TAMPERE UNIVERSITY OF TECHNOLOGY

ROBERTO SHAW CAMP CASTILLO

AN OIL FLOW MONITORING SYSTEM BASED ON WEB SERVICES

Master of Science Thesis

Examiner: Professor José L. M. Lastra
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ABSTRACT

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The increasing importance of condition monitoring in the manufacturing industry has prompted many new developments in the area. While some have focused on different ways of processing monitored data, few have touched the subject of the communication network components, protocols, and standards used in monitoring networks. Additionally, monitoring systems have traditionally been built on top of existing network architectures further complicating the factory floor network by introducing additional communication protocols. At the same time, Web Service based solutions have been implemented in the upper levels of the manufacturing industry, namely the corporate network.

Proposals implementing Service Oriented Architecture (SOA) based approaches that ease the communication exchange for scheduling, ERP and MES systems have been created. While the use of this technology has brought many improvements, the extent of the potential benefits that Web Services can provide have been limited by the scope to which they have been applied to. This thesis proposes a solution that brings the SOA paradigm to the lower levels by utilizing Web-Service embedded intelligent devices. It does so by analyzing the particular case of the lubrication flow monitoring systems used in the paper industry. The fact that the average paper machine requires anything between 600 and 1500 lubrication points presents a unique opportunity to implement a Web Service based system where there is a need to monitor huge amounts of sensors and flowmeters in a distributed manner.

Lastly, this thesis evaluates existing circulating oil flow monitoring architectures, and uses this analysis to propose a potential improvement that brings Web Services to the condition monitoring arena. Tests that evaluate the performance parameters of intelligent Web Service capable devices, and their results are presented. The reliability and overall behavior of the proposed system is analyzed and scrutinized.

PREFACE

This work represents more than just my efforts to complete my studies. In a sense, it represents the end of a small era in my life, a time during which I not only learned many new things, but a time which so far I have come to consider the best of my short life. As such, acknowledging everyone that took part in it, in one way or another, is a difficult task, but one that needs to be done nonetheless.

Firstly, I would like to thank Prof. José M. Lastra for taking me under his wing, both as a Research Assistant and a student. I have learned many things in the time I spent working and studying under him, and would not be where I am at the moment were it not for the opportunities he gave me, I will be forever thankful.

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Roberto Shaw Camp Castillo
Tampere, September 2010

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LIST OF ACRONYMS

ANSI	American National Standard Institute
CAD	Computer Aided Design
CAN	Controller Area Network
CDDB	Communication Description Database
CNC	Computed Numerically Controlled
COM	Component Object Model
DBMS	Database Management System
DCOM	Distributed Component Object Model
DCS	Distributed Control System
DPWS	Device Profile for Web Services
DTM	Device Type Manager
EDDL	Electronic Device Description Language
ERP	Enterprise Resource Planning
FBD	Function Block Diagram
FDT	Field Device Tool
GUI	Graphical User Interface
GUM	Guide to the estimation of Uncertainty in Measurement
HART	Highway Addressable Remote Transducer Protocol
HCF	HART Communication Foundation
HMI	Human Machine Interface
HTTP	Hypertext Transfer Protocol
IEC	International Electrotechnical Commission
IL	Instruction List
IPC	Association Connecting Electronic Industries

ISA	The Instrumentation, Systems and Automation Society
LCD	Liquid Crystal Display
LD	Ladder Diagram
MES	Manufacturing Execution System
MESA	Manufacturing Enterprise Solutions Association
ODBC	Open Database Connectivity
OPC	OLE for Process Control
PDM	Product Data Management
PLC	Programmable Logic Controller
PNO	Profibus Nutzerorganisation eV
RTU	Remote Telemetry Units
SAMIA	Service-bAsed Monitoring for Industrial Ambients
SCADA	Supervisory Control And Data Acquisition
SCM	Supply Chain Management
SFC	Sequential Function Chart
SOA	Service Oriented Architecture
SOAP	Simple Object Access Protocol
ST	Structured Text
UDDI	Universal Description Discovery and Integration
UDP	User Datagram Protocol
UI	User Interface
WSDL	Web Service Description Language
WS	Web Service
XML	Extensible Markup Language

LIST OF SYMBOLS

Q	Flow rate $[lts/min]$
A	Cross section area $[m^2]$
$\bar{v}$	Average fluid speed $[m/s]$
π	Pi
D	Diameter $[m, ft]$
Re	Reynolds number
ρ	Density $[kg/m^3]$
μ	Absolute fluid viscosity $[Ns/m^3]$
B	Bias error
$\bar{I}$	Average of taken values
I_t	True value
σ	Standard deviation
$\bar{x}$	Mean
$\sigma(\bar{x})$	Standard deviation of the mean average value
$\sigma(\bar{u})$	Standard uncertainty of mean average value
k	Coverage factor
σ_p	Precision
$t_S T$	Student's t distribution factor
n	Number of measurements
Acc	Accuracy
$\dot{m}$	Mass flow rate $[Kg/min]$
K	Flowmeter conversion factor
MFR	Maximum flow rate $[lts/min]$

1. INTRODUCTION

The objective of this chapter is to set the base context of this thesis. Section 1.1 is dedicated to the background. Based on the background Section 1.2 establishes the problem and justify the need to solve it. Section 1.3 establishes the work realized while Section 1.4 outlines the thesis.

1.1 Background

The manufacturing industry has had and continues to have many different driving forces. The increase in global competition, the fast growth of technology, environmental factors, the increasing importance of manufacturing productivity and product quality are just a few of the forces that continually move the manufacturing industry forward. While manufacturing technology can be considered to be one of the most important driving forces, there are many aspects and disciplines to consider, some of which have been historically underestimated like maintenance and condition monitoring. Until the last few decades maintenance was considered to be an economic nuisance due to the high costs breakdown maintenance presented. It is now understood, however, that by implementing predictive maintenance it is not only possible to reduce maintenance costs, but it is also possible to greatly increase production [Rao 96]. Consequently, this has led to the understanding that this can be accomplished using condition monitoring as a means to obtain important machine behavior parameters, analyze them, and predict potential breakdowns, thus preventing them. In essence, condition monitoring enables the capability to give predictive maintenance according to the needs of any given system, saving money and avoiding costly breakdown maintenance.

Among all the many different manufacturing industries, the pulp and paper industry can arguably be said to be quite complex. The creation of paper requires a series of complicated processes that entail many different considerations. In addition to all the processing required to produce paper, it is also necessary to maintain the paper machines in operation. Problems such as: bearing failures, mechanical wear, down-time, unavailability and economical losses caused by inadequate lubrication are just some of the problems that plague constant production [Day 96, Cutler 96, Holmberg 01]. Additionally, paper machines may require between 500 and 1200 lubrication points and paper mills may have up to 3798 lubrication points [Mac-Lub 10, Bloch 96]. These reasons, added to the fact that manual lubrication of some points is impossible due to the fact that they are unreachable while the machine is operation, merit the need of independent automated lubrication systems [Reynolds 98].

The rather late appreciation for the importance of maintenance and monitoring has driven many improvements in both lubrication systems and monitoring systems. Some companies offer integrated solutions, while others offer stand-alone, modular and expandable monitoring systems. Independently of the type of system however, there is a common factor that plagues these systems: *Network integrability*.

1.2 Problem Definition

The use of multiple communication networks and fieldbuses complicates horizontal and vertical integrability between lower factory level communication and the higher level corporate network. This network integrability problem is especially present in companies that implement many different types of communication protocols. Additionally, flow monitoring systems usually require the implementation of special flow computers or Programmable Logic Controllers (PLCs) which calculate flow rates [Ralston 08]. Once the calculations are done the information is then transferred to the upper local and remote monitoring stations, only then can it be possible to accomplish vertical communication integration with the corporate network. Figure 1.1 shows a typical flow monitoring system.

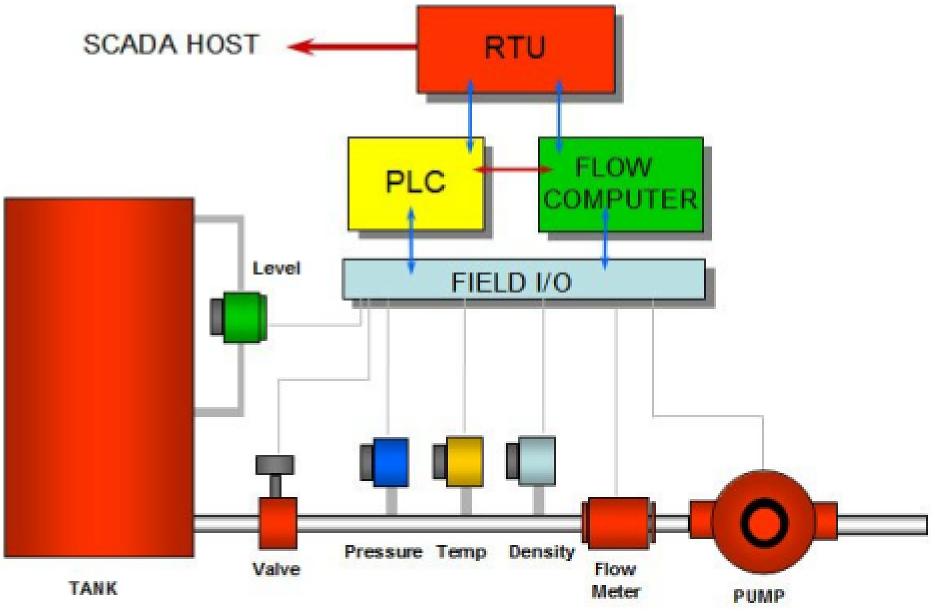


Figure 1.1: Typical flow measurement system. Adopted from [Ralston 08].

The system shown in Fig 1.1 is not the way all flow monitoring systems are implemented. It does, however, present the three main issues that complicate the integration of this type of system into the factory floor. The first problem is the fact that a separate flow computer might be needed to make the necessary calculations. And even if the PLC were enough, the fact that the same PLC controls part of the process makes it to a certain degree an invasive monitoring system, which may or may not be something that is desired. The second problem, which can be considered a direct consequence of the first problem, is the number of communication layers necessary. The first would be the sensor connection to the fieldbus which collects basic voltage and/or current data. Once this is done, the fieldbus uses its own communication protocol to communicate the obtained information to the PLC and/or the flow computer. After the information is processed by the flow computer and/or the PLC, the information is transferred via Remote Telemetry Units (RTU) to the Supervisory Control And Data Acquisition (SCADA) system of the factory. Last but not least, a third direct consequence of these problems is the centralization of the monitoring systems.

1.2.1 Justification of the Work

In the last years many different technologies have emerged and improvements in the way communication is done have been accomplished. Service Oriented Architecture (SOA), although originally created to work on high level communication, has started to infiltrate the manufacturing industry. This architecture is a paradigm that allows system integration based on Services. One way of implementing this paradigm, and the most common, is by means of Web Services (WS). Additionally, different profiles, in the form of technologies and protocols allow the adjustment of this paradigm to different types of systems, essentially allowing interoperability between different software implementations [Zeeb 07]. Among these profiles there exists the Device Profile for Web Services (DPWS). This profile implements standards such as: WS-Policy, WS-Addressing, SOAP messaging over User Datagram Protocol (UDP), WS-Discovery, WS-Transfer, WS-Eventing and WS-Security. These different profile components address most of the necessary things that enable different software interoperability between different vendors. The possibility of including this kind of communication capability in any type of industrial controller creates a whole new category of intelligent devices which can potentially remove the network integrability problem completely.

Due to the continuous need of quality, products and effective production in the manufacturing industry require the use of reliable monitoring systems that help maintain good machine operation. The SOA principles can function as a basis to design systems that exploit the advantages of the paradigm. Implementing Web Service interfaces and protocols in devices by means of the DPWS opens many doors of possibility. By including *high level* communication protocols in these devices it is now possible to change the typical communication schema between factory floor devices and upper level production management and monitoring systems. Thus, potentially changing the way manufacturing systems have been working for decades.

1.2.2 Problem Statement

As previously explained, given that there are many types of manufacturing processes, and every one of them has different sensors, communication protocols and control complexity, it is quite difficult to adapt a monitoring system to any given process. This is why the many different types of monitoring systems that have been implemented throughout the years have been tailored for the manufacturing process they are to monitor. This causes a network integrability problem at the horizontal and vertical levels, while also adding internal communication layers that must be dealt with in a specific and different way every time.

