Research Report
ISSN 0167-9708
Coden: TEUEDE

Eindhoven
University of Technology
Netherlands

Faculty of Electrical Engineering

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by
J.H.M. van Oostrom

EUT Report 89-E-229
ISBN 90-6144-229-X

October 1989

Eindhoven University of Technology Research Reports

EINDHOVEN UNIVERSITY OF TECHNOLOGY

Faculty of Electrical Engineering
Eindhoven The Netherlands

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This report was submitted in partial fulfillment of the requirements for the degree of Master of Electrical Engineering at the Eindhoven University of Technology, The Netherlands.
The work was carried out from March 1988 until December 1988 under responsibility of Professor J.E.W. Beneken, Ph.D., Division of Medical Electrical Engineering, Eindhoven University of Technology, at the Department of Anesthesiology, College of Medicine, University of Florida, Gainesville, Florida, under supervision of M.L. Good, M.D., J.S. Gravenstein, M.D., and J.J. van der Aa, M.E.

CIP-GEGEVENS KONINKLIJKE BIBLIOTHEEK, DEN HAAG

Oostrom, J.H.M. van

Intelligent alarms in anesthesia: an implementation / by J.H.M. van Oostrom. - Eindhoven: Eindhoven University of Technology, Faculty of Electrical Engineering. - Fig., tab. - (EUT report, ISSN 0167-9708, 89-E-229)
ISBN 90-6144-229-X
Met lit.opg., reg.
SISO 608.1 UDC 616-089.5 NUGI 742
Trefw.: anesthesie; patiëntbewaking.

SUMMARY

Abnormal and potentially dangerous fault conditions in the anesthesia breathing circuit include leaks, obstructions, disconnects, incompetent valves and CO_2 absorber malfunction. Because the current alarms of monitoring devices are not specific enough, there is a need for an intelligent alarms system that can determine the integrity of the breathing circuit. Three signals were measured at three different places: CO_2 partial pressure at the Y-piece, airway pressure at the patient side of the inspiratory valve and airway flow at the patient side of the expiratory valve. From these measurements features were extracted for each signal, and the feature changes were analyzed. From these analysis a rule base was designed, which was implemented in an expert system by using the SIMPLEXYS expert systems language. Real time signal analysis and feature extraction were implemented in a multitasking environment. Initial tests were performed.

It was found that an implementation of the total system was possible on an IBM-AT with the multitasking environment MultiDos-Plus. The intelligent alarms system was able to distinguish the following malfunctions: incompetent inspiratory valve, incompetent expiratory valve, exhausted CO_2 absorber, obstruction at the Y-piece, obstruction at the inspiratory hose and obstruction at the expiratory hose. The rule set is currently being expanded with rules for leaks and disconnects.

SAMENVATTING

Abnormale en potentieel gevaarlijke foutencondities in het beademings circuit dat tijdens anesthesie gebruikt wordt, bestaan onder meer uit lekken, verstoppingen, losgeraakte verbindingen, nietwerkende kleppen en een niet goed functionerende CO_2 absorber. Omdat de huidige alarmering van de monitors niet specifiek genoeg is en onvoldoende informatie geeft, is er behoefte aan een intelligent alarmerings systeem dat kan uitzoeken wat er mis is in het beademings circuit. Voor de implementatie wordt gebruik gemaakt van drie signalen die gemeten worden op drie verschillende plaatsen: partiële CO_2 druk bij het T-stuk, druk in de inademings gedeelte van het beademings circuit, gasstroom in het uitademings gedeelte van het beademings circuit. Uit deze metingen werden features gehaald, en de veranderingen van de features werden geanalizeerd. Uit de resultaten van deze analyze werd een regelset ontworpen, welke in een expert systeem geïmplementeerd is m.b.v. de SIMPLEXYS expert systeem taal. Real time analyze en feature berekening zijn geïmplementeerd in een multitasking omgeving. Voorlopige tests zijn uitgevoerd.

Een implementatie van het totale systeem bleek mogelijk te zijn op een IBM-AT met de multitasking omgeving van MultiDos-Plus. Het intelligente alarm systeem kon de volgende fouten onderscheiden: niet-werkende inademings klep, niet-werkende uitademings klep, uitgeputte CO_2 absorber, verstopping van het T-stuk, verstopping van de inademingsbuis en verstopping van de uitademingsbuis. Op het moment wordt de regelset uitgebreid met regels voor lekken en onderbrekingen.

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INTRODUCTION

This project was done as part of the fulfillment of the requirements for a M.Sc. degree in Electrical Engineering at the Eindhoven University of Technology, Division of Medical Electrical Engineering, The Netherlands. The research was performed at the University of Florida, College of Medicine, Department of Anesthesiology in Gainesville, U.S.A. Funding for the research was provided by Ohmeda in Madison WI, manufacturer of anesthesia equipment.

Problem definition

During surgery, a patient is under anesthesia. This is an induced state in which the patient is unconscious, insensitive to pain, and the muscles of the patient are relaxed to the point where respiration must be supported by external means; an anesthesia system is used for this support. The risk of anesthesia is small. It is estimated that between 2 and 10 anesthesia related incidents result in death for every 10,000 anesthetics [ORK86]. A large percentage of these incidents are due to human error and equipment failure [COO78]. Monitoring devices are used by the anesthesiologist for early detection of unwanted situations. Most monitors are equipped with alarms that generate a sound when a user settable threshold has been exceeded. At some critical moments, many monitors can and will sound an alarm and the clinician is overwhelmed with an abundance of tones; it is the clinician's task to analyze the multitude of unspecific alarms and reach a conclusion about what exactly is going on.

An unwanted situation can be the result of either an equipment malfunction or a patient problem. The first thing the anesthesiologist does is to check the equipment. If this appears to work well, the anesthesiologist checks the patient. It is our goal to develop a system that helps the anesthesiologist to reach a conclusion about the nature of the alarm situation. This study is a start; it focusses on the integrity of the anesthesia system.

If we let a computer monitor the anesthesia system (in the

same way as the anesthesiologist does) and if we give the computer the same knowledge the anesthesiologist uses to reach a conclusion about the source of the alarm, such an aid could be developed. This report describes how a clinician monitors the anesthesia system and how to implement this knowledge in a computer so that an intelligent (alarms) system can be developed, that aids the clinician to reach a conclusion about the possible problem more rapidly.

Problem approach

For now, we limit our intelligent alarms system to the integrity of the breathing system of the anesthesia system (for a description of the anesthesia system and the breathing system see chapter 1).

A definition of what can go wrong with the breathing system has to be made. It has to be determined which signals have to be measured and where in the system they have to be measured. A continuous analysis of these measurements has to be made to determine whether a malfunction exists and if so, what exactly. Symbolic data will be derived from the signals and these will be given to an expert system containing the domain specific knowledge, which will reach a conclusion about the integrity of the breathing circuit. The following is a list of tasks that needed to be done to implement an intelligent alarms system. These tasks will be described in this report.

- Define the malfunctions that we want to detect.
  Make a comprehensive list of all dangerous malfunctions by interviewing anesthesiologists and studying the used anesthesia system (chapter 2).

- Define which signals must be measured to detect these malfunctions, and where in the system they must be measured.
  Find out which monitors are normally used and which monitors are available. Place the sensors so that an optimal malfunction detection can take place (chapter 2).

- Record the signals that result after wilful introduction of

the earlier defined malfunctions (with a simulated patient). Sample the signals so they can be processed by a computer, and plot them.

- Analyze the recorded data, define and extract their important features.
  Define important features for every signal, calculate the features (chapter 3).

- Analyze the features, define how these features change for every malfunction.
  Extract detection rules for every malfunction (chapter 4).

- Incorporate the derived knowledge in an expert system.
  Make an expert system that reaches a conclusion about the integrity of the system, using a set of detection rules (chapter 5).

A real time implementation of the intelligent alarms system has been made; it is described in chapter 6.

Chapter 1: An introduction in Anesthesia

1.1 Introduction

Anesthesia is a state of unconsciousness, analgesia (the blocking of pain), and relaxation of the muscles. This state is needed during surgery to help the surgeon perform the operation. The anesthetic state is induced by an anesthesiologist, usually a physician trained to administer anesthetics.

The most common method in the U.S.A. to obtain anesthesia is inhalation of one or more anesthetic gases. Because all the patient's muscles are relaxed, he can not breathe himself. The anesthetic mixture, a mixture of anesthetic gas(es) and oxygen, prepared by an anesthesia machine and supplied by a ventilator, is forced into the patient via a breathing circuit and through a tube brought into the trachea (endotracheal tube).

1.2 Anesthesia machine

There are several different anesthesia machines in use. I will concentrate on the Ohmeda Modulus II Anesthesia System, which is used in Shands hospital in Gainesville.

The Modulus II is most often used with a circle breathing system. In a circle system the gases, exhaled by the patient, are reused. A great advantage of this method is that the quantity of anesthetic agent that is needed decreases, because the exhaled (unused) fraction of the agent is reused. In the patient's lungs CO_2 is replaced by oxygen, so the patient exhales CO_2 that has to be removed from the breathing circuit; this is done by the CO_2 absorber.

The following 5 parts can be identified in the inhalation anesthesia system:

- High pressure system
  connections to the wall outlet or gas tanks.

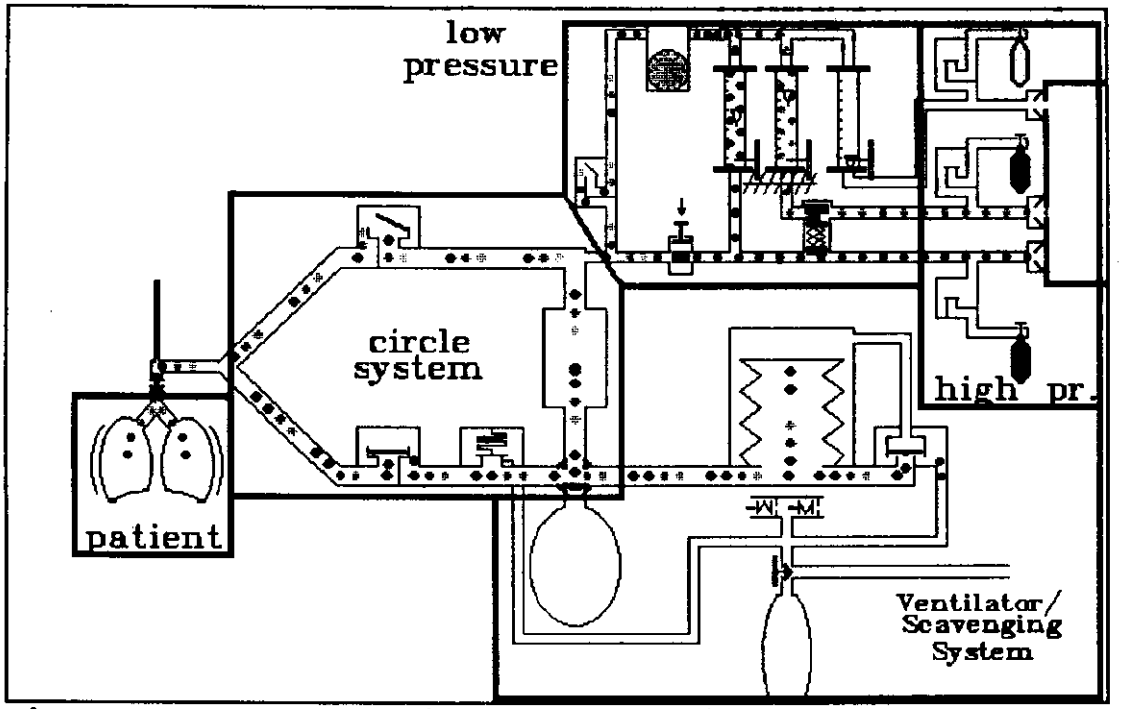

Figure 1.1: Block diagram anesthesia system
composed by J.S. Gravenstein M.D.

