

Troubleshooting

The following section contains some of the general troubleshooting done during the development of the puka reduced testing platform.

MATLAB script execution freeze

When running puka it sometimes freezes at after entry to *newPT.m*:

Listing 8.4: Last log entry

```
mar 27, 2016 8:03:00 PM
   matlabcontrol.LoggingMatlabProxy eval(String)
FINER: ENTRY [P,T,th,Qd] = newPT(y, .1, onsetTime,
   endTime)
```

Does not return from *engEvalString()*, but when the Java process is stopped, the execution of the MATLAB script finishes. The instance of MATLAB does not respond during this time, so no information about where in the execution it might stop.

Listing 8.5: Expected log entry

```
mar 27, 2016 8:12:48 PM
   matlabcontrol.LoggingMatlabProxy eval(String)
FINER: ENTRY [P,T,th,Qd] = newPT(y, .1, onsetTime,
   endTime)
mar 27, 2016 8:12:48 PM
   matlabcontrol.LoggingMatlabProxy eval(String)
FINER: RETURN
```

After some trail and error we found the problem in one of the parameters given to the MATLAB engine on start up. The application does not work with proxy: *setHidden()* set to `true`. Something

in the implementation creates problems. Without any debug information from either MATLAB or Java, we do not know exactly what causes this bug. But when run with *setHidden* to `false`, the call to initiate *newPT* returns and the execution continues.

Peak detection sample rate assumption

In the MATLAB scripts containing the respiration analysis, the authors have assumed a given sample rate of 1000 Hz. This is evident in comments and code in *newPT.m* and *classifyPeaks.m*.

To avoid future confusion, we introduce a sample rate variable set in each script which is in the case of the GUI application set in *preferences* and in the case of the command line application in the *Settings* class.

Misc bugs

List of smaller, syntactical or otherwise easily fixed bugs found in the source code of puka.

- **frmRespiration.java:43** – ',' instead of ':', might be change in MATLAB, but this results in y being set to a scalar instead of an array.

List of Figures

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