SOA and DPWS embedded devices provide the possibility of addressing these problems. Questions remain, however, as to the real capability of these devices, and their capability to integrate into the actual manufacturing industry. Not only that, but the amount of information that these devices would need to process to solve the previously presented problems should by no means be considered to be small. It is because of this that the following questions are asked:

Is it possible to completely solve the network integrability problem in flow monitoring systems by means of DPWS embedded devices and Web Services? Are DPWS embedded devices capable of pre-processing and composing flowmeter data correctly and reliably and, at the same time handle the necessary Services and Events needed to monitor lubrication flow monitoring systems?

1.3 Work Description

1.3.1 Objectives

1. Thoroughly analyze existing lubrication flow monitoring systems and define the positive and negative aspects of their design.

2. Design a communication architecture based on SOA and DPWS embedded devices that allows easy and loosely coupled integration with similar parallel systems and higher level corporate systems.

3. Determine the processing capabilities of DPWS embedded devices and how accurately they behave in lubrication flow monitoring systems.

1.3.2 Methodology

Review and analysis of the state-of-the-art on flow monitoring systems

Existing lubrication flow monitoring systems implemented in the paper machine industry are studied and reviewed. The way they approach existing monitoring system issues is thoroughly evaluated. Advantages and disadvantages of these existing architectures are concluded and used to develop a monitoring system based on SOA. Based on the conclusions of the state-of-the-art study a flow monitoring system with a SOA based architecture is proposed, constructed and tested.

Study of DPWS-capable embedded controller accurate measurement capabilities

One of the most commonly used flowmeter types in oil flow lubrication monitoring systems is tested in unison with a DPWS-capable controller. The measurement accuracy and linearity of the device is studied and evaluated. Additionally, the data processing capabilities of the device are proved.

Implementation of oil flow lubrication monitoring system based on Web Services and Events

A monitoring program and UI is implemented on the WS enabled device to observe the behavior of multiple oil flowmeters. Web Services and events that allow the remote control and monitoring of the system are configured.

Empirical study

A testbed utilized for empirical study implementing a conventional circulating oil lubrication system is used. A pump transfers oil from a lubrication oil tank to a series of positive displacement flowmeters that allow flow adjustment. These flowmeters in turn are connected to a DPWS embedded device which is processing the information provided by the flowmeters.

This system is used to test the processing and measurement accuracy capabilities of Web Service enabled devices. Additionally, local monitoring tools are created and evaluated in terms of UI, ease of use and display of relevant information. Other WS invocation and event subscription tools are used to test the remote monitoring capabilities of the systems as a whole.

1.3.3 Assumptions and Limitations

The focus of the work presented in this thesis is aimed at automatic circulating oil lubrication systems for the pulp and paper industry that require the monitoring of hundreds of lubrication points. The development presented here addresses the evaluation of Web Service capable devices as measurement and processing units. As well as the network communication architecture integrability to actual manufacturing systems.

Assumption 1: The circulating oil lubrication system used as a testbed closely resembles the real systems used in the pulp and paper industry.

Assumption 2: The DPWS embedded devices utilized in terms of memory and processing, are capable of supporting a considerable amount of flowmeters.

Assumption 3: The software tools that allow and provide remote monitoring already exist and support Web Services.

1.4 Thesis Outline

This thesis, excluding the present chapter which has served as an introduction, is organized in the following manner. Chapter 2 focuses on the technologies involved in flow monitoring systems, the current ways these systems are implemented and the technologies that are used in the proposed monitoring system. Chapter 3 elaborates on the implemented system and the tests that were done. Chapter 4 explains the results observed and obtained. Lastly, Chapter 5 elaborates on the improvements accomplished versus the existing systems and concludes with thoughts on the subject.

2. FUNDAMENTS AND COMMERCIAL APPLICATIONS REVIEW

In this chapter a review of the relevant subjects and technologies is presented. Section 2.1 concerns itself with condition monitoring, flow measurement and some of the commercial flow monitoring systems in paper machines. Section 2.2 elaborates on the different integration technologies that usually compose any given monitoring system. Lastly, a summary that joins the aspects of flow monitoring systems and integration tools is presented in Section 2.3.

2.1 Condition Monitoring, Flow Measurement and Commercial Flow Monitoring Systems

One of the most important issues in the modern manufacturing industry is maintenance; as it is necessary to maintain manufacturing machines in operation, a good maintenance program has become a very important factor in the last few decades.

While the original principal of maintenance is *breakdown maintenance*, which is applied only when a machine ceases to work, it has become more and more common to implement *preventive maintenance* [Rao 96, Beebe 04]. Among the different types of preventive maintenance there is *predictive maintenance*. Which, as implied by the name, consists on giving maintenance before any type of fault occurs without incurring in scheduled maintenance.

This leads inevitably to the concept of *condition monitoring*. In order to implement any type of predictive maintenance it is necessary to monitor the important performance parameters that relate to the correct functioning of any given manufacturing system. As such, by correctly implementing condition monitoring it is possible to measure and diagnose potential failures, thus predicting and consequently preventing possible problems. [Beebe 01] defines it more eloquently:

> *"Condition monitoring, on or off-line, is a type of maintenance inspection where an operational asset is monitored and the data obtained analyzed to detect signs of degradation, diagnose cause of faults, and predict for how long it can be safely or economically run".*

Table 2.1: Improvements caused by condition monitoring. Adopted from [Rao 96].

Case Study Example	
Capital Equipment	1 million saved over 2 years on 100K investment
Food Manufacture	Up-time from 60% to 90% deferred expenditure of 1m+
Cable Manufacture	Break-downs reduced by 52% in 12 months
Confectionery	Maintenance employment base down 20% Up-time exceeding 95% from 85%
Paper Manufacture	Inspection driven vibration monitoring, saving 180,000

There are many reasons why manufacturing industries have the need to implement condition monitoring systems. It is not only necessary due to the actual increasing global competition or the required increase in quality, reliability, health and safety [Rao 96]. There is also the fact that maintenance costs can be as high as 15% of a company's turnover [Day 96], while 15% to 40% of manufacturing costs are also attributable to maintenance [Rao 96]. These are just some of the reasons why condition monitoring is such an important issue in the manufacturing industry. By introducing condition monitoring systems into de actual manufacturing industry, it is possible to accomplish many improvements, [Rao 96] presents a case study example shown in Table 2.1 which shows the savings achieved by five different companies.

Condition monitoring and relevant diagnostics are accomplished by obtaining relevant parameter values. These parameters depend on the machines and processes that are to be monitored, some examples of these parameters are: temperature, pressure, flow, vibration, viscosity, density, level, etc. Depending on the monitored system, these parameters can be analyzed by themselves and/or combined to produce additional aggregated data that allows for predictive maintenance and machine life extension. Even if a certain machine is designed to last a certain amount of time, it has been stated that only 10-20% of machines actually last as long as they are supposed to [Beebe 04].

Once it is known what parameters should be monitored it is possible to obtain relevant information from them. For instance, Figure 2.1 shows the principle of condition monitoring for any generic parameter that might be chosen. It is a basic trend graphic which shows some of the implicit information that can be obtained by continuously analyzing the parameter of interest. This kind of trending graph is widely used in monitoring systems. It can be of particular use in systems where the monitored value should be always be maintained within certain range values (e.g. temperature, flow). One specific example of systems susceptible to condition monitoring - and one pertaining to this thesis - can be the circulating oil flow monitoring systems used in paper machines. There are many more parameters that require monitoring in these particular systems, it is however of primary importance to monitor the constant flow of lubrication oil. To ensure the constant

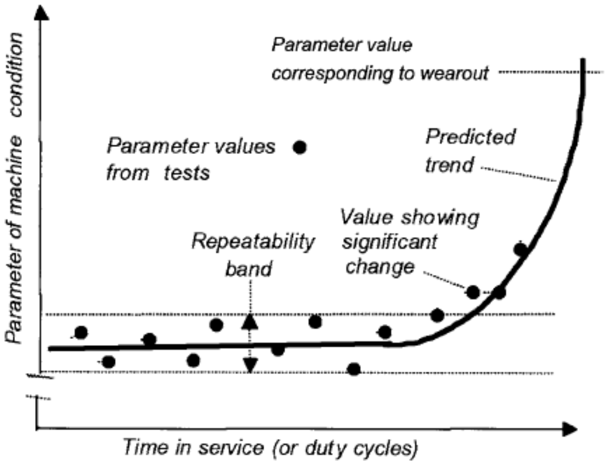


Figure 2.1: Principle of condition monitoring: trending. Adopted from [Beebe 04].

lubrication of these machines it is necessary to make sure that oil is being received by the mechanical components of any given machine, this can be done by means of *flow measurement*. Flow measurement can be defined as the measurement of matter in motion [Kopp 01b]. At the same time, matter can exist in three forms: liquid, solid and gas. In the particular case of flow measurement however, only the measurement of the movement of fluids is of concern, namely gases and liquids [Kopp 01b].

2.1.1 Hydraulic Systems

Hydraulic systems can roughly be divided into fluid power systems and lubrication systems. Both these types of systems require constant monitoring and diagnostics that allow the reliable and continuous operation of manufacturing machines. In order to accomplish the maximum achievable performance of any given production process it is necessary to observe the relevant parameters, and make sure that they do not deviate from the range that allows for adequate performance. If the process is not working as it should according to the monitored parameters, the process should be calibrated to the best operational range [Day 96].

Whether it is a fluid power or a lubrication system, hydraulic fluid systems are used extensively in a wide range of manufacturing industries. While fluid power systems focus on transferring energy, lubrication systems simply ensure the constant lubrication of moving mechanical parts. Even though the basic objective of lubrication systems is quite simple and straightforward, these systems are critical to manufacturing processes due to the fact that they prevent the deterioration of most of the mechanical components of machines and ensure constant and reliable operation. Additionally, the main contributor for mechanical part degradation in hydraulic lubrication systems is the contamination of the

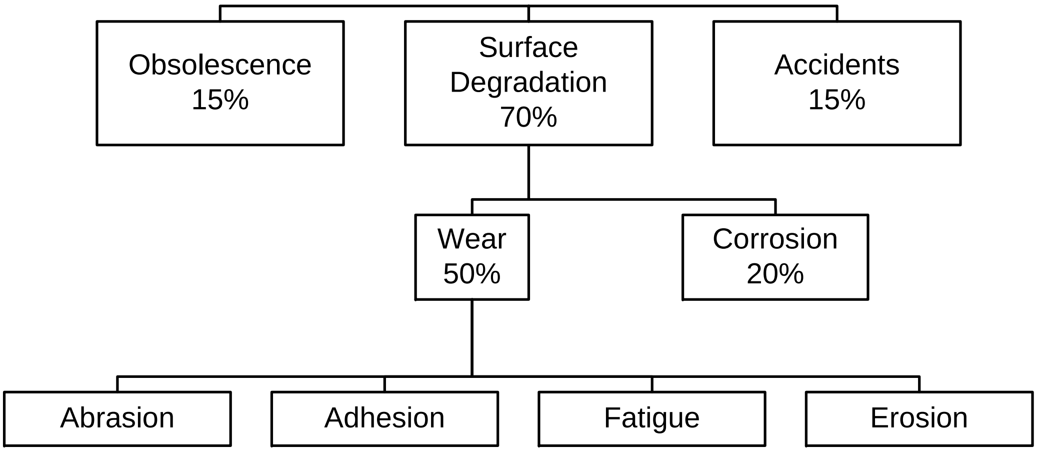


Figure 2.2: Reasons for replacing components. Adopted from [Day 96].

lubricant used. The existence of friction, dirt particles in the lubricant, or water in the case of synthetic oils, cause wear and accelerate the degradation that eventually lead to unavailability, shut-down and ultimately to machine breakdown [Day 96, Holmberg 01].

In the specific case of paper mills the mechanical components of most importance can be said to be the bearings. [Cutler 96] mentions a study of the different types of paper machine bearing failures and concludes that 34.4% of the failures are due to inadequate lubrication. Additionally, a study realized by [Rabinowicz 81] of the Massachusetts Institute of Technology and presented by [Day 96] studied the major reasons for component replacement. It was concluded that 70% of the neccesary replacements was caused by the surface degradation, 50% of which was caused by mechanical wear with its four modes, and 20% caused by corrosion due to the water contamination in mineral oils. A more complete representation of this study can be seen in Figure 2.2.