- Low pressure system
  flow control valves with flow meters, vaporizer to administer anesthetics.

- Scavenging system
  excess gas outlet.

- Ventilator system
  ventilator, hand bag.

- Circle breathing system
  CO_2 absorber, hoses to connect to the patient, endotracheal tube, unidirectional valves.

The high pressure and low pressure systems together are called the anesthesia machine.

1.3 Ventilator

The ventilator is the driving source of the anesthesia system. This device forces the gas mixture via the breathing circuit into the patient. In case of an emergency, a hand bag in the system can be used to manually ventilate the patient.

1.3.1 Ventilator settings

The ventilator can be set to accommodate patients of different age, weight, physical condition and the type of operation.
Typical controls on an anesthesia ventilator are:

- Minute volume dial
  This dial is used to set the number of liters per minute of gas delivered to the lung.

- Rate dial
  This dial is used to set the respiratory rate (number of breaths per minute).

- I:E ratio dial
  This dial is used to set the ratio of inspiration time to expiration time.

Some basic principles to set these values are:

- Minute volume = Tidal volume * Respiratory rate.
  At normal respiratory rates, the tidal volume should be 10-15 ml/kg body weight. This is the inspired tidal volume; it is delivered to the patient during the period called the inspiration time. There is also an expired tidal volume. It is different from the inspired tidal volume because the expired gas is at a different pressure, at a different temperature, has a different composition, and because the respiratory quotient is not exactly equal to one.

- Inspiratory Flow = Minute volume * (1 + E/I).
  The inspiratory flow (which is constant, due to the mechanics of the system) must deliver the gas volume during the

inspiratory part of the respiratory period; it is determined by the speed at which the tidal volume is transferred from the bellows to the patient. In general, lower inspiratory flows produce a lower peak inspiratory pressure and lead to a better distribution of gas within the lungs. The flow rate should be adjusted to allow for an inspiratory/expiratory ratio no greater than 1, in order to provide for adequate expiration. Inspiratory flow rates of 40-50 L/min are usually used in adult patients.

- Alveolar respiration should be adjusted to maintain the $PaCO_2$ (alveolar CO_2 level) at 30-35 torr* (by adjustments of respiratory rate, tidal volume, and I:E ratio).

- Regardless of the respiratory rate and the inspiratory flow rate, it is recommended that the I:E ratio is more than 1:1; otherwise there is not enough time for exhalation. [LIC74]

1.4 High pressure part

Two or more gases can be used with the Modulus II. Usually Oxygen and Nitrous oxide are used. For every gas it is possible to choose between wall supply or tank supply.

1.5 Low pressure part

Flow control valves set the flow of every gas. The flow control valves for oxygen and nitrous oxide are mechanically interconnected. This is done to be sure there is a minimum oxygen concentration of 25% in the gas mixture delivered to the patient [OHM83]. Vaporizers are used to add anesthetics to the gas mixture (nitrous oxide is an anesthetic gas, but by itself it does not provide a sufficient anesthesia). An oxygen flush valve allows the anesthesiologist to temporarily give the patient an extra dose of oxygen.

---

*1 torr is almost equal to 1 mmHg. 1 kPa is equal to 7.5 mmHg.

1.5.1 Flow settings

Not only the ventilator dials need to be set, also the fresh gas flow has to be set. Usually two gases are used: O_2 and N_2O. So the total gas flow and the fraction of O_2 (FiO_2) can be set.

The FiO_2 should be such that the concentration O_2 in the mixture is at least 21%. The FiO_2 should be as low as possible to avoid the toxicity of high concentrations of oxygen. For patients with normal lungs 40% O_2 is usually adequate, but during short periods 100% can be necessary.

1.6 Circle system

The circle system consists of two parts: the inspiratory limb and the expiratory limb. When the ventilator cycle starts, the inspiratory valve opens and the expiratory valve closes. Gas

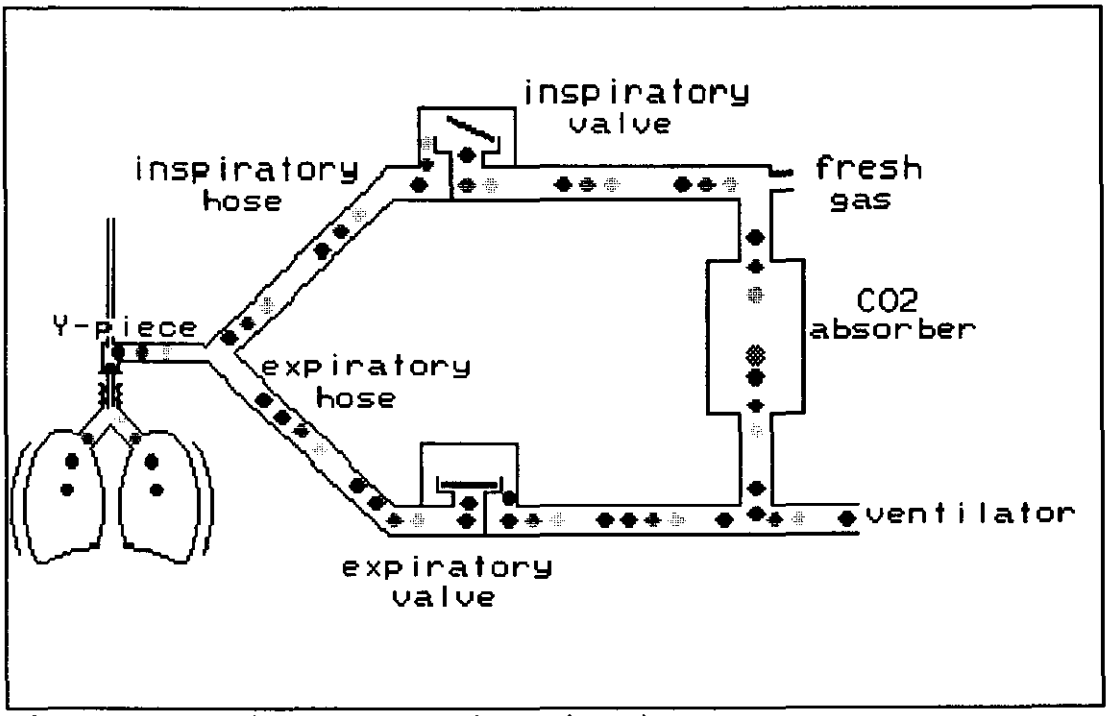

Figure 1.2: Circle breathing circuit

(both fresh gas and gas recirculated through the CO_2 absorber) flows through the inspiratory hose into the patient.

During expiration, the inspiratory valve closes and the expiratory valve opens, allowing gas to flow through the expiratory hose back into the ventilator and scavenging system. The patient's inflated lungs empty passively, much like a balloon deflates, after the ventilator has delivered the set tidal volume.

The CO_2 absorber is a canister filled with soda lime, which scrubs the gases passing through it from CO_2. The soda lime has to be replaced regularly, because it gets exhausted after extensive use.

1.7 Scavenging system

The scavenging system exists of an excess gas bag and some valves. During expiration the ventilator bellows gets filled. If the bellows overfills and hits the top of its case, the excess gas goes into the excess gas bag. If even more gas arrives, a valve opens and the gas exits the system. The scavenging system is needed to prevent the operation room from getting polluted with anesthetic gas mixtures.

Chapter 2: Signal measurement versus detection

2.1 Introduction

Our goal is to derive a conclusion about the integrity of the breathing circuit from information present in the signals measured in or near the breathing circuit. Many things can go wrong with the breathing circuit of an anesthesia machine. With the current technology, it is difficult to conclude what exactly goes wrong, because several different monitors may give partially overlapping and quite unspecific alarms.

Our first task is to find out which malfunctions should be detected and alarmed on. Secondly, we have to determine which signals are to be measured in the breathing circuit and where we should measure these signals in order to best detect these malfunctions.

2.2 What do we want to detect

The circle breathing circuit exists of disposable plastic hoses, unidirectional valves, and a CO_2 absorber. Because the hoses have to be easily replaceable, leaks and disconnects can occur. If the hoses kink, an obstruction may result. As indicated in 1.6, the soda lime of the CO_2 absorber can get exhausted, resulting in inadequate ventilation by CO_2 rebreathing.

The uni-directional valves consists of a disc that elevates when the pressure on one side higher is than the pressure on the other side. The disc's movement is limited by a retainer. The disc is made of flexible plastic, and when it becomes moist (humidity of expired gas is high) it is possible that the disc gets stuck in the open position. The dome is transparent and removable, so a stuck valve can be confirmed and repaired.

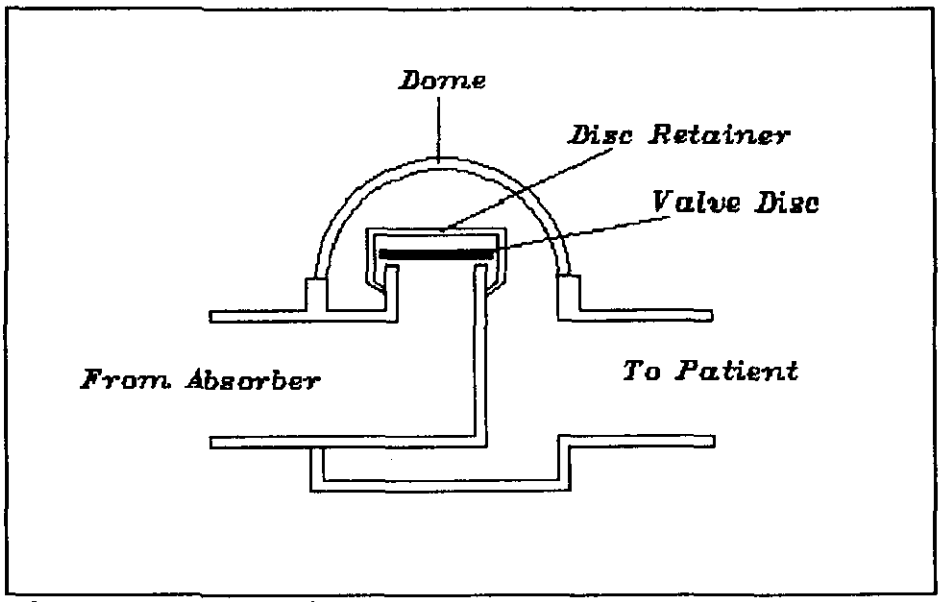

Figure 2.1: Inspiratory valve

From the information we have about the system and from interviews with anesthesiologists we have set as our goal to automatically detect the following malfunctions:

Exhausted CO_2 absorber
Incompetent Inspiratory valve
Incompetent Expiratory valve
Obstruction Endotracheal tube
Obstruction Inspiratory hose
Obstruction Expiratory hose
Leak Inspiratory hose
Disconnect Inspiratory hose
Leak Expiratory hose
Disconnect Expiratory hose
Leak Y-piece
Disconnect Y-piece
Leak Ventilator hose
Disconnect Ventilator hose
Leak CO_2 canister
Leak Endotracheal tube cuff
Disconnect Endotracheal tube cuff
Leak Fresh Gas Flow
Disconnect Fresh Gas Flow

2.3 Which signal do we want to measure?

In order to detect malfunctions, several signals will have to be measured from the circle system. If possible, we would like to use the standard set of measurements.