With the need for maintenance and condition monitoring established, the next step is to determine what should be observed and analyzed. It is therefore necessary to audit the system and evaluate its most critical components. Once the components that have the most probability of affecting the correct behavior of a system are identified, the parameters that can measure that component behavior are selected. Hydraulic systems have many different parameters and techniques to monitor hydraulic systems. Table 2.2 shows some possible techniques that can be used in the monitoring of hydraulic systems according to [Day 96]. In a similar fashion to the Table 2.2, which classifies monitoring parameters according to monitoring techniques, [Rinkinen 07] classifies the different condition monitoring parameter possibilities as shown in Figure 2.3.

As previously mentioned, hydraulic systems parameters are many, and affect machine components in different ways. Some of the most important parameters are viscosity, acid-

Table 2.2: Techniques for monitoring hydraulic equipment. Adopted from [Day 96].

Technique	Description
Visual inspection	regular inspection of equipment, including leaks
Contaminant monitoring	monitoring the general dirt level of the system
Wear debris analysis	monitoring the type and quantity of wear debris generated
Energy methods	power current torque temperature measurement
Operational parameters	pressure flow speed others
Dynamic measurements	vibration stress waves noise spectrum analysis acoustic emissions

ity, additives and water content. These parameters will not be explained as they are beyond the scope of this work, other important parameters are presented by [Day 96] in Table 2.2.

Operational parameters

Flow rate

This parameter is one of the most basic and important parameters that should be monitored. It is important because it allows to regulate the amount of oil entering and exiting any given component. It can function as a direct measure of performance in the case of pumps of flow control valves. If measured in unison with other parameters it is possible to estimate the general condition of components (e.g. motor and cylinder speeds). Flow rate can be measured with many different types of flowmeters and must be done under standard conditions of pressure and temperature as these affect the viscosity of oils. Measuring flow can also function as an effective way of measuring leakage [Day 96].

Temperature

The measurement and monitoring of temperature in hydraulic systems is another very important issue. As temperature can affect the viscosity of oils and cause degradation it is important to keep the temperature in check since the life of hydraulic fluid can be reduced by half for every 10 °C increase above 50 °C. It should also be noted that a change in temperature will indirectly affect the existing leakage due to the change in viscosity. Depending on the type of flowmeter being used, temperature may also affect the measurements taken by the flowmeter [Day 96, Kopp 01b].

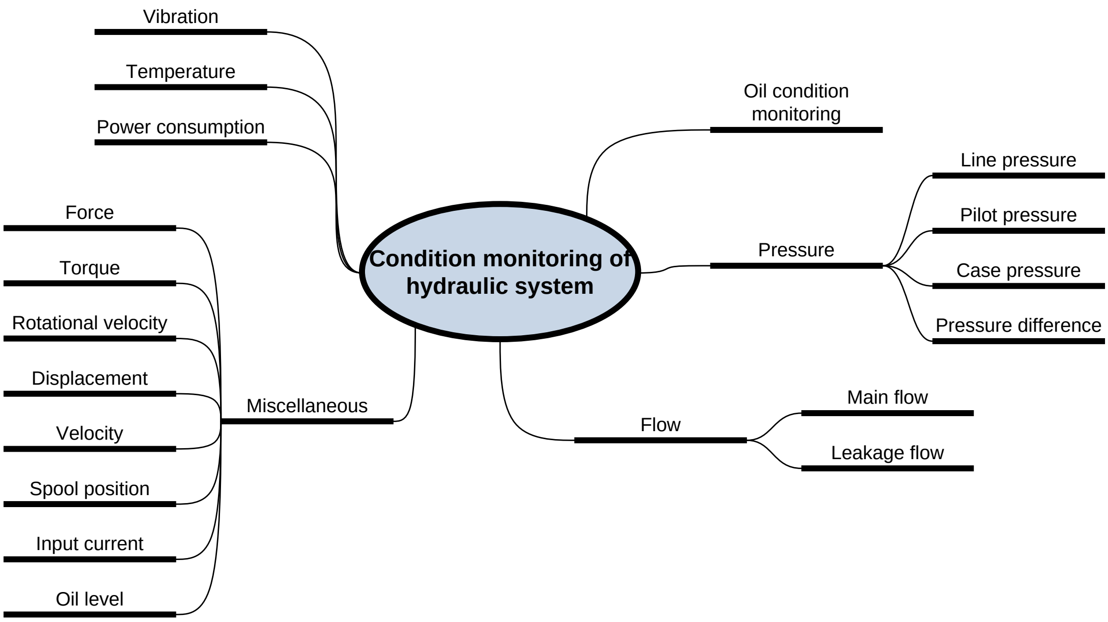


Figure 2.3: Monitoring of hydraulic systems. Modified from [Rinkinen 07].

2.1.2 Fundamentals of Measuring Flow

As previously defined, flow is related to the movement of matter in whatever its states; solid, liquid or gas. In order to measure flow it is necessary to implement the use of flowmeters. Thus, the purpose of flowmeters and measuring flow is to measure and/or monitor the flow of matter across a reference plane or a cross-sectional area. This can be done by measuring either in terms mass or the volume that passes through a medium in a defined period of time [Miller 83, Jamal 02, Kopp 01b]. Matter in motion, and more specifically fluid flow can be characterized and derived from the *equation of continuity*, *Bernoulli's Theorem* and the work of *Osborne Reynolds* [Kopp 01b].

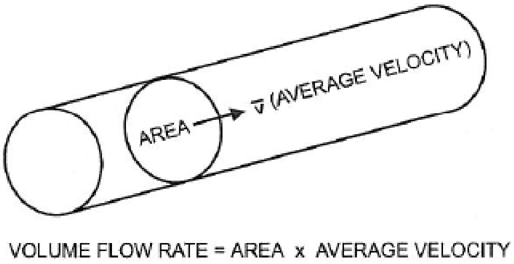


Figure 2.4: Volume flow rate relationship to area en velocity. Adopted and modified from [Kopp 01b].

Equation of continuity

If we consider a closed conduit such as the one in Figure 2.4 and take the rate of flow to be Q, the cross-section of the conduit to be A, and $\bar{v}$ as the average speed of the fluid, it is possible to obtain the flow rate assuming a constant volume flow by means of Equation 2.1 [Kopp 01b]:

$$Q = A \times \bar{v} \tag{2.1}$$

Given that the principles of measuring flow follows the laws of physics, and the two most used principles are the conservation of mass and energy, it can be concluded that both mass and energy remain unchanged in both ends of the flow conduit. This, of course, assuming that flow is not diverted and no energy is added or removed from the flow. Following these premises it can be said that the flow rate in a closed conduit will be the same regardless of the cross section area (A) [Jamal 02].

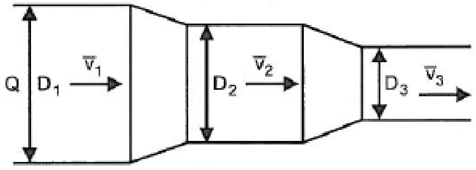


Figure 2.5: Equation of continuity. Adopted from [Kopp 01b].

Figure 2.5 shows a flow conduit with different diameters and different average speeds in different conduit sections. If we consider the laws of energy and mass conservation the following derivation in Equation 2.2 becomes evident [Kopp 01b]. Equation 2.2 is known as the equation of continuity, and it is the basic measurement principle used in variable area flowmeters.

$$\begin{aligned} Q &= \frac{\pi(D_1)^2}{4}\bar{v_1} = \frac{\pi(D_2)^2}{4}\bar{v_2} = \frac{\pi(D_3)^2}{4}\bar{v_3} \\ &= A_1\bar{v_1} = A_2\bar{v_2} = A_3\bar{v_3} \\ &\text{And} \\ &\bar{v_1} < \bar{v_2} < \bar{v_3} \end{aligned} \tag{2.2}$$

Bernoulli's Theorem

As shown by the continuity equation there is a direct relationship between the area and the average flow speed when obtaining the volumetric flow rate. Bernoulli's theorem is based precisely on the change of flow speed observed in the continuity Equation 2.2. The change of speed is related to a conversion of energy from kinetic energy, namely the velocity head, to potential energy otherwise known as pressure head. With this it may be concluded that there is no energy loss in the flow inside a closed conduit, there is only an inverse change of pressure in relation to a change of velocity. In other words, while a smaller area in a closed conduit increases the flow velocity, it reduces the present pressure. These principle is the base for all pressure based flowmeters (e.g. orifices, Venturis, flow nozzles, etc.) [Kopp 01b, DeCarlo 84].

Reynolds number

The Reynolds number was given its name in honor of Osborne Reynolds who in 1883 gave new insight to the behavior of fluids. He accomplished this by introducing some dye in a conduit at variable flow velocities and observing the way the dye behaved depending on the different flow velocity. At low velocity he observed that the dye followed a straight line, a phenomena that is now called laminar flow. It was also observed that as the velocity of flow was increased the flow started behave in a sinuous manner which indicated instability, this flow is now known as transitional. Once the velocity reached a certain point, the flow became what is now deemed turbulent flow. Figure 2.6 shows these different flows [Kopp 01b].

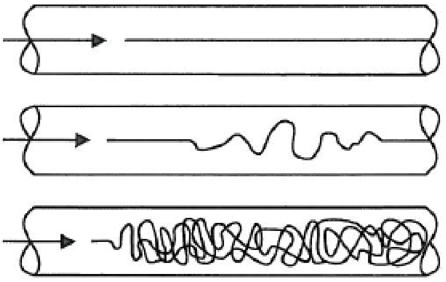


Figure 2.6: Osborne Reynolds experiments. Adopted from [Kopp 01b].

While these experiments enlighten the way fluids behave, probably the most important contribution made by Reynolds is the *Reynolds Number* (*Re*). This number has no dimension and it helps indicate the type of behavior that any fluid is presenting whether it is in laminar, transition or turbulent form. When the Reynolds number is dominated by viscous forces (laminar flow) the number is 2000 or smaller. When dynamic forces are dominating (turbulent flow) the number is 4000 or higher. Lastly, if the number is between 2000 and 4000 the flow is in transition. It is possible to calculate Reynolds number with equation 2.3 [Kopp 01b].

$$Re = \frac{\rho v D}{\mu} \tag{2.3}$$

Where

Re = Reynolds number

ρ = fluid density $[kg/m^3]$

D = a dimension $[m]$

v = average fluid velocity $[m/s]$

μ = absolute fluid viscosity $[Ns/m^3]$

Measurement performance parameters

In order to measure flow or any other operational parameters the use of flowmeters and sensors is necessary. These devices however entail other issues of importance, the accuracy of the measurements that are obtained by them should always be questioned due to the fact that errors and measurement uncertainty are always present in measurements. When taking multiple repeated measurements under the same conditions the obtained value will not always be the same; this is mainly due to the fact that environmental factors, such as temperature, relative humidity, and other uncertainty factors may affect the taken measurements. To account for all these uncertainties a series of parameters are used to measure to what degree a measurement device can be trusted, terms such as accuracy, overall uncertainty, systematic error, bias error, repeatability, hysteresis and reproducibility to just mention a few [Miller 83, Dietrich 73].

Bias error and uncertainty

According to [Miller 83] and following the ISO 5168 [ISO 78] standard, accuracy is a combination of bias and precision errors. Bias error can be considered to be a directional displacement in any measurement that is taken, while precision error is the capability of the sensor to take the same or similar measurement in a repeatable fashion. It is also important to note that bias errors can be corrected by addition or subtraction, but precision errors are random around the bias and can only be corrected by changing to a more precise sensor [Miller 83]. Figure 2.7 provides a graphical interpretation of bias errors.