2.3.1 Monitors

We want to detect malfunctions in a system where gases flow, and where CO_2 is added and extracted. The logical thing to do is to measure CO_2, pressure and flow. In anesthesia monitoring CO_2 and pressure are usually monitored, but flow monitoring is not common. It is much more common to measure expired volume, the integral of the (expiratory) flow over the expiratory period. CO_2, pressure and volume monitors are now standard and widely available. In the Ohmeda Modulus II the Ohmeda 5200 CO_2 monitor, the Ohmeda 5500 airway pressure monitor and the 5410 volume monitor are used. Other signals, like O_2 percentage, oxygen saturation, blood pressure and anesthetic agent percentage, are usually measured by additional monitors. In a system where flow and CO_2 monitoring are the major features, we choose to use CO_2, pressure and flow signals.

2.3.2 Previous work

Previous work has been done in this field by Rob Bastings [BAS87] and Jan van der Aa [AA87]. They measured CO_2, pressure and flow signals at the Y-piece. As result of these measurement they could detect 5 clusters of malfunctions:

cluster 1:
- Endotracheal tube leak
- Leak in expiratory hose
- Ventilator tube leak

cluster 2:
- Leak in inspiratory hose
- Partial disconnect of the fresh gas flow

cluster 3:

Incompetent inspiratory valve

cluster 4:

Incompetent expiratory valve
Exhausted CO_2 absorber

cluster 5:

Increased airway resistance (obstructions)

It was not possible to distinguish between malfunctions within a cluster. The advantage of an integrated sensor at the Y-piece, that they used, is that there is only one sensor that has to be placed. The disadvantage is that malfunctions far from the sensors are hard to pick up and because all sensors are located in one place, the detection is not optimal. Ideally we would like to have a sensor in every limb of our system, but this would require a very complicated build-up of the system, with a higher possibility of errors, and a higher possibility of sensor malfunction.

Traditionally, in the Modulus II with circle breathing system, the CO_2 is measured at the Y-piece, pressure in the inspiratory hose and flow in the expiratory hose. This is the setup we choose to use. It gives us the advantage of using standard equipment and thus easier testing, because we can setup our system with a standard anesthesia system.

Chapter 3: Data analysis

3.1 Introduction

If a computer program is to derive conclusions from analog signal wave forms, samples of the wave forms are needed as input to the computer. On practical grounds, we conclude that for our signals a sample rate of 20 Hz is enough to extract the important information from these samples.

3.2 General approach

First we have to determine the kind of information the signals contain. A set of features of each signal has to be defined, so that the feature set resembles the signal's clinically useful information closely.

We limit our signals to (almost) periodic signals, that can be described by a sequence of segments with the following attributes:

- horizontal { HORIZ }
- slope { SLOPE }
- exponential curve { EXPON }

Each attribute has parameters associated with it. HORIZ has start-time, end-time, level. SLOPE has start-time, end-time, start-value, slope. EXPON has start-time, end-time, time-constant.

A-priori information about the signal must be available to know in which phase (or segment) the signal is (every phase has an attribute associated with it).

So a signal analysis routine consists of the following parts:

- phase detection
  Determines in which phase the signal is.

- parameter calculation
  Calculates the parameters for each phase.

- parameter validation
  Determines if the parameter can be calculated.

3.2.1 Phase detection

Phase detection is more difficult than it seems at first. With well-defined, noise-free signals, it would not be difficult, but data from patients is corrupted with noise and artifacts. To determine the phase, we can use both the signal and the derivative. Limits have to be set to determine the phase. This work was done by Rob Bastings [BAS87]. The next quote from his report describes his method of phase detection. "The samples are filtered with a digital low pass filter (moving average filter, HvO) to obtain a mean value. A positive and negative amplitude can be obtained by filtering the samples above and below the mean value. The low and high thresholds are defined as the sum of the mean value and 50% of the positive and negative amplitude respectively. (...) This method decreases the number of false level detections.

An estimation of the derivative is used to determine if a high or low level is reached." ([BAS87] p. 24,25)

3.2.2 Parameter calculation

The parameters that have to be calculated are slopes (of a curve segment), levels (of a horizontal line) and time constants (of a curve segment). The developed signal-processing routines are robust with regard to noise, i.e. noisy data still yield a good enough result. They are not artifact-resistant; artifacts must be detected (and removed) by another method.

3.2.2.1 Calculating levels

In the calculation of the level of what we call 'a horizontal line', (in practice this line will be noisy, and it will not always be strictly horizontal either), two levels can be important: the maximum and the minimum. In some cases the maximum is important, in other cases the minimum. In the ideal

'horizontal line', the maximum and the minimum are of course the same.

Maximum and minimum can be calculated with the following algorithm:

```
if ( sample > max ) max = sample;
if ( sample < min ) min = sample;
```

A proper initialization of max and min is needed (eg. min >= highest possible minimum if the search is for a minimum).

3.2.2.2 Calculating slopes

Since our signal is noisy, the slopes must be calculated in a way such that noisy signal values yield an accurate value for the slope.

Assume that our data points are modelled by the line

$$y = ax + b \tag{3.1}$$

We want to calculate a. If the k^{th} data point has an error (distance from the line) with magnitude

$$| ax_k + b - y_k | \tag{3.2}$$

The sum of the errors over all m data points is

$$\sum_{k=1}^{m} | ax_k + b - y_k | \tag{3.3}$$

Since this error sum is a function of a and b, a and b can be chosen so that the function has a minimum. We actually use a different function (3.4) to minimize (the least squares method; its computations are easier and its results better understood), but the results are similar.

$$(a,b) = \sum_{k=1}^{m} (ax_k + b - y_k)^2 \tag{3.4}$$

The conditions to minimize this are:

$$\frac{\delta\Phi}{\delta a} = 0, \qquad \frac{\delta\Phi}{\delta b} = 0. \tag{3.5}$$

Applying this results in:

$$\sum_{k=1}^{m} 2(ax_k + b - y_k)x_k = 0 \tag{3.6a}$$

$$\sum_{k=1}^{m} 2(ax_k + b - y_k) = 0 \tag{3.6b}$$

Taking in account that $\sum_{k=1}^{m} 1 = m$, the solution for a and b is:

$$a = 1/d \left(m \sum_{k=1}^{m} x_k y_k - \sum_{k=1}^{m} x_k \sum_{k=1}^{m} y_k \right) \tag{3.7a}$$

$$b = 1/d \left(m \sum_{k=1}^{m} x_k^2 \sum_{k=1}^{m} x_k y_k - \sum_{k=1}^{m} x_k \sum_{k=1}^{m} y_k \right) \tag{3.7b}$$

where

$$d = m \sum_{k=1}^{m} x_k^2 - \left(\sum_{k=1}^{m} x_k \right)^2 \tag{3.8}$$

[CHE85]

We use equations (3.7a) and (3.8) to calculate the slope of a curve.

3.2.2.3 Calculation time constants

For an exponential curve a similar calculation is used to calculate the time constant T, were we take the natural logarithm of the samples, minus the offset of the exponential curve.

$$y = \exp(-Tx) + y_0 \tag{3.9}$$

$$\ln(y - y_0) = -Tx \tag{3.10}$$

$$y' = -Tx \qquad (3.11)$$

Our signals are assumed to have only the attributes described above. In order to represent the signal by segments having only these attributes, we must have a-priori information about the signals to be able to describe the signal as a sequence of segments (phases). We have to determine which attribute a signal has in which segment, and hence which features need to be calculated when.

3.2.3 Parameter validation

Parameter validation is done for EXPON and SLOPE. In our algorithms, if less than ten samples are available for slope calculation, the feature value is not valid (the calculated slope will not be reliable enough). All the other features are always calculated, because at this stage the intelligence to determine if a feature is valid or not is not available. This will be available in a later stage (an expert system).

3.3 CO_2 signal

The CO_2 signal, measured at the Y-piece, consists of 2 major parts: 1) the plateau during expiration, 2) the zero plateau during inspiration.

status	attribute	feature
1	HORIZ	Inspired CO_2 level
2	SLOPE	Up slope
3	HORIZ	Expired CO_2 level
4	SLOPE	Down slope

Table I: CO_2 signal

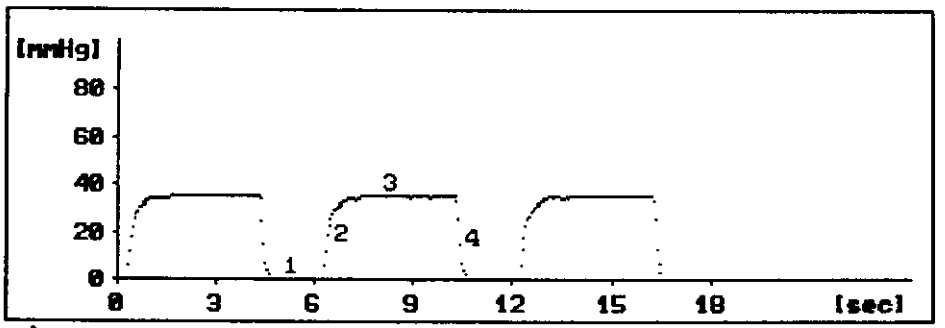

Figure 3.1: Normal CO_2 signal

During inspiration, gas (fresh gas and gas through the CO_2 absorber) is forced into the patient. This gas normally does n ot contain any CO_2. During expiration the CO_2 level will increase until it reaches a level that is approximately equal to the alveolar CO_2 level.

The CO_2 signal at the Y-piece is described in table I and in figure 3.1.

3.4 Pressure in the inspiratory limb

A breathing circuit with a lung can be modeled by a resistor-capacitance circuit.