In a similar manner, [Dietrich 73] mentions that some of the most common and generic sources of uncertainty are; (1) uncertainties in standards or in calibration equipment, (2) uncertainties due to operator error, (3) environmental uncertainties, including variation of temperature, pressure, flow rate, power supplies, (4) lack of repeatability-instability uncertainties, (5) functional uncertainties caused by malfunctioning equipment, (6) uncer-

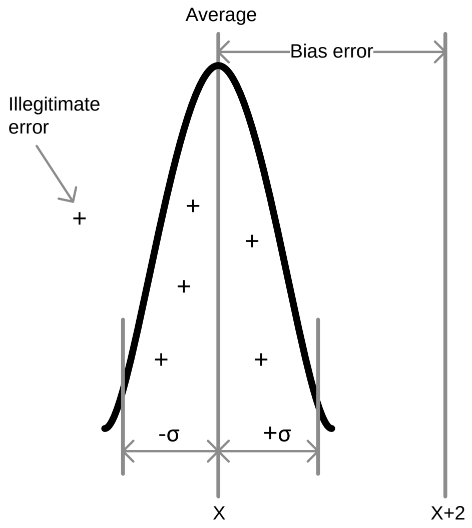


Figure 2.7: Bell curve for device with good precision but non-negligible bias error. Modified from [Miller 83]

tainties cause by lack of cleanliness, (7) uncertainties due to poor quality surface texture and incorrect geometry and (8) uncertainties associated with lapse of time which produces changes in equipment or workpieces. [Boam 01] also points out uncertainties in the measurement of flow that are not mentioned by [Dietrich 73] and are also of great importance, see Table 2.3.

Calculating bias error

In order to calculate bias error it is necessary to calculate the average value of the measurements taken and equate them with the true value that should have been measured. Equation 2.4 can be used to calculate the directional bias error.

$$B = \frac{\bar{I} - I_t}{I_t} \cdot 100 \tag{2.4}$$

Where

$\bar{I}$ = Average of taken measurements

I_t = True value

While Equation 2.4 uses the average of the obtained measurements it is also possible to equate the single point error for each measurement and obtain the average of the single error points. This will give the same result as Equation 2.4. Additionally, the sign of the obtained result is also important as it signifies if the bias error is above or below the true value. Hence the name directional bias error [Miller 83].

Table 2.3: Important uncertainty categories.

Category	**Description**
Measured quantity	Flow is a dynamic quantity and may vary, therefore creating a potential change in measurement accuracy
Measuring process	The flow measuring process should be well defined, measurement intervals, instrument change and average calculations affect the final result
Method or procedure	The way a measurement is done may cause incorrect measurements (e.g. incorrect assumptions, unknown disturbances)
Sampling	Appropriate sampling methods should be implemented to avoid uncertainties in this category
Handbook values	Values of physical properties taken from reference books cause uncertainty if factors such as geographical location and altitude are not taken into account
Data processing	Errors may exist in the software procedures implemented in flow measurement causing incorrect readings and calculations

Estimating uncertainty

According to the Guide to the estimation of Uncertainty in Measurement (GUM) there are two type of evaluations that can assist in the estimation of uncertainty. Type A evaluations that are based on statistical methods, and Type B evaluations that are based on non-statistical methods based on probabilities and observations [ISO 78, ISO 07, Boam 01, Scott 82]. In the case of Type A evaluations it is necessary to obtain n measurements and to follow the steps shown below[Boam 01]:

1. Obtain the mean value $\bar{x}$ of the measurements
2. Calculate the standard deviation σ of the taken measurements
3. Calculate the standard deviation of the mean $\sigma(\bar{x})$ or average value
4. Obtain the standard uncertainty $u(\bar{x})$ of the mean value

Type B evaluations of uncertainty as mentioned previously rely on other means of calculation that are not necessarily statistical. These may be based on previous experience, manufacturers specifications, calibration certificates and other similar sources [Boam 01]. The steps required for Type A evaluations rely mainly on the Standard Deviation from which the *standard uncertainty* can be derived. This value however, gives a 68% interval, that is, the measured quantity is the true value with that percentage of confidence. Type B evaluations on the other hand, may be based on different confidence percentages. Taking into account the different confidence levels obtained from different sources it is possible to obtain an *expanded uncertainty* that can later be made to be compatible with the standard uncertainty [Boam 01]. This can be accomplished multiplying the expanded uncertainty with a coverage factor k as seen in Equation 2.5.

$$U(x_i) = k \cdot u(x_i) \tag{2.5}$$

The k coverage factor is defined and depends on the confidence factor and the probability distribution associated with the source or sources of uncertainties being taken into consideration [Boam 01, ISO 07].

Precision and accuracy

Precision and accuracy are two terms commonly used in many different applications and contexts. According to [Miller 83] both precision and bias error can be considered to define the overall accuracy of a device. While accuracy can be said to be the closeness of the measured value to the true value, precision is the ability of the device to repeat the measurements and is sometimes stratified as repeatability and reproducibility [Wikipedia 10]. Before the calculation of accuracy can be made, it is necessary to calculate precision. To accomplish this the standard deviation has to be calculated. The precision can then be obtained by multiplying the standard deviation σ, by a correction factor $t_S T$ that can be obtained from the Student's t distribution for a certain confidence level, see A.1 in Appendix A. The correction factor is chosen based on the number of measurements tested and results in equation 2.6 shown below [Miller 83].

$$\sigma_p = t_S T \cdot \sigma \tag{2.6}$$

In addition to the directional bias error defined in Equation 2.4, there is also the bias error range which gives the error around the average of the measured values using the same confidence factor used in Equation 2.6. This bias error range is defined by Equation 2.7 where n represents the number of measurements made [Miller 83].

$$\pm B = \frac{\sigma_p}{\sqrt{n}} \tag{2.7}$$

With the precision and bias error range defined the accuracy can be obtained by combining these factors resulting in Equation 2.8 [Miller 83].

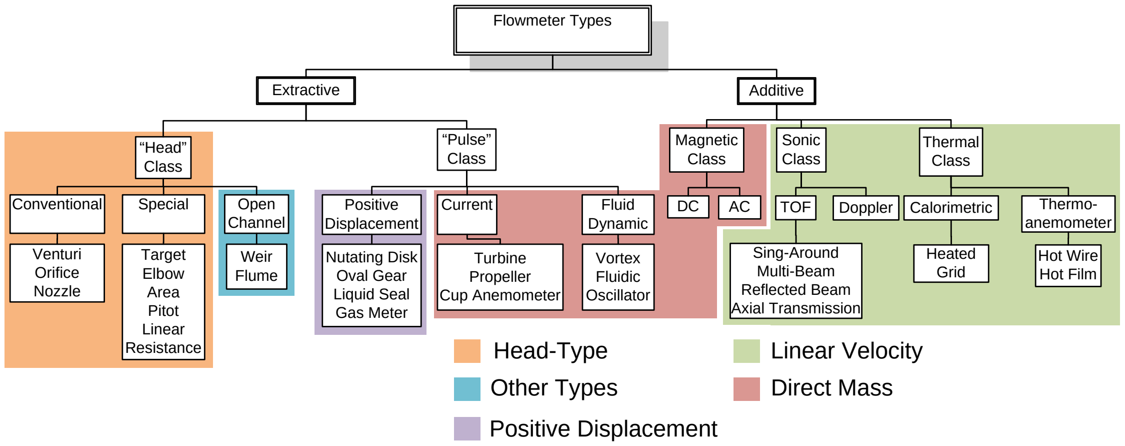


Figure 2.8: Flowmeter types.

$$Acc = B \pm \sqrt{\left(1 + \frac{1}{n}\right) \cdot \sigma_p^2} \tag{2.8}$$

2.1.3 Sensing Principles and Devices

There are many different ways of measuring and estimating flow. Section 2.1.2 explained the fundamental points of flow measurement and how the principles of physics can be used to calculate flow. In a similar manner, there are many different classifications for flow measurement devices. [DeCarlo 84] classifies flowmeters based on the energy approach on which the sensor is based, namely: Extractive energy approach and Energy additive approach. The *extractive approach* uses the energy generated by flow itself to observe the change between potential energy and kinetic energy or vice-versa, resulting in a quantifiable measurement. On the contrary, the *additive approach* introduces an outside source of energy into the flow, this results in a change in either the flow or the source of energy that is then converted into a flow measurement.

Another way of classifying flow meters is by the principles used in calculating the measurement. [Jamal 02] defines seven different types of flowmeters: Linear Velocity Meters, Head-Type Flow Meters, Positive Displacement, Direct Mass Meters, Energy Meters, Multiphase Meters and Other Types of Meters. Figure 2.8 maps the flowmeter types defined by [Jamal 02] to the classification defined by [DeCarlo 84].

While the classifications shown in Figure 2.8 are accurate from certain perspective, it does not account for recent developments in sensor technology and classifies the flowmeter types in a very specific manner. [Kopp 01a] comments that while the most common way of categorizing flowmeters is based on the measurement technology they use, it is also worth classifying them by *process dominated factors*. These additional characteris-

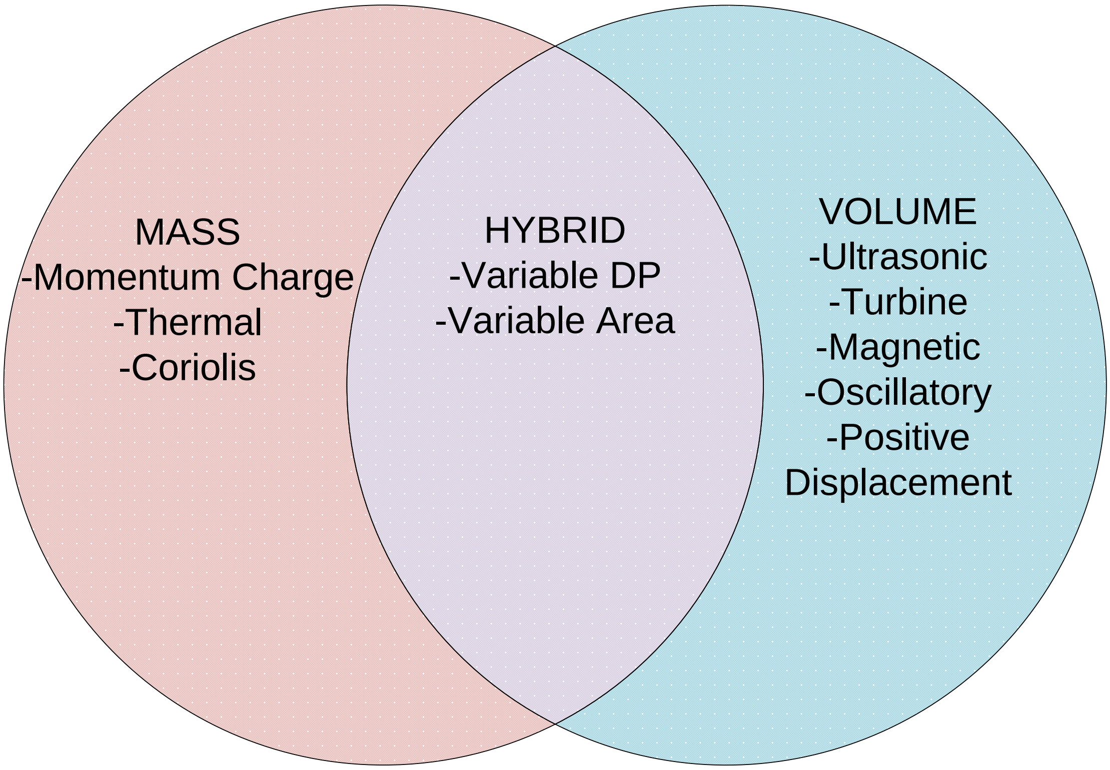


Figure 2.9: Mass, volume and hybrid flowmeter classification.

tics are:

1. Type of measurement: mass or volume.
2. Information provided by the flowmeter: rate of flow or total.
3. The fluid state the flowmeter can handle - liquid, gas, steam or slurries.

As a consequence of this classification and considering that some processes require mass flow information and others volumetric flow information, it is possible to realize that: some meters that are normally considered to be volumetric are actually velocity meters, and some meters do not provide measurements that are neither mass nor volume [Kopp 01a]. This allows for a new classification that is divided into three simple subcategories: mass, volume, and hybrid. Figure 2.9 shows some examples of this new classification. Taking this classification into consideration the following sub-sections will cover the most important and commonly used flowmeters.

Mass flowmeters

This type of flowmeter is designed to measure the flow of fluids in terms of mass per time unit. That is, as opposed to other type of flowmeters that measure the volume or

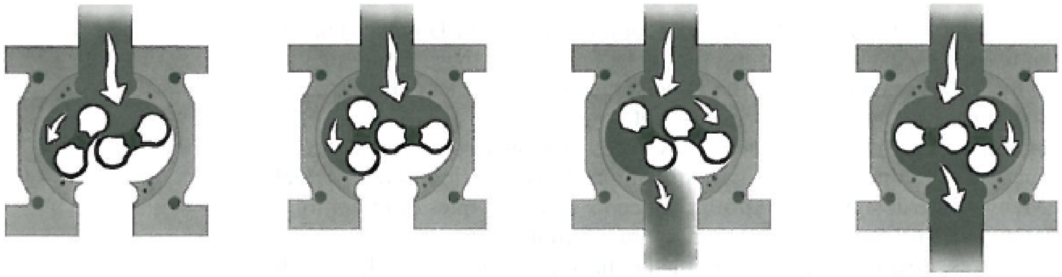


Figure 2.10: Bi-rotor positive displacement flowmeter. Adopted from [Barnes 01]

velocity of fluids, this measurement is based on the properties of mass of the fluid. The main advantage behind this type of measurement is that it is based on the calculation of the weight of the fluid. This yields highly accurate results that are independent of external factors that might affect a process like temperature, or pressure [DeCarlo 84, Smith 01].

Mass flow calculations can be either *inferential* or *true*. Inferential mass-flow measurement is based on a mathematical calculation made from two measurable parameters which are density (ρ) and velocity(V). By measuring these two parameters, and taking into consideration the conduit area (A) it is possible to use Equation 2.9 and estimate mass-flow rate [DeCarlo 84].

$$\dot{m} = \rho \cdot A \cdot V \tag{2.9}$$

Opposed to inferential mass-flow measurement, true mass-flow measurement is concerned with the direct measurement of mass without having to take into consideration other parameters and properties of the fluid and its state. This can be done with Newton's second law which states that: *"When an unbalanced system of forces acts on a body it produces an acceleration in the direction of the unbalanced force that varies in inverse proportion to the mass of the body"* [DeCarlo 84].

Volume flowmeters

Volume based flowmeters, as opposed to mass flowmeters focus on calculating the volume of flow that moves through a conduit. In reality the only flowmeters that can be considered to measure flow are the positive displacement meters. The rest of the flowmeters in actuality measure the velocity of flow. Granted that mass flow and rate of flow can be inferred by means of mathematical calculations most of the existing flowmeters can be classified under the volume type [Kopp 01a]. The following sections will explain the working principles of some of the flowmeters most commonly used in circulating oil flow monitoring systems.

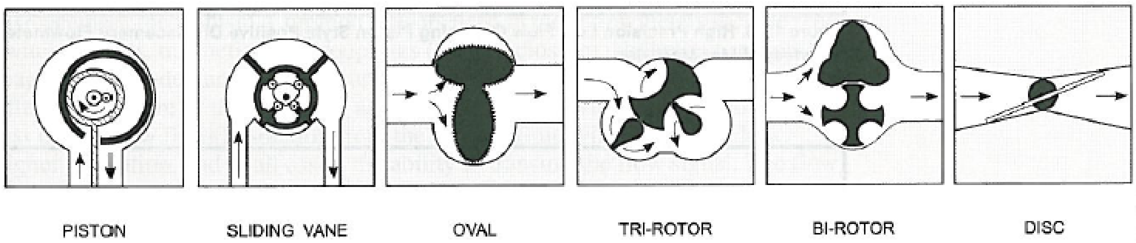


Figure 2.11: Positive displacement flowmeters. Adopted from [Barnes 01]

Turbine

This type of flowmeters is one of the *pulse* type flowmeters mentioned in the flowmeter classification made by [DeCarlo 84] and shown in Figure 2.8. According to [Olivier 01] these flowmeters can be considered to be some of the most accurate for both liquid and gas measurements. They have been available since the 1940's and cover a flow range from 0.001 gpm to over 25,000 gpm and can be used with clean fluids in very wide range of temperatures.

The working principle behind these sensors is relatively simple, a turbine meter consists of a rotor with a certain amount of blades that have a certain angle to the direction of the fluid flow. This causes the rotor to move and spin at speed proportional to the fluid flow passing through it. Depending on the flowmeter, or the application it is being used in either the pulses generated by the blades are counted, or the rotational speed of the shaft is measured. Whether the pulse counting type, or the shaft rotational calculation type is chosen it is possible to convert the measured value into a flow measurement [Olivier 01, Jamal 02].

Positive displacement

Unlike the turbine meters which are relatively new to the industry, positive displacement flowmeters have been around since the 1800s. The first practical flowmeter of this type emerged in the gas industry and was invented in 1816 by an Englishman named Samuel Clegg. Similarly, other patents for similar displacement meters can be found to be just as old. Positive displacement flowmeters follow the basic principle of displacement discovered by Archimedes in the third century B.C. when he observed that *"any shape object will displace its volume of fluid when submerged"* [DeCarlo 84, Barnes 01, Miller 83, Husain 99, Liptàk 03].

The principle behind the workings of a positive displacement flowmeter can be clearly observed from Figure 2.10. A chamber of a known volume is created with some type of mechanical component inside the chamber. When there is flow inside the flowmeter the

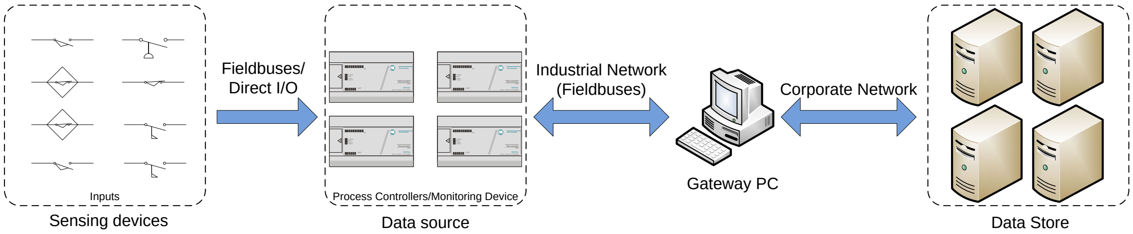


Figure 2.12: Typical architecture of process monitoring systems.
Modified from [Jestratjew 09].

chamber is filled with the fluid which starts displacing the mechanism inside the chamber. This generates a rotation in the case of the bi-rotor flowmeter of Figure 2.10. Each time the chamber is filled and emptied it generates a *bucket* of fluid which volume is known. At the same time, the bi-rotors can trigger an additional mechanism that counts the pulses generated by the flow. These pulses can then be used with a constant conversion factor to obtain the flow rate. While originally these flowmeters were used as totalizers, it is now possible to change the counting mechanism to any type of electronic sensor that can convert pulses to a flow rate [DeCarlo 84, Barnes 01, Miller 83]. Figure 2.11 shows some of the different types of positive displacement flowmeters that exist.

Hybrid flowmeters

As the name implies this type of sensors use both mass and volume based measurements to obtain a flow measurement [Jamal 02]. Most, if not all, of the hybrid flowmeters that exist fall under the *category of differential pressure* or *head* flowmeters. That is, they measure flow based on calculations derived from a measured pressure. While some of these flowmeters are used in flow monitoring systems (e.g. rotameters), they will not be covered in this thesis.

2.1.4 Commercial Flow Monitoring Systems in Paper Machines

Many different types of monitoring systems have been implemented throughout the years, most of these are tailored to the manufacturing system/process it is designed to monitor. While monitoring itself is simply the observance and analysis of a systems behavior, current condition monitoring systems require that such information is readily accessible from both near and far. The former referring to local monitoring stations and the latter to remote control rooms and corporate level monitoring interfaces. This is commonly accomplished by implementing fieldbus communication networks and systems capable of using such networks. In the end, this leads to a common pattern followed in the implementation of these monitoring systems, a generic and common architecture can be seen in Figure 2.12.

As can be observed from the Figure 2.12, a typical industrial monitoring system has three components: A data source, a communication infrastructure and a data store [Jestratjew 09]. This is the normal approach to monitoring systems because it is the most intuitive and straightforward approach, mainly due to the fact that all systems are different and there is no common standard to implement monitoring systems. In most systems all the information can be obtained from the controlling entity, namely a process controller. The advantages to this can be many. For instance, if the desired variables are already being measured, there no need to install additional sensors; however, there is a need to program routines that handle the information gathering. Additionally, there is a need to adapt and use the communication infrastructure to be able to obtain the information gathered by the data source. Once the information has been gathered in a conventional information system it can be stored in any given format according to the systems existing standards.

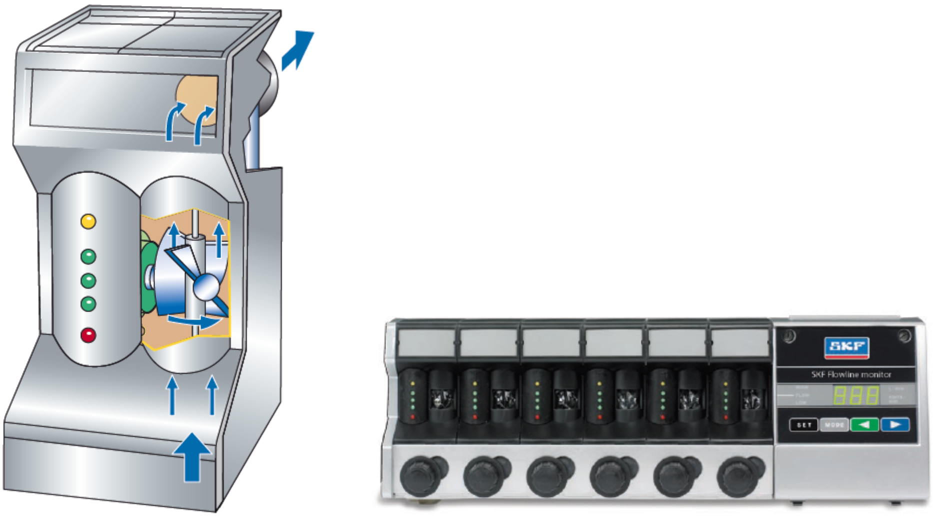
Circulating oil flow monitoring systems are not very different from the generic systems previously mentioned. The varying factor is mainly the way a monitoring system is integrated or designed in conjunction with the oil flow monitoring system. Hence, the way the monitoring system is designed and implemented depends on the manufacturer and on the requirements of the system or factory where they are installed. It is therefore no surprise that they are all different and that academic information regarding this systems is practically non-existent. By analyzing the main differing and most important aspects in these systems it is possible to divide their components in many different ways. One such possible classification, having four aspects to itself, can be the following:

1. General specifications.- Main approach used by the system, components and general functioning principle.
2. Supported flow meter range.- Concerned with flowmeter types and the ranges they support for monitoring applications.
3. Control/Configuration/Monitor User Interface.- The interface used to configure, control and monitor the behavior of the monitoring system.
4. Hardware architecture.- Communication and information flow capabilities of the system, namely the communication architecture supported by the system so that it may easily and seamlessly integrate to the process to be monitored.

The following sections will analyze existing systems based on the previously mentioned aspects and will evaluate the advantages and disadvantages of each of the systems.

SKF System

The SKF Group was founded in 1907 and is currently one of the global leaders in the supply of products, solutions and services related to rolling bearings, seals and lubrication



(a) Flowline meter (b) Flowline monitor

Figure 2.13: SKF Flowline system. Adopted from [SKF 08c]

systems [SKF 10]. One of the main technologies developed and provided by SKF is related to lubrication systems. Whether they are centralized lubrications systems, total loss lubrication systems or minimal quantity lubrication, SKF offers these types of systems for many different types of industries.

General specifications. This system is especially designed to be installed in paper machines, and allows for the automatic lubrication of many lubrication points. While the number lubrication points per unit or station is quite limited and ranges between 2-10 flowmeters it is possible to expand these units by means of communication networks. One of the main features of this system is the oil cleaning system it implements [SKF 08b]. It is based on a designed accomplished by [Rinkinen 07] in a joint investigation program between SKF, Safematic and the Tampere University of Technology [Härkkönen 07]. This system cleans both dust particles and water content in the oil circulating in the system allowing for better performance and longer oil life.

Supported flow meter range. This system uses turbine flowmeters to calculate the flow. The flowmeter uses a propeller that generates pulses detected by an inductive sensor, much like the positive displacement flowmeters explained in section 2.1.3. The calculated value is then tuned depending on the oil viscosity grade and temperature [SKF 08c]. Figure 2.13(a) shows the flowmeter used in this system.

While the flowmeter range offered by this system is limited to only two different sensors shown in Table 2.4, the flow rate range offered by these meters is quite wide [SKF 08c]. This allows for the system to be highly adaptable to many different types of lubrication applications, albeit it might result in over-dimensioning the flowmeters to the required application.

Table 2.4: Flowline meters and ranges.