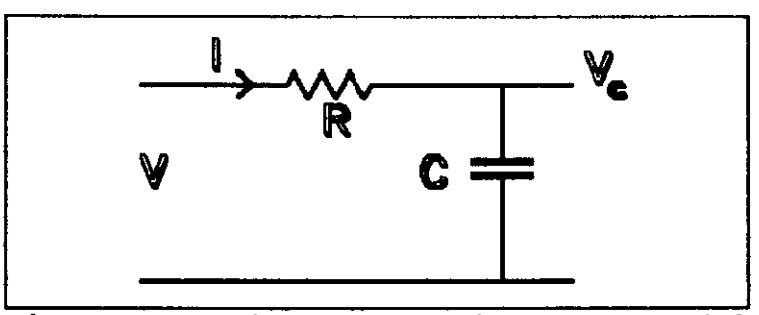

Figure 3.2: Simple electrical lung model

The flow is modelled with the current I, the pressure with voltage V.
Equations:

$$I = C\ dV_c/dt \qquad (3.12)$$

$$I = (V - V_c)/R \qquad (3.13)$$

During inspiration, the gas is forced into the patient with a constant flow (I=constant). So V_c has a linear increase (from eq. 3.12) and V also has a linear increase because of eq. (3.13).

During expiration the capacitor (representing mostly compliance of the lungs) is discharged, resulting in an exponential decrease.

status	attribute	feature
1	SLOPE	up slope, maximum
2	EXPON	time constant
3	HORIZ	minimum

Table II: Pressure signal

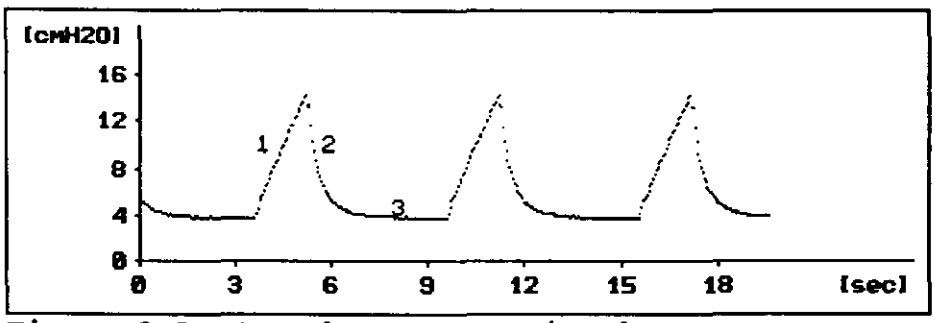

Figure 3.3: Normal pressure signal

The pressure signal in the inspiratory hose is described in table II and in figure 3.3.

3.5 Flow in the expiratory hose

As described in 3.4, the flow through the inspiratory hose during inspiration is constant. Since only the flow in the expiratory limb is measured, no flow is measured during inspiration. Only when the expiratory valve is open, flow can be measured. When the expiratory valve opens at the beginning of

expiration, there is a steep increase in the flow. As described in 3.4, the capacitor discharges and hence the flow decreases exponentially.

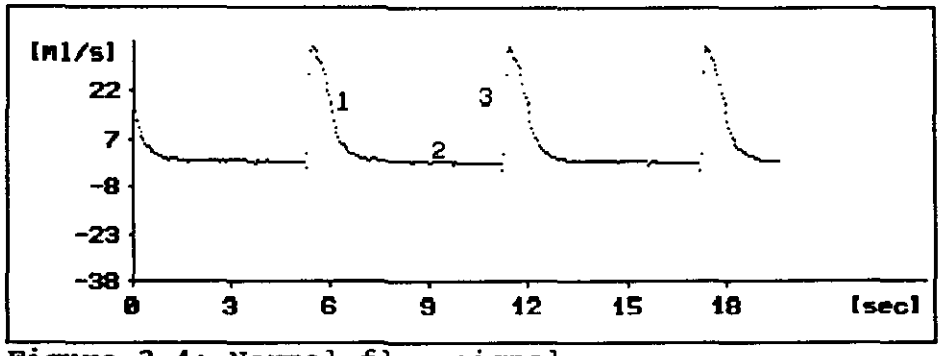

Figure 3.4: Normal flow signal

The expiratory flow signal is described in table III and in figure 3.4.

status	attribute	feature
1	EXPON	time constant
2	HORIZ	minimum
3	-----	maximum

Table III: Flow signal

Chapter 4: Feature analysis

4.1 Introduction

The set of features, that describe all the relevant information in the signals, has been defined earlier. The features to be extracted are described in table IV [BAS87].

flow:		
	FLW_MIN	minimum flow. [Liters/min]
	FLW_MAX	maximum flow. [Liters/min]
	FLW_B_TIME	breath time by flow. [sec]
	FLW_INS_T	inspiration time by flow. [sec]
	FLW_EXP_T	expiration time by flow. [sec]
	FLW_EX_VOL	expired volume. [Liters]
	FLW_T_CONST	time constant downstroke flow [sec]
pressure:		
	PRS_MIN	minimum pressure. [cmH_2O]
	PRS_MAX	maximum pressure (PIP). [cmH_2O]
	PRS_B_TIME	breath time by pressure. [sec]
	PRS_INS_T	inspiration time by pressure [sec]
	PRS_EXP_T	expiration time by pressure [sec]
	PRS_SLOPE	up slope pressure. [cmH_2O/sec]
	PRS_T_CONST	time constant downstr press [sec]
CO_2:		
	CO2_INS	inspired CO_2 pressure level [mmHg]
	CO2_EXP	expired CO_2 pressure level. [mmHg]
	CO2_B_TIME	breath time by CO_2. [sec]
	CO2_DO_TIME	'inspiration time' by CO_2. [sec]
	CO2_EXP_T	expiration time by CO_2. [sec]
	CO2_UP_STR	CO_2 up stroke. [mmHg/sec]
	CO2_DO_STR	CO_2 down stroke. [mmHg/sec]

Table IV: Extracted features

From the values of the features in this set, conclusions have to be reached about the integrity of the breathing system. An expert system (see chapter 5) will be used in the diagnosis of the breathing system. Such a system uses symbolic input, often with names like 'normal' and 'abnormal', where 'normal' is not a numerical value, but a logical one; it indicates that some feature is within some range operationally defined to include all 'normal' values. In this application, the following three statuses were sufficient to describe the necessary features:

UC Unchanged

The feature value is within a band around a normal value*.

UP Up

The feature value is higher than the upper threshold.

DN Down

The feature value is lower than the lower threshold.

The thresholds were defined as 20% higher and 20% lower than the normal value or 'baseline'. This gives a 40% 'normality band'. This relative value (the band width is expressed as a percentage) gives problems if 'normal' is close to zero. Therefore a band width of 2 (-1 to +1) was taken if the feature's value was smaller than 5. This is useful for the CO_2 and flow signals, because their minimum is zero.

The values used here are arbitrary values. More research needs to be done about how to derive 'baselines' and how to set the detection bands, in order to get optimum detection. This research is planned for the future.

4.2 Normal curves versus malfunctions

In order to know how the signals (or rather the features) behave in the case of a malfunction, we measured the three signals with the set of malfunctions of 2.2, generated by the anesthesia simulator (a modified anesthesia system that can introduce a number of malfunctions [GOO87]).

The data from these measurements were analyzed, and the features were extracted with the techniques described in chapter 3. The feature values were plotted in graphs in order to compare the time course of the values, that result from any single malfunction, with the normal values.

---

*Normal value is the value of a feature when there are no malfunctions or disturbances. A feature value that didn't change over a certain period of time can be called a normal value, since the anesthesiologist didn't find it necessary to change something.

The absolute changes of all features during a malfunction was obtained and listed. For a list of the used abbreviations and units, see table IV. The format of these tables is:

signal FEATURE normal value -› malfunction value

BS_CO2_ABSORBER: 'there is an exhausted CO2 absorber'

flow:	normal*			
pressure:	normal			
CO_2:	CO2_INS_P	0	-› 5	
	CO2_DO_STR	118	-› 111	

INCOMP_INS_VALVE: 'there is an incompetent inspiratory valve'

flow:	FLW_EX_VOL	36	-› 15	
	FLW_MAX	32	-› 16	
pressure:	normal			
CO_2:	CO2_INS_P	0	-› 5	
	CO2_EXP_P	48	-› 60	(slow response)**
	CO2_DO_STR	118	-› 20	
	CO2_UP_STR	100	-› 120	(slow response)

INCOMP_EXP_VALVE: 'there is an incompetent expiratory valve'

flow:	FLW_EXP_VOL	36	-› 20	
	FLW_MIN	0	-› -11	
pressure:	normal			
CO_2:	CO2_INS_P	0	-› 18	
	CO2_EXP_P	50	-› 60	(very slow response)
	CO2_DO_STR	118	-› 90	
	CO2_UP_STR	100	-› 70	

OBST_ET_TUBE: 'there is an obstruction in the endotracheal tube'

flow:	FLW_EX_VOL	36	-› 33	
	FLW_T_CONST	1	-› 2.5	
	FLW_MAX	32	-› 15	
pressure:	PRS_MAX	13	-› 28	
	PRS_SLOPE	6	-› 13	
	PRS_T_CONST	1	-› 3	(noisy)
CO_2:	CO2_UP_STR	100	-› 65	

OBST_INSP_HOSE: 'there is an obstruction in the inspiratory hose'

flow:	FLW_EX_VOL	36	-› 33	
pressure:	PRS_MAX	13	-› 29	

---

*normal means that all the features of this signal are normal.

**It takes a few breaths to reach this value.

	PRS_SLOPE	6	-› 13
CO_2:	normal		

OBST_EXP_HOSE: 'there is an obstruction in the expiratory hose'

flow:	FLW_T_CONST	1	-› 2.5
	FLW_MAX	32	-› 15
pressure:	PRS_T_CONST	1	-› 1.7
CO_2:	normal		

DISC_Y_PIECE: 'there is a disconnect at the Y-piece'

flow:	FLW_EX_VOL	36	-› 7
	FLW_MAX	32	-› 20
pressure:	signal flat*		
CO_2	signal flat		

DISC_INSP_HOSE: 'there is a disconnect of the inspiratory hose'

flow:	FLW_EX_VOL	36	-› 8
	FLW_MAX	32	-› 20
pressure:	signal flat		
CO_2	signal flat		

DISC_EXP_HOSE: 'there is a disconnect of the expiratory hose'

flow:	FLW_EX_VOL	36	-› 7
	FLW_MAX	32	-› 20
pressure:	signal flat		
CO_2:	signal flat		

DISC_FGF: 'there is a disconnect of the Fresh Gas Flow'

flow:	FLW_EX_VOL	36	-› 20
	FLW_MAX	32	-› 22
pressure:	PRS_MAX	13	-› 4
	PRS_T_CONST	1	-› 0.5
CO_2:	CO2_DO_STR	118	-› 180
	CO2_UP_STR	100	-› 80

DISC_VENT_HOSE: 'there is a disconnect of the ventilator hose'

flow:	signal flat
pressure:	signal flat
CO_2:	signal flat

---

*signal flat means that the signals have so little variation that no breath detection could be performed.

Leaks of three different sizes were measured. Leaks of sizes 1.5mm, 2mm and 3mm (diameter) were introduced. The format of the following result table is:

signal FEATURE normal value -› 1.5mm, 2mm, 3mm leaks

LEAK_Y_PIECE:

flow:	FLW_EX_VOL	28 -› 21, 18, 15
	FLW_MAX	38 -› 32, 28, 23
pressure:	PRS_MAX	18 -› 16, 15, 14
	PRS_SLOPE	6 -› 4.5, 4, 3
	PRS_T_CONST	0.3 -› 1, 3, 6
CO_2:	CO2_DO_STR	100 -› 30, 40, 50
	CO2_DO_TIME	1.5 -› 3.5, 4.5, 4.5

LEAK_INSP_HOSE:

flow:	FLW_EX_VOL	28 -› 21, 19, 15
	FLW_MAX	37 -› 32, 29, 25
pressure:	PRS_T_CONST	0.3 -› 2, 4, 6
	PRS_MIN	7 -› 7, 7, 6
	PRS_MAX	18 -› 16, 15, 13
CO_2:	CO2_DO_STR	100 -› 70, 70, 50

LEAK_EXP_HOSE:

flow:	FLW_EX_VOL	28 -› 21, 19, 15
	FLW_MAX	37 -› 32, 28, 25
pressure:	PRS_MAX	18 -› 16, 15, 14
	PRS_T_CONST	1.2 -› 2, 4, 6
	PRS_SLOPE	6 -› 6, 6, 3.5
CO_2:	CO2_DO_STR	100 -› 50, ≈50, 60
	CO2_DO_TIME	1.8 -› 1.8, 1.8, 4.2

LEAK_VENT_HOSE:

flow:	FLW_MAX	38 -› 33, 32, 30
	PRS_EX_VOL	28 -› 27, 22, 21
pressure:	PRS_MAX	18 -› 16, 15, 13
	PRS_SLOPE	6 -› 5, 4, 3
	PRS_T_CONST	0.3 -› 2, 4, ?
CO_2:	CO2_DO_TIME	1.5 -› 1.5, 1.5, 3.5
	CO2_DO_STR	100 -› 100, 100, 30

Examples of the graphs are given in figures 4.1 to 4.6. The feature values during a malfunction have to be compared with the values in the normal situation (right and left picture). The graphs give a good impression of the stability of the features

in the normal situation.

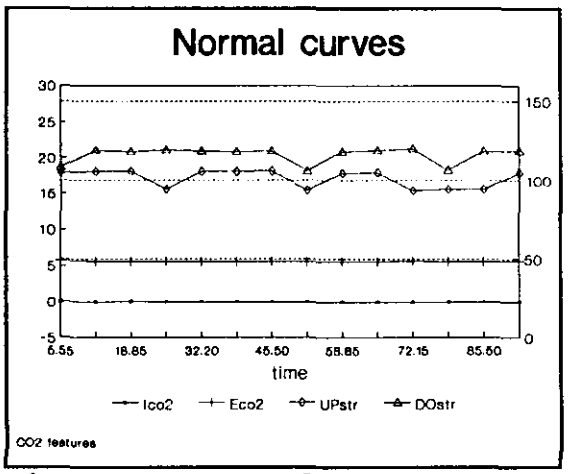

Figure 4.1: CO_2 features

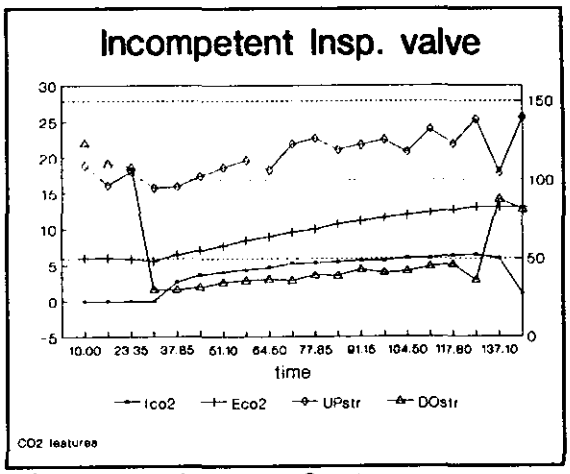

Figure 4.2: CO_2 features

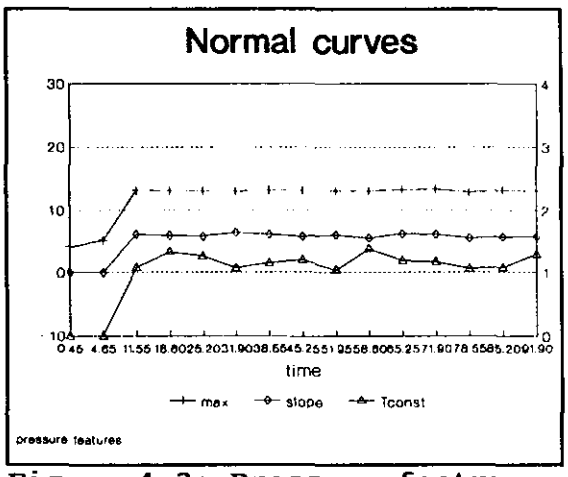

Figure 4.3: Pressure features

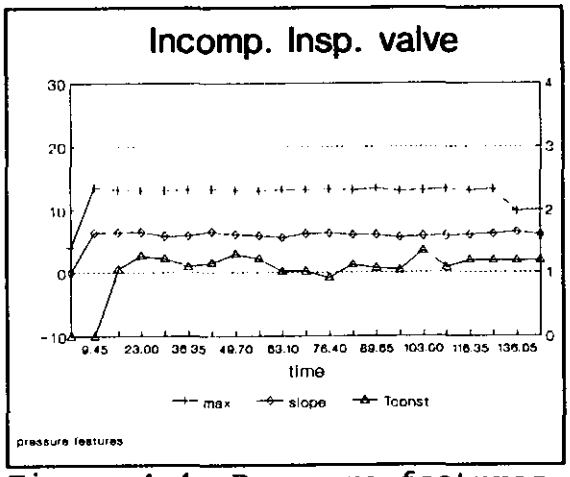

Figure 4.4: Pressure features

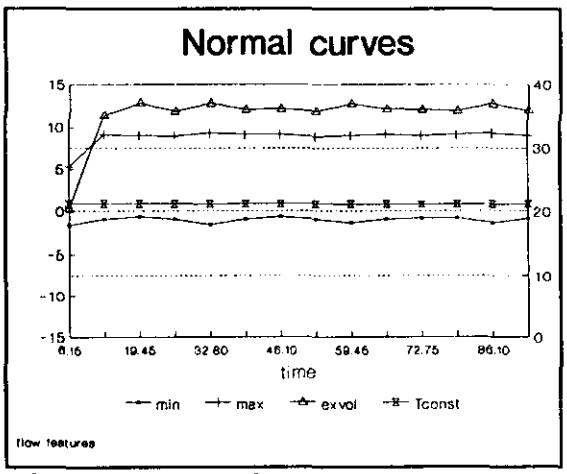

Figure 4.5: Flow features

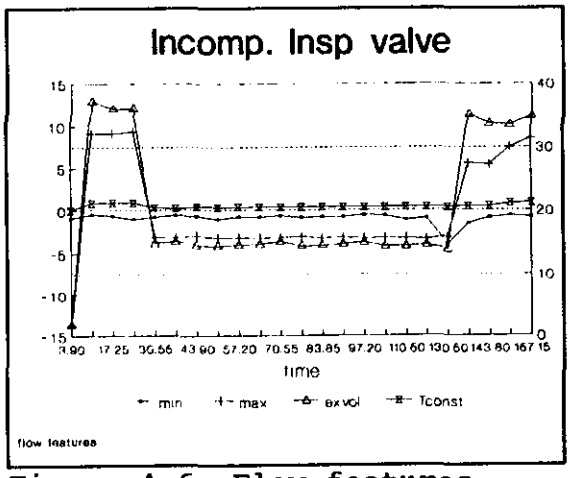

Figure 4.6: Flow features

4.3 Detection rules

From the measurements described in the previous paragraph, the attributes up, down or unchanged can be added to each feature in case of a malfunction. A description of every malfunction can be made in the form of rules, that describe the status of the feature set. The detection rules were derived from the differences between the values of the normal and the disturbed features. A straight forward translation of the observations for rule BS_CO2_ABSORBER would be:

FLOW_normal and PRESSURE_normal and CO2_INS_up and CO2_DO_STR_normal

Now, for all rules, we take the following three steps:

1. delete all features that are normal; normal is the default. In this example, this gives the following rule:

   CO2_INS_up

2. delete features that are superfluous, especially if they are unreliable or noisy. In this example, there are none of those.

3. add enough features to make the rule unique, i.e. prevent the rule from being true if other problems arise. In this example, CO2_INS_up does occur with other problems, eg. INCOMP_INS_VALVE and INCOMP_EXP_VALVE (see the list above). This step is the most difficult; it requires a thorough (expert level) understanding of the problem. This step may reintroduce features that are normal or features that are not up or not down. In the example, the following rule is obtained:

   CO2_INS_up and FLW_EX_VOL_unchanged and not FLW_MIN_down

After these steps, no two rules should be equivalent, nor should any rule be subsumed under another rule (a SIMPLEXYS knowledge acquisition tool to automatically perform these tests is under

development).

The list of all rules is as follows:

BS_CO2_ABSORBER:
CO2_INS_up and FLW_EX_VOL_unchanged and not FLW_MIN_down

The rule uses inspired CO_2 because the CO_2 is not scrubbed out by the CO_2 absorber. The flow and pressure signals are normal.

INCOMP_INS_VALVE:
FLW_EX_VOL_down and FLW_MAX_down and CO2_DO_STR_down
and not FLW_MIN_down

Expired flow and maximum flow are down because in this case expiration takes place through both the expiratory hose and the inspiratory hose. The CO_2 downstroke is prolonged, because during the first part of the inspiration the gas, that is already in the inspiratory hose, passes the CO_2 monitor. This gas contains CO_2, because it is the previous exhaled gas. There is no reverse flow in the expiratory hose.

INCOMP_EXP_VALVE:
FLW_MIN_down

There is reverse flow through the expiratory hose, because inspiration takes place through the inspiratory and expiratory hose.

OBST_INSP_HOSE:
PRS_MAX_up and PRS_SLOPE_up

The slope of the pressure is up, because the resistance of the inspiratory circuit has changed. The pressure maximum is up, because there is a pressure build-up caused by an increased airway pressure.

OBST_EXP_HOSE:
FLW_T_CONST_up and PRS_T_CONST_up

The time constants of flow and pressure are up, because the resistance of the expiratory circuit has changed.