Flowmeter	**Range**
FL15-xx	0,05 - 15,0 l/min
FL50-xx	5.0 - 50 l/min

Flowline user interface, configuration and visualization. The user interface and flow rate visualization offered by this system is quite straightforward. It consists on several LEDs that show whether the present flow rate is within the configured range it should be in. Three green LEDs indicate normal flow, one yellow LED indicates low flow and one red LED indicates high flow rate. The unit also includes a numerical display that allows for local configuration. The physical appearance of the SKF flowline monitor can be seen from figure 2.13(b) [SKF 08b, SKF 08a, SKF 08c].

In addition to this, it is also possible to connect to the SKF flowline monitor to a PC or Laptop via RS-232 and RS-485. This allows for flowmeter configuration, monitoring and OLE for Process Control (OPC) connection that allows for interaction with the *SKF Flowline Software* [SKF 08c].

Hardware and system architecture. As previously mentioned, this system supports a small amount of flowmeters per unit, namely ten meters per unit. While smaller options are also available (2,4,6 and 8 flowmeters), the use of this system in paper machine lubrication system implies the necessity to monitor hundreds of lubrication points. To be able to accomplish this, the SKF flowline monitor system implements a series of communication possibilities that expand both the supported number of flowmeters and the reach of the information obtained by them. To expand the number of flowmeters the flowline monitor units can connect to other units via Controller Area Network (CAN) serial bus. In order to transfer the information to the *SKF flowline software*, to a remote monitoring system or to a Distributed Control System (DCS), the system uses a RS-232 HUB or a USB-CAN interface converter [SKF 08c]. Figure 2.14 shows a generic view of all the different connections that are possible in this system.

By observing Figure 2.14 it is possible to understand that the number of sensors can be extended using a CAN serial bus connection. From that connection it is possible to expand to higher tiers by means of a gateway, which in this case represents a CAN HUB, or a USB-CAN interface. Whichever option is chosen, it is then possible to interconnect to computers, laptops and remote monitoring stations using the company software or

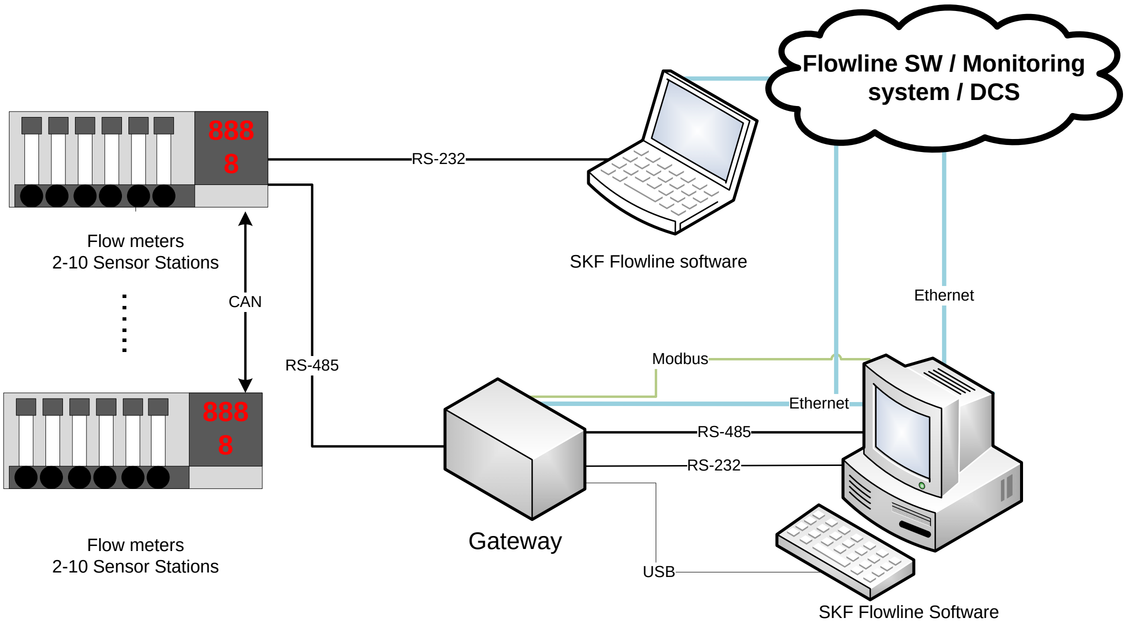


Figure 2.14: SKF Flowline connection architecture.

DCSs. For this latter option, Modbus, RS-232, RS-485, USB and Ethernet connections are supported.

SENSO System

The SENSO system is a lubrication oil flow monitoring system designed by Sensodec. Sensodec Ltd. was founded in 1984 as a private company, but soon after, between 1985 and 1986 was bought by Valmet. At the same time, in 1989 Valmet became a part of the prolific Finnish paper company Metso. Sensodec continued to function as a part of Valmet Automation between 1989 and 1999 at which point it ceased to be and became a part of the systems offered by Metso [Karjalainen 05]. While the most actual and promoted Sensodec system is the *Sendodec 6S*, where 6S stands for *Sixth Sense*, which mainly monitors vibrations [Metso 10]. There is also the Sensodec 10 system, whose older version, the Sensodec 10L is still very much in use despite dating back to the early 1990s.

These systems have been very successful in the pulp and paper industry. Metso announced having received many orders for these systems from M-Real Sverige AB in Sweden, UPM-Kymmene in Finland, Shandong Chenming Paper Holdings Ltd. in China and others [Käppi 01]. The success is probably due to the many different qualities that the system has, namely the capability to monitor the mechanical condition of bearings, shafts, motors and other drive train components by means of easy to use analytical tools [Metso 10]. The following sections will elaborate on the Senso 160 Series 2 and Sensodec 10L systems that are used to monitor lubrication oil flow in paper machines.

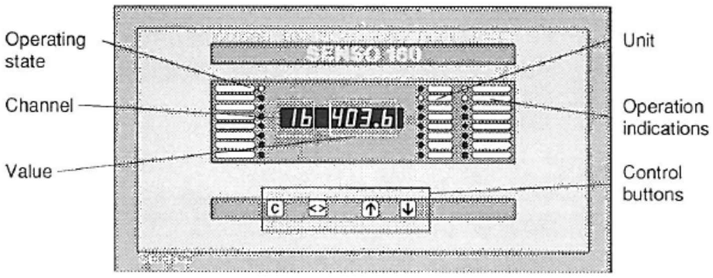


Figure 2.15: Senso 160 user interface. Adopted from [Senso 92]

General specifications. While the Senso 160 Series 2 and the Sensodec 10L carry different names, and appear to be independent systems, they are just two parts of one whole. The Senso 160 system refers to the independent flowmeter stations to which the meters are connected to. These stations can hold up to 28 flowmeters, have an additional three channels for two-wire analog signals, and have configurable high, low and zero flow alarms [Senso 92]. It also includes an interface that allows this system to connect to the Sensodec 10L, this enables the whole system to expand. Given that each individual unit has a unique net address ranging between 1 and 255 it is possible to expand the flowmeter network until they number in the thousands. It is important to note that while these two systems compliment each other, the Senso 160 system can be stand alone and be used for local monitoring independently of the Sensodec 10L system [Senso 90, Senso 92].

Flow measurement. The Senso system is designed especially for flowmeters that generate pulses at different frequencies (e.g. positive displacement, turbine meters, etc). The capability of the system in terms of flow range is only limited by the measurement computer and not by the sensors used in the system itself. In principle, the Senso 160 system behaves like a configurable flow computer that counts the pulses in a certain time window and computes a flow value depending on the configured constants and the desired flow rate unit. Equation 2.10 is the algorithm used by the Senso 160 system to calculate flow based on the counted pulses and configured parameters [Senso 92].

$$M = [K_1 \times A] + K_2 \tag{2.10}$$

Where

M = measured value called onto display (bar, l/min, pints/min, etc)

K_1 and K_2 = scale constants

A = sensor signal (l/sec, pulses/l, mA/mV etc,)

As can be noted from the units in the A and M variables shown in 2.10 this system is capable of both calculating flow rate in different units, and measuring different types of

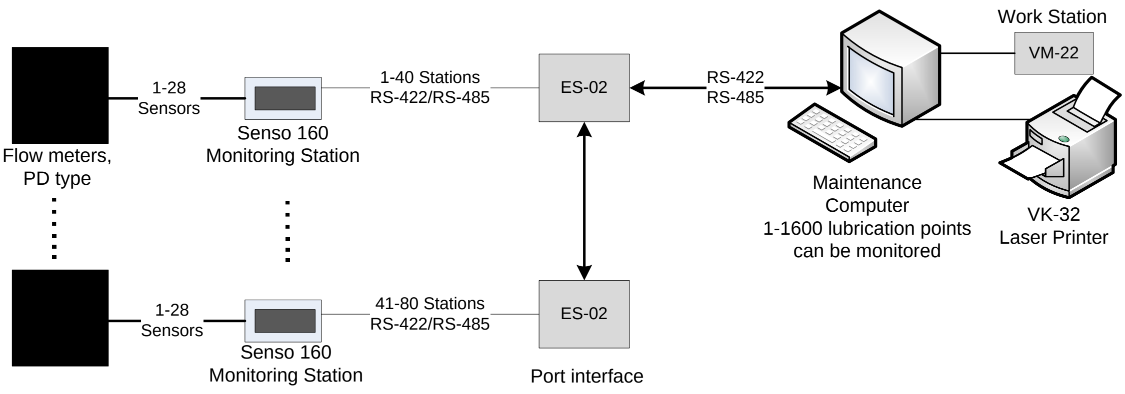


Figure 2.16: Senso 160 and Sensodec 10L.

parameters, like pressure, temperature and others.

User interface. The user interface offered by the Senso 160 system is a mixture of LEDs, buttons and segment displays. The display shows the channel that is being monitored and the value of the measured value for the selected flowmeter. There are LEDs that indicate the operating state of each unit and LEDs that indicate the operation status; (1)PWR, which indicates that the system is energized. (2) RUN, which blinks when the system is in normal operation. (3) COM, indicates that the system is connected to the Sensodec 10 monitoring system. The User Interface (UI) also has a series of control buttons that allow to navigate the options of the interface and allow for its configuration [Senso 92]. Figure 2.15 shows the basic components of the user interface of this system.

Hardware architecture. As previously mentioned, each Senso 160 system is capable of handling the information provided by 28 flowmeters and other sensors, whether they be temperature, pressure or water contamination sensors. In order for these units to expand the flowmeter network they need to be connected to the Sensodec 10 monitoring system. This system is mainly a maintenance computer, or monitoring station where the Sensodec 10 software is running and monitoring the information gathered by the Senso 160 systems. To expand the network of the Senso 160 units *ES-02* port interfaces are used. Each of these port interfaces can handle up to 40 Senso 160 units which transfer the information using RS-422 and RS-485 serial communication. The ES-02 port interfaces then transfer the gathered information to a maintenance computer or a monitoring system [Senso 90]. Figure 2.16 shows the basic communication architecture of this system.

Table 2.5: Variolub meters and ranges.

Flowmeter	**Range**
SMD 1B	0,05 - 1,0 l/min
SMD 2	0.1 - 8 l/min
SMD 3	4.0 - 40 l/min

Variolub System

The Variolub system was originally designed by Vogel AG, a company dedicated to many different types of lubrications systems. While recognized as a world leader in centralized lubrication technology for machinery and systems, Willy Vogel AG was acquired by SKF in mid 2004. While SKF already had some lubrication systems for bearings, bearing units, seals, mechatronics and services, the acquisition of Vogel allowed SKF to further expand and compliment its lubrication business area [Taube 05]. Furthermore, in August 2006, SKF took over Safematic, which was founded in Finland in 1972 and had made its name as a lubricant specialist for the pulp and paper industry [Härkkönen 07].

In actuality, the lubrication business area of SKF compliments all its original lubrication systems with the ones originally designed by Vogel and Safematic, resulting in high quality, dependable systems. An example of this merger is evident in the *SKF Flowline System* previously explained. While the Variolub system is now officially a part of the SKF group, its high modularity and integrability to other systems merits its explanation as a stand alone system.

General specifications. Much like the previously explained systems, the Variolub system is based on the use of pulse generating meters. It is capable of handling up to 12 throttling flowmeters or flow limiters per unit. A unit in this particular case is a pulse meter named *IPM12*. Each IPM12 unit can be connected to other such units, thus further expanding the number of flowmeters the whole system can handle. Additionally, the system can connect to a series of different monitoring units; laptops, computers, remote monitoring systems, handheld displays, and programming and display units [SKF 09, Vogel 01].