OBST_ET_TUBE:
OBST_INSP_HOSE and OBST_EXP_HOSE

According to the feature changes, it appears that there is an obstruction both in the inspiratory hose and the expiratory hose.

DISC_Y_PIECE:
DISC_PATIENT_HOSE

DISC_EXP_HOSE:
DISC_PATIENT_HOSE

DISC_INS_HOSE:
DISC_PATIENT_HOSE

DISC_PATIENT_HOSE:
FLW_EX_VOL_down and FLW_MAX_down and PRS_flat and CO2_flat

There is no breath detection on the pressure and CO_2 signals. The expiratory flow is down. When the inspiratory hose is disconnected, flow will only be detected if the disconnect occurs at the absorber side of the sensor.

DISC_FGF:
FLW_EX_VOL_down and FLW_MAX_down and PRS_MAX_down and PRS_T_CONST_down

Less gas, and at a lower pressure, will flow into the system if the fresh gas hose is disconnected.

DISC_VENT_HOSE:
GENERAL_FAILURE

There is no breath detection at all, because the driving force failed. There is no gas flow in the system.

GENERAL_FAILURE:
CO2_flat and FLW_flat and PRS_flat

The leak rules are currently under development. Proposed rules are given below:

LEAK_PATTERN:
FLW_EX_VOL_down and FLW_MAX_down and PRS_MAX_down and PRS_T_CONST_up and CO2_DO_STR_down

LEAK_Y_PIECE:
LEAK_PATTERN and CO2_DO_TIME_up and PRS_SLOPE_down

LEAK_INS_HOSE:
LEAK_PATTERN and PRS_MIN_down

LEAK_EXP_HOSE: { == LEAK_Y_PIECE }
LEAK_PATTERN and PRS_SLOPE_down and CO2_DO_TIME_up

LEAK_VENT_HOSE: { == LEAK_Y_PIECE }
LEAK_PATTERN and PRS_SLOPE_down and CO2_DO_TIME_up

Chapter 5: An introduction in expert systems

5.1 What is an expert system?

Ever since the invention of the computer, man tried to let computers think like humans. Computers are mainly used to do straight forward things, which usually contain a lot of repetition. This is mostly non-intelligent work. In order to let a computer solve problems like humans do, that computer program has to be intelligent. One approach to make a program intelligent is to provide it with lots of high-quality, specific knowledge about some problem area. These programs are called expert systems.

The biggest problem with building an expert system is to define what knowledge should be used, how to obtain the knowledge and how to implement it. Figure 5.1 shows the participants in building an expert system and their relations.

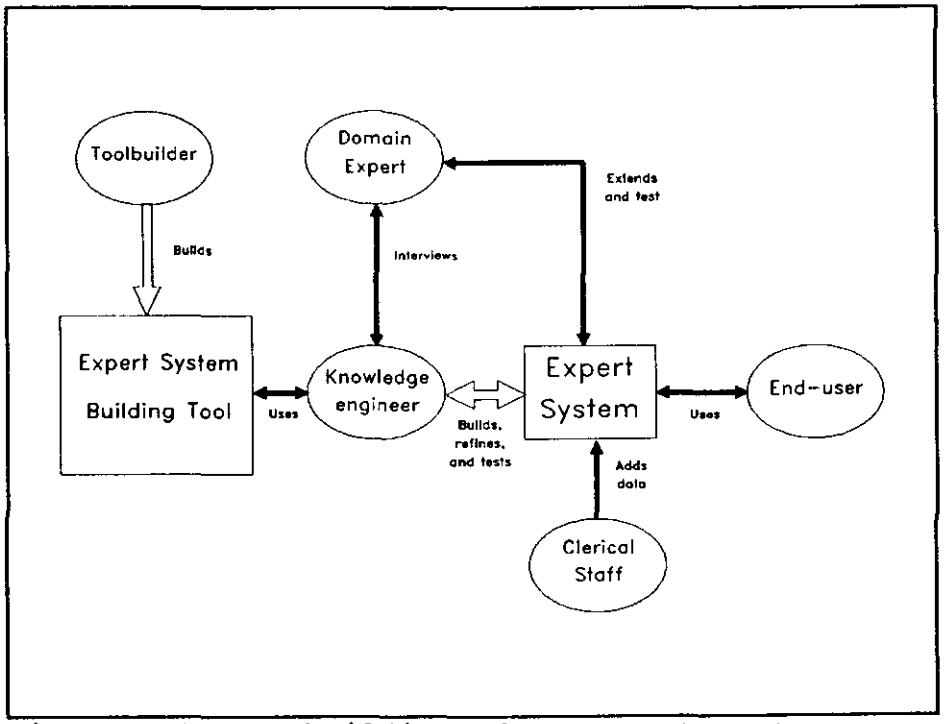

Figure 5.1: The building of an expert system
From Waterman p.8 [WAT86]

The domain expert is the person who has the knowledge about the particular problem area. The knowledge engineer is the person who collects the knowledge and implements it in the expert system. The knowledge can be acquired by interviewing the domain

expert. An expert system building tool is used to implement the knowledge into a computer program. The path to follow when building an expert system is straight forward. Problems arise when interviewing the domain expert to extract his knowledge. The expert often cannot define his knowledge in a precise, unambiguous way. Another problem arises when the knowledge has to be represented in a computer program. There are hardly any general purpose expert system building tools available for general purpose, and usually a new tool is designed for every application.

An expert system consists of two major parts: the knowledge base and the inference engine [WAT86].

5.1.1 Knowledge base

Most expert systems are rule based. That means that the knowledge is contained in rules like "if an animal has a long neck and eats leafs then it is a giraffe". Advantage of this method is that rules are easy to read and easily understood.

Another method of implementing knowledge is a semantic net. States and relations between the states are described. In a semantic net it is well described how some part of the knowledge influences another part of the knowledge. With semantic nets searching is optimized and checks on correctness are easier to perform.

5.1.2 Inference engine

The inference engine manipulates the knowledge so that a solution of the problem can be reached. Some expert system building tools have a complete inference engine built in, with other tools the inference process is defined by the way the knowledge is implemented (eg. how the rules are defined).

5.2 SIMPLEXYS: an expert system building tool

There are many expert system building tools on the market, but none of them is capable of reaching a solution in a short time. Speed was usually not a primary design issue. In our application,

a conclusion about the integrity of the breathing circuit has to be reached every breath (eg. every 6 seconds). An expert system that could run in a real time environment was desired.

At the Eindhoven University of Technology, an expert system building tool named SIMPLEXYS (SIMPLe EXpert sYStem) was designed by J.A. Blom of the Division of Medical Electrical Engineering. A first version of SIMPLEXYS was available for our development.

SIMPLEXYS is an expert system building tool based on a semantic network, although the nodes of the network are defined by rules. The semantic network consists of a collection of nodes (rules) and relations (relations, that specify how a rule uses other rules). A rule is either a primitive that represents an atomic concept (therefore no other rules are needed in its evaluation), or it is a composite: a higher level concept, some type of combination of other rules. The rules that represent the conclusions to be evaluated are called goal rules or simply the goals.

Conclusions (goal rules) are evaluated by evaluating their constituent rules, if any, recursively, until the recursion ends when finally the primitive rules are reached. This type of evaluation is called backward chaining [BLO88].

5.2.1 The SIMPLEXYS rule compiler

The SIMPLEXYS expert system language is written in Pascal (a C version is forthcoming) and the rules are compiled to Pascal code by the SIMPLEXYS rule compiler. Pascal procedures and variables can be defined, for example to perform some action when a rule becomes true (display a message, control a process etc.). These procedures and variables are contained in the Pascal code file with the compiled rules. This code file can be compiled with a Pascal compiler, resulting in a fast and efficient program.

5.2.2 A SIMPLEXYS program

A definition of the syntax of the SIMPLEXYS expert systems language is beyond the scope of this thesis, but a few concepts will be shown in the following small example program:

```
00      DECLS
01      type up_do_uc_nv = (UP, DN, UC, NV);
02      var flw_min : uc_do_uc_nv;
03
04      procedure message( mess_text : string );
05      begin
06        writeln( mess_text );
07      end;
08
09      INITG
10      {put all the global initialization code here}
11      {executed only once}
12
13      INITR
14      {put all the run initialization code here}
15      {executed every run}
16
17      RULES
18      exit: 'exit the expert system program'
19      BTEST keypressed
20
21      running: 'The breathing circuit expert system is running'
22      STATE
23      INITIALLY TR
24      THEN GOAL: INCOMP_EXP_VALVE
25
26      INCOMP_EXP_VALVE:'There is an incompetent expiratory
        valve'
27      (FLW_MIN_DOWN)
28      THEN DO message('Incompetent expiratory valve');
29
30      FLW_MIN_DOWN: 'There is reverse flow'
31      BTEST (flw_min = DN)
32
33      PROCESS
34      ON exit FROM running TO *
```

line 00: The code in the DECLS part is Pascal code with the procedures and Pascal variables definition.

line 09: The Pascal code in the INITG part is executed only when the expert system program is started up. For example if a serial port has to be initialized.

line 13: The Pascal code in the INITR part is executed when a new run of the expert system is started.

line 17: The RULES part contains the SIMPLEXYS rules with the knowledge. If the exit rule becomes true (if a key is hit), the program stops looping. In the running rule the goal of the expert system is defined. The inference engine will try to evaluate the goal rule.

line 19: BTEST is a boolean test which returns the evaluation of the following test.

line 22: A STATE rule defines which goals are to be evaluated if that STATE rule's value is true. Here the only goal is INCOMP_EXP_VALVE.

line 23: Rules can have one of four values: True(TR), False(FA), Possible(PO) and Undefined(UD). Initially all the rules are UD. When a rule is evaluated it becomes TR, FA or PO. If PO is the result of an evaluation, neither TR nor FA could be assigned to the rule. In that case, an alternative path of evaluation could possibly be followed to reach a conclusion. With the INITIALLY keyword a rule can be assigned a initial value other than UD.

line 27: In this example, rule INCOMP_EXP_VALVE needs only the evaluation of rule FLW_MIN_DOWN.

line 27: THEN DO is used if an action has to be performed when the rule evaluates to true.

line 33: The PROCESS section describes the dynamics of the rule evaluation process: when to evaluate which rules.

line 34 The expert system program continuously loops until the exit rule becomes true.

5.3 Implementation in SIMPLEXYS

SIMPLEXYS proved to be a useful tool for the implementation of our intelligent alarms system. It provides both a fast expert system and an easy interface with a powerful language like Pascal. A language like Pascal is needed because interfacing routines which interface with other parts of the system have to be written.

Chapter 6: Program considerations

6.1 Introduction

Our intelligent alarms system can be divided into the following three functional parts, each of which has been described in previous chapters.

- Signal analysis (chapter 3)
- Feature analysis (chapter 4)
- Rule evaluation (chapter 5)

In this chapter we describe how these parts work together. The problems encountered during the implementation and their solutions are described.