In addition to the wide range of possible UIs that the Variolub system offers it has some additional features. Given the nature of IPM12 measuring units and their capability the system is highly modular and easily adaptable to many different applications. It also, depending on the flowmeters used, is capable of bypassing lubricant flow, thus allowing for maintenance [SKF 09, Vogel 02].

Flow measurement. As previously mentioned, the devices that measure flow in this system are the IPM12 units. In the same manner as the *SKF Flowline system* and the

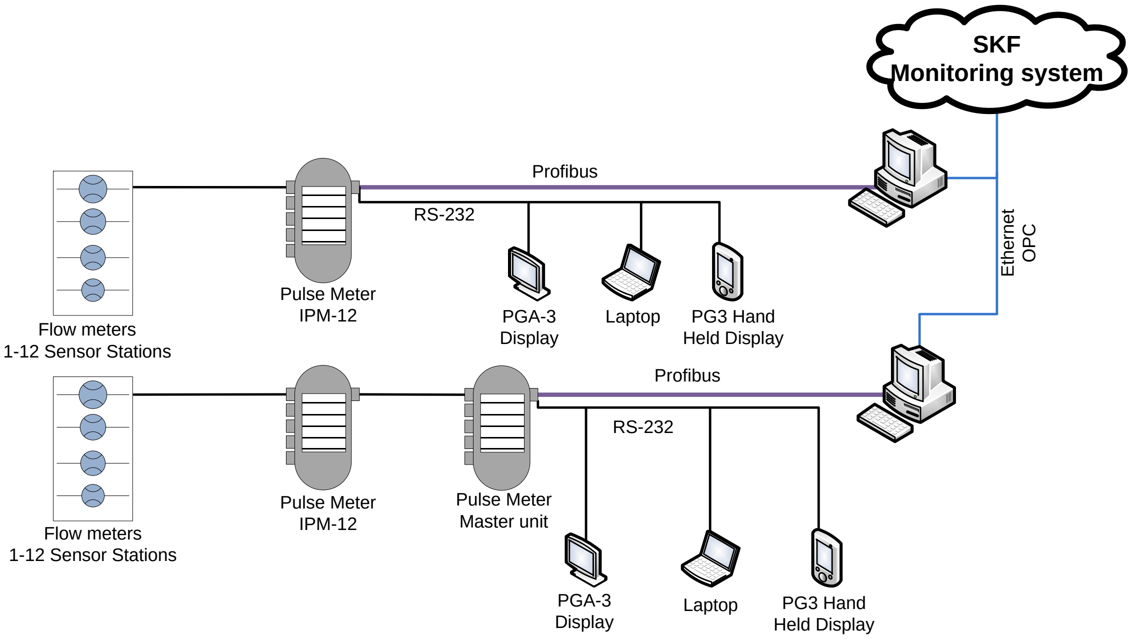


Figure 2.17: SKF Variolub architecture.

Senso System, they are designed to count the pulses generated by the flowmeters. This system can basically be paired with three different types of flowmeters, these flowemeters are shown in Table 2.5.

While in unison the flowmeters cover a wide range of flow measurement (0,05 - 40 l/min), this system may have the same problem of sensor overdimensioning as the SKF Flowline system.

User interface. One of the strongest features of this system is the many different UIs it is capable of supporting. Firstly, it uses the *PGA 3* programming display to set the flow thresholds, both high and low for the alarm settings. This programming display can be both fixed and mobile and physically looks very much like the teach pendants that are usually used to program robots. The use of laptops or personal computer further allows this system to expand to other monitoring systems like the SKF VARIOLUB software, or the SKF monitoring system. A downstream OPC connection via ethernet can also be used to transfer information to remote monitoring systems [SKF 09, Vogel 01].

Hardware architecture. In terms of a communication network architecture the Variolub system offers broad options when it comes to its own Vogel-SKF products. While the IPM 12 is capable of sustaining twelve flowmeters, it is possible to expand this number by serially connecting another IPM 12 device via RS-232 serial communication using a master-slave paradigm. It is then possible to use either the *Profibus* industrial network

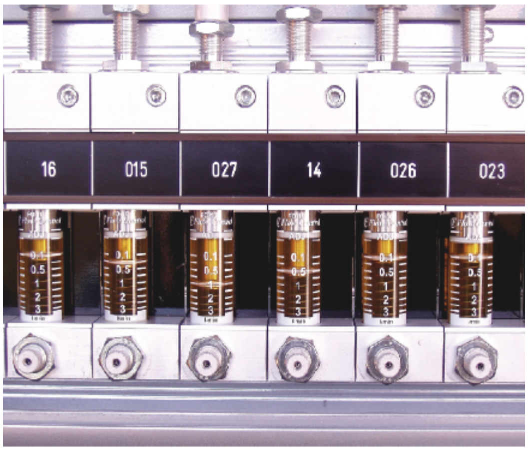


Figure 2.18: Flow Control Rotameters. Adopted from [Flow 07a].

or RS-232 serial communication to connect the flowmeter network to any of the devices previuosly mentioned in the UI section [SKF 09].

The system can also connect via OPC interface (ethernet) to a remote SKF monitoring system, further expanding the range of the information obtained by the flow measurement units. One particular advantage of this system is that the same IPM 12 measuring unit that collects the information from the flowmeters is an information transfer interface capable of supporting both RS-232 and Profibus. This avoids the need of intermediate layers between the flowmeter and the local monitoring user interfaces. Figure 2.17 shows all the generic connections possible in this system as the were previously explained.

Flow Control System

Flow Control is a Finnish company that was created in 1995 and is situated in Muurame, Finland. The company is specialized in circulating oil lubrication flowmeters and systems for chemical, pulp and paper industries. Their main customers are leaders in the pulp and paper industry based in Finland, Sweden, other European countries, USA, Japan, Australia and Indonesia [Flow 10]. Two of their main circulating oil lubrication systems are the *FO-OilFlow* system and the *RealFlow* Digital Oil flowmeter.

General specifications. As Flow Control offers two circulating oil lubrication systems, both of them will be briefly explained. Unlike the systems presented previously, both of the Flow Control are considerably simpler.

The *FO-OilFlow* system uses rotameters, which are a type of variable area differential pressure flowmeter. The advantage behind these types of meters is mainly that no preprocessing of information is needed to be able to know the flow rate going through the meter, since the cylinder tube of the meter already has a scale that shows the current flow

Table 2.6: FO-OilFlow system flowmeters.

Flowmeter	Range
FO-10-x	0,1 - 3,0 l/min
FO-20-x	3 - 10 l/min
FO-30-x	5 - 26 l/min
FO-40/2-x	15 - 30 l/min
FO-50-x	20 - 50 l/min
FO-70-x	30 - 70 l/min
FO-100-x	50 - 100 l/min

rate. The disadvantage is that this greatly limits the reach the flow rate information has, as it is only possible to view the flow rate locally. This is why this kind of circulating lubrication oil system is only suited to work with certain applications. Although Flow Control offers low flow alarm sensors that can be connected to an external interface that further allows to transmit, if not the flow rate, at least alarms indicating whether or not the flow is within the desired range [Flow 07a]. Figure 2.18 shows the rotameters used in the FO-OilFlow system.

In a more familiar manner to the flow monitoring systems of other companies, the *RealFlow* system also works with positive displacement volumetric meters. This system includes a mountable panel where all the desired flowmeters are mounted on, and connected to the control box that functions as a flow computer calculating the flow rate of the oil moving through the meters. The control box of this system has a small Human Machine Interface (HMI) that allows for high and low flow alarm limits. It also functions as a interface to remote monitoring systems and DCSs [Flow 07a].

Flowmeters. As already mentioned both these systems use different measurement principles to calculate flow rate. The rotameters used in the FO-OilFlow system are designed for self-cleaning every time the circulation of oil is stopped and started again. This is done by means of a teflon ring that is attached to the flow indicator float of the sensor. Additionally they offer a very wide range of flow rate measuring capabilities, thus reducing the possibility of overdimensioning meters and making it possible to select a more correct and appropriate meter for different necessities, see Table 2.6 [Flow 07a].

The RealFlow system positive displacement meters, unlike the rotameters shown in Table 2.6 require pre-processing before being able to estimate flow rates. This is done, as in most meters of this type, by using inductive sensors that allow for pulse counting to be done by a flow computer. Additionally, these meters count with a LED that pulses in unison with each detected pulse, the higher the flow rate, the faster the LED blinks, the lower the flow rate, the slower it blinks [Flow 07b]. By observing Table 2.7 it is

Table 2.7: RealFlow system flowmeters.

Flowmeter	**Range**
RF-1	0,1 - 1,0 l/min
RF-2	0,2 - 2,0 l/min
RF-3	0,5 - 5,0 l/min
RF-4	10 - 30 l/min
RF-5	20 - 60 l/min
RF-6	50 - 100 l/min

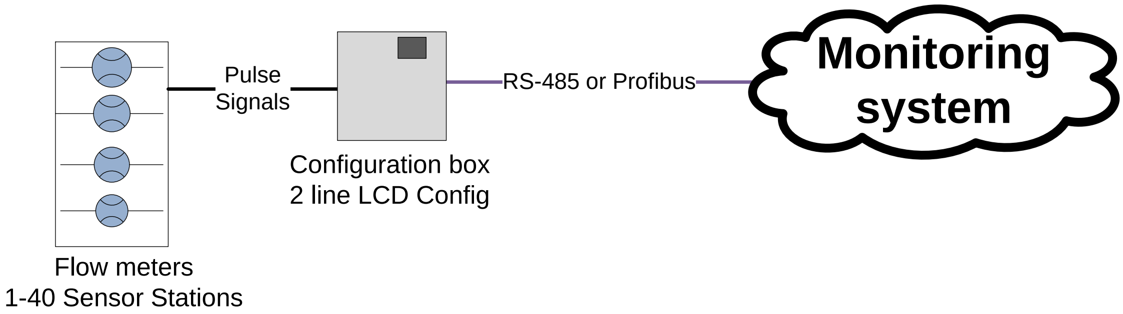
possible to see that, in a similar manner to the FO-OilFlow system, the range covered by the flowmeters is considerably wide and allows for the correct dimensioning of flow monitoring systems.

User interface. The FO-OilFlow System does not have a UI per say. Due to the fact that this system relies on the inherent measuring capabilities of the rotameters, their manual calibration, and their flow rate scale there is no need for a UI. The control unit that is used to sense low flow and optionally, high flow alarms have LEDs that display the status of these alarms. These control units can hold either 1-22 flowmeter signals, or 1-34 flowmeter signals and be connected to other remote monitoring systems that may or may no have a UI [Flow 07b].

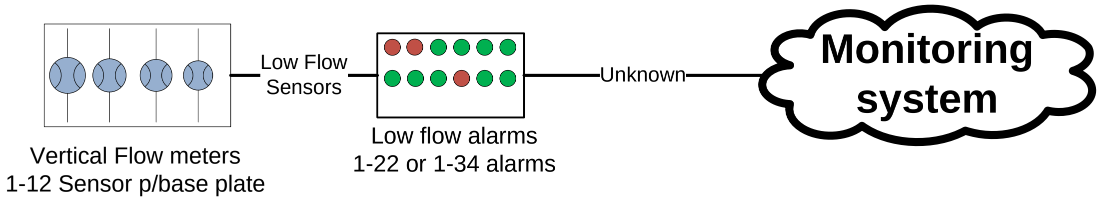
The RealFlow system on the other hand, does have a UI. It is mounted on the control box that receives all the flowmeter signals and allows for both high and low flow alarms. It is a simple Liquid Crystal Display (LCD) display to show what meter is being configured and has a series of push buttons that help in the navigation and control of the UI.

Hardware architecture. The FO-OilFlow system architecture is quite straightforward. It simply interconnects the low and high flow alarm signals that are generated by inductive sensors to the control unit. This unit can manipulate this signals as normal discrete control signals that can be transmitted to another remote monitoring system. Figure 2.19(b) shows a generic configuration of this type of system.