6.1.1 Signal analysis

We assume that the data is sampled with a frequency of 20 Hz. These samples are the input for the signal analysis routines. The signal analysis consists of the following parts (see chapter 3):

- phase detection
  determines in which phase (segment) a signal is
- feature update
  updates the current feature calculation

Every sample has to be processed in order to determine in which phase a signal is, and if the phase has changed. Once the phase has been determined, it is known from a-priori knowledge which calculations have to be performed. For every sample the feature currently calculated has to be updated.

The signal analysis part is a loop that is executed for each sample, i.e. 20 times per second. This loop consists of procedures for sample retrieval, with timing provided by an A/D converter (the program waits until a new sample is available),

phase detection (and therefore breath detection) and feature calculation.

6.1.2 Feature analysis

After the signal analysis has been performed and a complete breath was detected, the features are available for the features analysis part (see chapter 4). The detection of a breath is not straight forward. Three signals are now analyzed; because the sensors are not in the same place, and because there is some delay between the physical input to the sensor and the electrical signal output from the sensor (especially the CO_2 monitor), the completion of a breath will be detected at a different time for each signal. We choose to solve this problem by waiting until in all signals a full breath is detected; a breath detected flag will then be set. If one signal did not detect a breath within a certain time (eg. 10 seconds), all the features of that signal will be set to not valid (NV) and the breath detected flag will be set. The advantage of this method is that the information that is available will be analyzed, even if some other information is missing. The feature analysis is on a breath to breath basis.

6.1.3 Rule evaluation

The rule evaluation part (written in the SIMPLEXYS expert systems language, see chapter 5) takes the symbolic information from the feature analysis part, evaluates the rules and displays the result of the evaluation (alarm messages).

The rule evaluation is also performed on a breath to breath basis.

If all three parts have to be incorporated into the same program, the problem is that one part has to run 20 times per second, and two other parts have to run every breath (eg. approximately every 6 seconds). Either the feature analysis with the rule evaluation has to run in 1/20 second or there has to be a multi-tasking operating system where several tasks can run at the same time.

The computing power and memory of an IBM-AT or compatible is sufficient for this task. However, the operating system mostly

used for these machines (MS-DOS) is a single tasking operating system. There are several multi-tasking operating systems for the IBM-AT (eg. XENIX, a sort of UNIX or MS-WINDOWS, a graphical multi-tasking environment), but these programs tend to demand a lot of memory and/or a special compiler. There is a multi-tasking shell on the market, that does not have these drawbacks, and that accommodates our needs: MultiDos-Plus by Nanosoft Associates (Natick, MA).

6.2 MultiDos-Plus

MultiDos-Plus is a multi-tasking extension to MS-DOS. It allows the users to load multiple programs in their computer and have them run concurrently.

At start-up, the MultiDos-Plus program will replace the interrupt driven system services for screen and keyboard I/O, disk access and DOS functions with its own routines. MultiDos-Plus assigns CPU time slices to the various programs. Programs with higher priority receive more time slices than programs with lower priority. The time slice interval is based on the timer interrupt in the computer and is about 55 milliseconds in the IBM-AT. Programs which cannot execute for any reason (waiting for keyboard input, waiting for disk access etc.) are not assigned time slices.

A program that runs under MultiDos-Plus can be in one of two states: foreground or background. Only one program at a time can be in the foreground. If a program is in the background, screen I/O is written to an invisible screen. There are commands to put a program in the background or foreground.

MultiDos-Plus provides message queues, which can be read by any task, to make communication (data) or task control possible (eg. timing by signal and wait) [MUL86].

6.3 Intertask communications

In our system three tasks have to run at the same time:

- Task 1: Analyze (signal analysis)

- Task 2: Features (feature analysis)
- Task 3: BS-expert (expert system)

Communication between the tasks is necessary, because data has to flow from task 1 to task 2 and from task 2 to task 3. It is also necessary for one task to be able to control the other tasks. Therefor a control queue for every task was defined; each task monitors its control queue and the other tasks can put control characters in it. Five message queues were defined:

DATA	QUEUE NUMBER
task 1 -> task 2	5
task 2 -> task 3	6
CONTROL	
task 1	1
task 2	2
task 3	3

A set of control characters, that is recognized by all the tasks, was defined for the control queue:

A	Abort task
S	Suspend task
R	Reset baselines
N	New log file

6.3.1 Information block

An information block was defined to hold all the information available about the system. The information block contains the latest information on a breath to breath basis. For every signal it contains some information like the name of the signal, whether the monitor was calibrated or not, etc. It also contains the features that describe the signal with information like name, value, unit etc. The information block is defined as follows:

INFORMATION BLOCK

```
SIGNAL1
 name                          (signal name)
 available(Y/N)                (monitor present and working?)*
 calibrated(Y/N/ONGOING)       (monitor calibrated)*
 cal.time                      (time when last calibrated)*
   FEATURE1
    name                       (feature name)
    unit                       (unit of feature)
    value                      (value of feature)
    valid(Y/N)                 (value valid or not?)
    accepted(Y/N)              (valid accepted or not?)**
    stat(UP/DN/UC)             (static status)
    dyn(UP/DN/UC)              (dynamic status)**
    PhysLowLimit               (lower physical limit)**
    PhysHighLimit              (upper physical limit)**
   FEATURE2....
   FEATURE3....
SIGNAL2....
  FEATURE1....
  FEATURE2....
```

The information block is filled by several tasks. Every time more information becomes available, the block is updated. Every task can extract information from the information block. The expert system for example can use the feature names to give feedback to the anesthesiologist. Currently only the static status is used by the expert system, but expansion of the part of the information that is used is expected.

6.4 Implementation

An implementation of the described techniques resulted in a demonstration prototype. In this prototype the data is read out of a data file. Message queue 4 is used by task 3 to signal task 1 that the run of the expert system is ready, and that new

---

*This information is currently not available from the monitors.

**Currently not used (reserved for future use)

features can be sent. This was necessary because the file read routine does not have any timing in it, and the features would be overflowing the data message queue if no signal and wait were performed.

The programs for the three tasks were written, and the communication between the tasks was made. Only the SIMPLEXYS expert system is in the foreground during normal execution. The expert system program also provides some control functions to control the other tasks. The keyboard is monitored by the program and the other tasks can be suspended, aborted etc. A simple user interface is made existing of a line with available comments at the top of the screen, a line at the bottom of the screen where messages can appear like "suspending", "aborting" etc. The center of the screen is used to print the messages resulting from the evaluation by the expert system.

For demonstration purpose it was desired that the data could be shown on a screen. Since MultiDos-Plus only supports the low resolution CGA graphics of an IBM AT(PC), a second PC was used to display the curves on a high resolution EGA screen. A serial communications routine for the two machines was written. The samples (one for every signal) are sent to the serial port when they are read out of the file. The other PC runs an interrupt based receive program that interrupts when a byte is received at the serial port. The interrupt service routine gets the byte from the port and puts it into a ring buffer. With this method no byte will ever be lost (provided there is no noise on the line). If three floating point values (12 bytes using the Microsoft C compiler) are received, the three samples are displayed.

6.4.1 Flow measurement

Ohmeda provided three monitors to measure the necessary signals in the breathing circuit: the Ohmeda 5200 CO_2 monitor, the Ohmeda 5500 airway pressure monitor and the Ohmeda 5410 volume monitor. The CO_2 and the pressure monitors have an analog output at the back. These signals are easy to sample with an A/D converter board in the PC. The volume monitor does not provide an analog flow signal; instead it provides a pulse every time 3 ml gas has passed through the sensor. A signal that can be either high or low determines the direction of the flow. A routine that counts

the pulses was written. An interrupt is generated for every pulse and the interrupt service routine counts the pulses and determines the flow direction. Appendix C describes this routine.

Chapter 7: Conclusions an Recommendations

7.1 Conclusions

It was possible to build a working prototype of the intelligent alarms expert system on an IBM-AT in the multitasking environment of MultiDos-Plus. Tests were performed on a second data set that was obtained from the anesthesia simulator; this is another data set than the development set. The system was twice as fast compared to a run in real time. The following malfunctions could be identified:

- Incompetent inspiratory valve
- Incompetent expiratory valve
- Exhausted CO_2 absorber
- Obstruction at the Y-piece
- Obstruction in the inspiratory hose
- Obstruction in the expiratory hose

It is expected that leaks and disconnects can also be detected, but it will be difficult to distinguish between all the leaks and disconnects. New rules for the leaks and disconnects are currently under development.

Apart from some unexplainable crashes during startup, MultiDos-Plus is good way to do multitasking under the single task operating system MS-DOS.

7.2 Recommendations

1. The rules for the disconnect and the leaks have to be implemented. Extensive tests of the intelligent alarms system have to be performed with both simulator data and real patient data. Although it is not possible to introduce malfunctions while ventilating a real patient it is important to test the system in a normal situation to see how it behaves in the real, violent environment of the operating room.

2. The use of the information block has to be reconsidered; it causes some overhead when it is sent from one task to another and at this moment hardly any information of the block is used. It is a good way to present the information, but if the information expanses, it may slow down the system.

3. Implementation of more sensors (second flow device, ventilator settings) can provide a more accurate detection of malfunctions.

4. The way the time constants of the flow and pressure are calculated has to be reconsidered. They do not provide a very stable calculation of the time constants.

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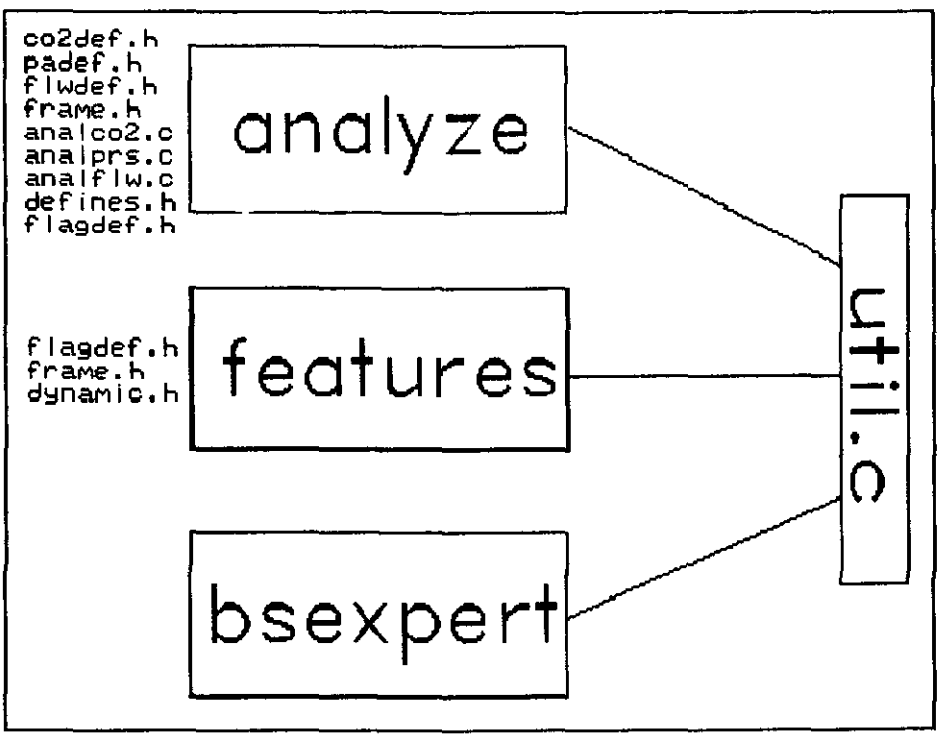
APPENDIX A: Programming tools

The data analysis program and the feature extraction program are written in C and compiled with the Microsoft C compiler version 4.0 (at this moment a change to version 5.1 is made). The expert system is written in SIMPLEXYS and compiled by the SIMPLEXYS rule compiler and the Turbo Pascal compiler version 4.0.

For the C programs some utility routines, to be used in both programs, were written. The source code is contained in "util.c".

The data analysis routines are contained in "anal.c"; several include files are needed for this (see fig. A.1). "anal.c" and "util.c" were compiled and Microsofts library utility was used to put both object files in "alarms.lib". The data analysis ("analyze.c") and the feature extraction ("features.c") have to be linked with this library.



error

* Summary

```
int error( str );
char *str;                  pointer to error string to print
```

* Description

The funtion error() prints the error string on the screen, prints a dos error string if possible, and aborts the program that calls the function.

* Return Value

No return value.

* See Also

* Example

```
/* exit on error */

char filename[80];
FILE *data;

if ( ( data = fopen( filename, "w" ) ) == NULL )
  error( filename );

/* the program is aborted if the file cannot be opened */
```

*** Summary**

```
int get_features( address, len, queue )
int address;                    address of message
int len;                        number of bytes in message
int queue;                  queue number (1-31)
```

*** Description**

The function get_features() gets 'len' bytes for the message queue 'queue'. The bytes are stored consecutive, starting at 'address', so complex structures can also be send. This function is designed for the small model of the compiler. That means that all data is in one segment, and that the addresses only consist of the offset. An address is a pointer to a variable.
If there is no message in the queue, the function starts waiting until one arrives.

*** Return Value**

There is no return value.

*** See Also**

send_features, send_control, get_control, multi_dos_test

*** Example**

```
/* get a message out of queue 5 */

struct SIGNAL signal_frame[3];  /* defined in "frame.h" */

get_features( signal_frame, 3*sizeof( struct SIGNAL ), 5 );
```

*** Summary**

```
int get_time( t );
char *t;                          pointer to time array;
```

*** Description**

This function gets the date and time as a string, and stores it in array 't'. The array will contain 26 characters, and has the form:

```
  Tue Jul 26 15:05:11 1988\0\0
```

*** Return Value**

There is no return value.

*** See Also**

*** Example**

```
/* get the time and date */

char current_time[26];          /* string lenght will always be 26
*/

get_time( current_time );

printf( "%s\n", current_time );
```

*** Summary**

```
int init_flag( flg );
int flg;                          16 bits to be zeroed
```

*** Description**

The function init_flag() sets a 16 bits variable to zero. This can be used for the 16 bits flag structures.

*** Return Value**

No return value

*** See Also**

printf_bin

*** Example**

```
/* initialize flag structure */

struct CO2_FLAG flag;       /* defined in co2def.h */

init_flag( flag );
```

*** Summary**

```
int multi_dos_test();
```

*** Description**

The function multi_dos_test, tests whether the program is started up from DOS or MULTI-DOS. If the program was started from DOS the function prints an error message, and aborts.

*** Return Value**

No return value

*** See Also**

send_features, get_features, get_control, send_control

*** Example**

```
/* test for multi-dos */

multi_dos_test();

test_queue( queue );        /* never done if no multi-dos */
```

*** Summary**

```
int printf_bin( flg );
int flag;                          16 bits to be printed
```

*** Description**

The function printf_bin() prints a 16 bit variable as 0's and 1's. No return is added. This can be used to print a 16 bit flag structure.

*** Return Value**

No return value

*** See Also**

init_flag

*** Example**

```
/* print a flag */

struct CO2_FLAG flag;       /* defined in co2def.h */

flag.bc = 1;
flag.to = 0;
printf_bin( flag );
printf("\n");
```

*** Summary**

```
int send_control( queue, c );
int queue;                  queue to send to
char c;                          character to send

char get_control( queue );
int queue;                  queue to receive from
```

*** Description**

The functions send_control() and get_control() send or get one character to or from the specified queue 'queue'. These functions are built from send_features() and get_features(). Get_control() waits for a message if no message is available.

*** Return Value**

Function get_control() returns the character from the queue. Function send_control() has no return value.

*** See Also**

send_features, get_features, test_queue, multi_dos_test

*** Example**

```
/* send a character to queue 1 and get it out of there */

char control;

send_control( 1, "A" );

control = get_control( 1 );

if ( control=='A' ) exit( 1 );
```

*** Summary**

```
int send_features( address, len, queue );
int address;                          address of message
int len;                              number bytes in message
int queue;                          queue number (1-31)
```

*** Description**

The function send_features() sends 'len' bytes to the specified message queue, starting from 'address'. Complex structures can also be send, as long as the data of these structures are continuous in the memory. This function is designed for the small model of the compiler. That means that all data is in one segment, and that the addresses only consist of the offset. An address is a pointer to a variable.

*** Return Value**

There is no return value.

*** See Also**

get_features, get_control, send_control, multi_dos_test.

*** Example**

```
/* send features to queue 5 */

struct SIGNAL signal_frame[3];  /* defined in "frame.h" */

send_features( signal_frame, 3*sizeof( struct SIGNAL ), 5 );
```

*** Summary**

```
int suspend( nr );
int nr;                          task number
```

*** Description**

The function suspend() stops the program and waits for the character 'G' in its queue; In this case the task number is the queue number.

*** Return Value**

There is no return value.

*** See Also**

get_control, send_control

*** Example**

```
/* suspend the program */

control = get_control( 5 );

if ( control=='S' ) suspend( 1 );
```

*** Summary**

```
int test_queue( queue );
int queue;                    message queue number
```

*** Description**

The function test_queue() tests if there is a message in the specified queue. This can be used if the program wants to do some other task while waiting for a message (test the keyboard for a key for example).

*** Return Value**

Test_queue() returns 0 if no message is avaiable and returns 1 if there is a message in the queue.

*** See Also**

send_features, get_features, send_control, get_control, multi_dos_test

*** Example**

```
/* get a message from queue 1 */
/* display keystrokes while waiting */

while ( !test_queue( 1 ) )
{
  if ( kbhit() ) printf("%c", getch() );
}

control = get_control( 1 );
```

APPENDIX C: OMHEDA 5410 VOLUME MONITOR

This paper describes how an Ohmeda 5410 Volume Monitor can be interfaced with a IBM AT(XT), in order to get the flow, using the standard serial port (RS-232).

Signals

According to the 5410 Service Manual (page 36), the 5410 provides an Expired Flow signal at pin 3 of connector J2. The direction of the signal is given on pin 4 (high is reverse flow). Jumpers PJ3 and PJ4 have to be jumpered for transducer signals.
The signal on pin 3 will give a pulse for approximately every 3 milliliters of gas flow through the transducer.

Counting pulses

The only thing that has to be done is to count the pulses in one period of time (e.g. 1 second). The current flow can then be calculated by: flow := counter*3/delta. 'Counter' is the number of pulses received in period 'delta' (e.g 1 second). The numeric value of the flow derived by this formula will be the average flow over the period 'delta'.

RS-232 IBM AT(XT) interrupts

Because the flow pulses will come at an irregular time interval, the best way to count them is a method based on interrupts. The IBM machines provide two hardware interrupt channels for communications (one for COM1, one for COM2).
Four classes of these hardware interrupts are possible:

00	change in modem status register
01	transmitter holding register empty
10	data received
11	reception error or break condition received

We choose to use the interrupt when data is received. Any of the other interrupts could also be used. If this interrupt is enabled it gives a hardware interrupt when pin RD (3 on DB25, 2 on DB9) goes from low to high. Interrupt 0B is given if COM2 is used, 0C if COM1 is used. The following part of C code should be used to initialize the registers of the serial port (COM1).

```
outp( 0x3fb, 0 );          /* clear line control register */
outp( 0x3fc, 0x0B );       /* set RTS, DTR, user aux input #2 */
inp( 0x3fd );              /* read line status register   */
outp( 0x3f9, 1 );          /* enable interrupt on data received*/
```

In order to use any hardware interrupt, the corresponding bit in the interrupt mask register (IMR) has to be set. For the communication interrupt of COM1 this is done by:

```
in      al, 21H   ;get the content of IMR
and     al, efH   ;set bit for COM1
out     dx, 21H   ;send byte
```

Writing an interrupt service routine

Because we use an interrupt to update our counter, we have to provide an interrupt routine that replaces the current interrupt routine. Because the Microsoft C compiler doesn't provide a way to write such a routine, it is written in assembler.
Basics of an interrupt routine:

- push the used registers on stack
- do the tasks you want to do
  DO NOT use DOS, because it is not re-entrant
- pop the registers from stack
- IRET instruction

Because we want to use a variable in our interrupt routine that is shared by our C program, we have to make sure that the data segment is set to DGROUP (the name the MSC compiler uses for its small model data segment). If an interrupt is invoked, this is not automatically done. We also have to make sure that all names that we use for segments are the same as in the assembler program. See Microsoft C manual for details.
If the interrupt is a hardware interrupt, the interrupt service routine should end with:

```
mov  al, 20H
out  20H, al
```

This will clear the 'in service register' so that interrupts at a lower level as the one just completed, are re-enabled.

When the interrupt service routine is written, the address of the beginning of the routine has to be placed in the interrupt vector table. The interrupt vector table occupies 4 bytes (segment:offset) for every interrupt, starting with interrupt 0. The begin address of the vector table is 0000:0000. The address for the interrupt service routine 0C should thus be written at (0000:0030 hexadecimal).

Implementation

The interrupt service routine written to get the flow pulses from the Ohmeda 5410 Volume Monitor replaces the current interrupt 0C routine. COM1 is used to connect the flowmeter.
The interrupt routine tests status of the pin carrier detect (CD) by reading the modem status register. If CD is low the routine increases the counter, else it decreases the counter.
If pin 3 of connector J2 is connected to data received (RD) and pin 4 is connected to carrier detect (CD), the counter represents the volume passed since the last counter reset in amounts of 3 ml. When time information is known, the flow can be calculated.

The pin connections from the Volume Monitor to a DB9 serial plug are:

5410		PC (DB9)
1 (ground)	--------›	5 (ground)
3 (PULSE)	--------›	2 (RD)
4 (EXP FLOW)	--------›	1 (CD)

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Coden: TEUEDE

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