While the FO-OilFlow system does not require any pre-processing of information in order to return a flow rate value, it is still necessary to connect it to a control unit that monitors the status of the high an low flow alarms. In a similar manner, the RealFlow system needs to be connected to a control box that receives the pulses generated by the flowmeters, pre-processes the information to obtain a volumetric flow rate, and compares it to the configured alarm thresholds. It also offers the possibility to connect to remote monitoring systems by means of Profibus or RS-485 serial communication, much like the systems offered by other manufacturers. Figure 2.19(a) shows a generic image of how



(a) Real Flow



(b) FO Oil

Figure 2.19: Flow Control architectures.

this system may be interconnected.

Kytölä System

Kytölä Instruments Oy. was founded by Olli Kytölä in 1945 as a family company that had as an objective to develop and manufacture high quality measuring devices. It is currently based in Muurame, Finland and continues to manufacture and market flow metering and monitoring instruments. Its key applications are found in the pulp and paper, mining, steel, chemical and agriculture industries. Kytölä's products are mainly design to measure fluids and detect waste and leakage of air, gas, water or lubricants [Kytölä 10].

General specifications. The Kytölä system is somewhat similar to the RealFlow system manufactured by Flow Control. They are similar because they both manufacture their own meters and they both mount their flowmeters in a steel housing and connect them to a control box. The Kytölä systems capabilites, however, are quite different from the Flow Control systems. This system is capable of sustaining 48 lubrication points per station and is capable of linking up to 64 of these stations via serial bus. It is particularly designed for use with the Kytölä SR-oval gear flowmeters and allows for high, low and very low flow alarm configuration, with their respective relay outputs. It also has a LCD display with 4 x 20 characters with 4 push buttons for navigation and configuration and is well suited for lubrication oil monitoring, industrial oil flow monitoring and process control

Figure 2.20: SR oval gear meter. Taken from [Kytölä 10].

[Kytölä 09, Kytölä 10].

Flow measurement. The Kytölä Oval D measuring station is specially designed to use the Kytölä SR series flowmeters. These flowmeters are volumetric positive displacement meters with an oval gear, hence the name of the system. While the mechanical gear is different from the one used in the Flow Control system, the functional principle is exactly the same and is based on pulse counting. These sensors can use two different types of pulse detectors, one type is an inductive coil sensor designed by Kytölä, and the other is a NAMUR sensor. Both generate a small voltage pulse signal that is sent to the Kytölä flow computer that calculates flow rates based on the system configuration [Kytölä 04]. An example of the SR series flowmeters can be seen from Figure 2.20.

Table 2.8 shows all the different Kytölä SR models currently in existence and their different flow rate ranges. As can be seen, they offer quite a wide range of flow rate measurements and are quite appropriately dimensioned so that overdimensioning would probably not be a problem any given flow monitoring system.

User interface. The Kytölä systems can be said to have two different UIs. One of these UIs is the display that is local to the Oval D measuring station that allows to view three things: (1)alarms, (2)flows, (3)setup. The alarms section allows the user to view the high, low and very low limits for each of the configured meters. The flows section allows the user to observe the actual flow rate and the set point for the desired flow rate of that particular lubrication point. Lastly, the setup section allows the user to configure the serial communication parameters, the configuration data and the relay functions associated to each of the lubrication points. This UI counts with 4 navigation buttons and a 4x20 character LCD display [Kytölä 06, Kytölä 08].

The other UI this system has is named *OVALConf*, which stands for Configuration Program for Oval Flow Systems. This system allows the configuration of Oval D measuring units by means of a connected computer via serial communication. It allows for alarm

Table 2.8: Kytölä SR flowmeters.

Flowmeter	Range
SRx-1	0,1 - 1,0 l/min
SRx-2.5	0,25 - 2,5 l/min
SRx-6	0,6 - 6,0 l/min
SR-10	1 - 10 l/min
SR-20	2 - 20 l/min
SR-30	3 - 30 l/min
SR-60	6 - 60 l/min
SR-100	10 - 100 l/min

configuration, input card naming, station naming and remote monitoring. It also counts with diagnostic tools that allow to study the behavior of the system [Kytölä 02].

Hardware architecture. The communication architecture of the Kytölä system is very simple and straightforward, as most of the system components are already encapsulated in one big stainless steel housing. To extend the 48 meter units into a flowmeter network these stations are interconnected via RS-485 or RS-422 serial communication. A maximum number of 64 stations can be connected this way. These stations can the connect via RS-485, RS-422 or Modbus to a local monitoring system. Kytölä also created its own *Kytölä KVM* communication protocol for this purpose. From local monitoring computers to remote monitoring systems it is possible to connect via ethernet as can be seen from Figure 2.21, which shows the generic view of this systems architecture [Kytölä 09, Kytölä 06, Kytölä 08].

Commercial flow monitoring systems summary

The previous sections described some of the existing oil lubrication monitoring systems that are being used in the manufacturing industry. Table 2.9 classifies the features explained in the previous sections in a way that allows the evaluation and comparison of these systems. Each evaluation parameter belongs to different evaluation areas, these areas are described below.

1. Measurable variables.- This group includes the operational parameters these flow monitoring systems are able to measure, due to the nature of flow and lubricants, temperature, pressure and contamination are important factors in these systems.

2. Flowmeter types.- Different flowmeters have different ways of calculating flow rate as explained in Section 2.1.3, this either complicates or simplifies the preprocessing of the information obtained by these flowmeters. Accuracy and linearity

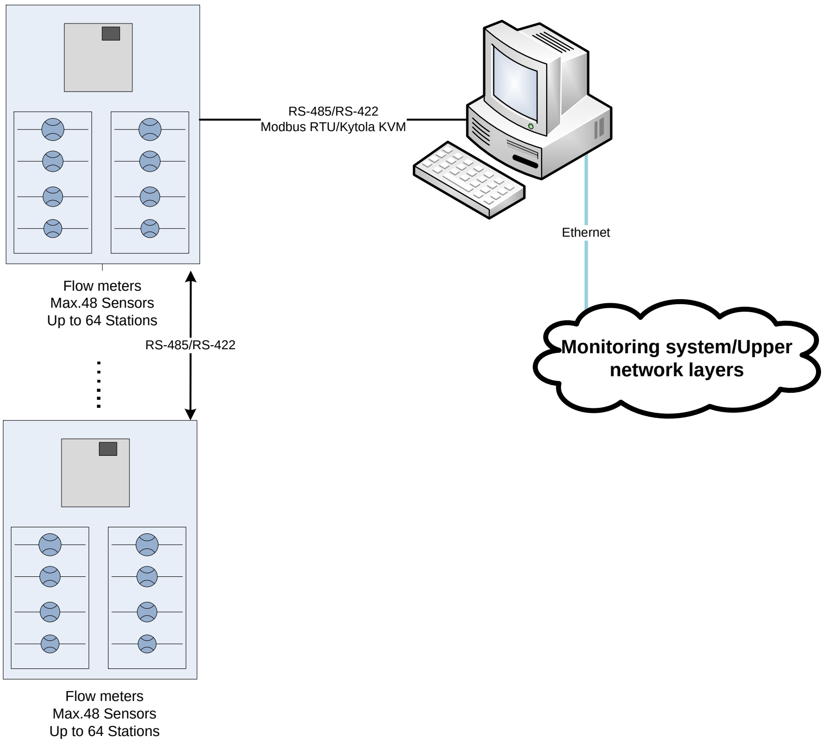


Figure 2.21: Kytölä architecture.

is different, so it should be considered depending on the application which these systems will be used in.

3. Supported amount of meters.- A very important factor in oil lubrication systems is the number of lubrication points supported by the system, this group classifies the amount of sensors per unit/station these systems can handle.
4. Supported signal types.- Refers to the signals that the system is able to process, be they digital like the ones generated by NAMUR sensors, or inductive coils. Or be they analog, like some temperature or pressure sensors.
5. Station features.- Refers to the capability of the system to be stand alone, modular and expandable via connection to other such stations.
6. User Interface.- Evaluates the different types of UI available in these systems.
7. Monitoring features.- Alarms, outputs, configurability of the system, local and remote monitoring capabilities are evaluated in this group.
8. Communication protocols.- Lists all the communication protocols that these systems are usually capable of supporting and compares the availability of these in the different systems.

Table 2.9: Flow monitoring systems comparison table.

General specs	**SKF Flowline**	**Senso 160 Series 2**	**Vario Lub/SKF**	**Kytölä**	**FO-OilFlow**	**RealFlow**
Measurable variables						
Flow	√	√	√	√	√	√
Temperature	√	√	×	×	×	×
Pressure	×	√	×	×	×	×
Water Content	×	√	×	×	×	×
Flow meter type						
Turbine meter	√	×	×	×	×	×
Gear meter	×	×	√	×	×	√
Oval gear	×	√	×	√	×	×
Rotameter	×	×	×	×	√	×
Supported # of meters						
0-25 meters/station	√	√	√	×	√	√
25-50 meters/station	×	×	√	√	×	√
50-75 meters/station	×	×	×	√	×	×
Signal types						
Analog signals	×	√	◇	×	×	×
Digital signals	√	√	√	√	√	√
Station features						
Stand-Alone	√	√	√	√	√	√
Modular	√	√	√	√	√	√
Station interconnectivity	√	√	√	√	◇	◇
User Interface						
LED UI	√	√	×	×	×	×
Digital Display UI	√	√	×	×	×	×
LCD Display UI	×	×	√	√	×	√
Button UI	√	√	√	√	×	√
Touch Screen UI	×	×	×	×	×	×
Monitoring Features						
Configurable measurements	◇	√	◇	√	√	√
High flow level alarm	√	√	◇	√	△	√
Low flow level alarm	√	√	◇	√	√	√
Low low(zero flow) level alarm	√	×	◇	√	×	×
Alarm bypassable	◇	√	◇	√	◇	◇
Multiple measurement units	◇	√	◇	◇	√	◇
Output relays/Outputs	√	√	◇	√	√	√
Local Monitoring	√	√	√	√	√	√
Remote Monitoring	√	√	√	√	√	√
Communication protocols						
RS-232	√	√	√	×	×	×
RS-485	√	√	×	√	×	√
RS-422	×	×	×	√	×	×
Modbus RTU	×	×	×	√	×	×
USB	√	×	×	×	×	×
Profibus	×	×	√	×	×	√
CAN	√	×	×	×	×	×
Ethernet-OPC	×	×	√	×	×	×
Ethernet	√	×	×	×	×	×
Kytola KVM protocol	×	×	×	√	×	×
√ = Supported	◇ = Unknown					
× = Unsupported	△ = Depends					

2.2 System Integration Tools in Condition Monitoring Systems

In the last decades there has been many developments in the manufacturing industry, the advent of fieldbuses and the realization of the advantages of decentralization have forever changed factory automation. While control devices such as PLCs, HMIs, sensors and actuators continue to evolve on their own, the focus of development has somewhat shifted towards a better horizontal and vertical factory integration. To accomplish this integration, a lot of work has been done in communications by many communities in the form of interface standards, the problem remains, however, since the integration of many different communication protocols and fieldbus standards is far from an easy task [Huovinen 10].

One such standard, comes in the form of an abstract hierarchical division model that describes the data transfer and information flow that exists in manufacturing enterprise integration. This standard, created by the joint committee of the American National Standard Institute (ANSI) and The Instrumentation, Systems and Automation Society (ISA), and named after these institutions as the ANSI/ISA-95 standard defines hierarchical levels at which decisions are made and addresses the interfaces between levels [Huovinen 10, Delamer 08]. There are five levels defined by this standard [Delamer 08]:

- Level 0 defines the physical processes of a factory.
- Level 1 refers to the Sensors and Actuators of any given system.
- Level 2 addresses Assembly Machines and Equipment.
- Level 3 focuses on Manufacturing Operations and Control.
- Level 4 refers to Business Planning and Logistics.

While this classification is quite accurate, this thesis will refer to the *Automation Pyramid* to classify these same levels. The levels addressed by both these classifications are practically the same. The difference is that the automation pyramid does not include Level 0 and extracts the *Supervisory Level* from Level 2 of the ISA-95 Standard. Figure 2.22 shows a mixed classification based on the ISA-95 standard and the automation pyramid, it also includes some of the protocols, standards and languages that enable this integration between levels to be accomplished. It is possible to observe that many different components are required to accomplish a full vertical integration between all levels, the interaction between these levels is fundamental to the integration of manufacturing systems and consequentially affect monitoring systems. The main objective of Figure 2.22 is to show all the most common and different communication integration technologies that are required in monitoring systems.

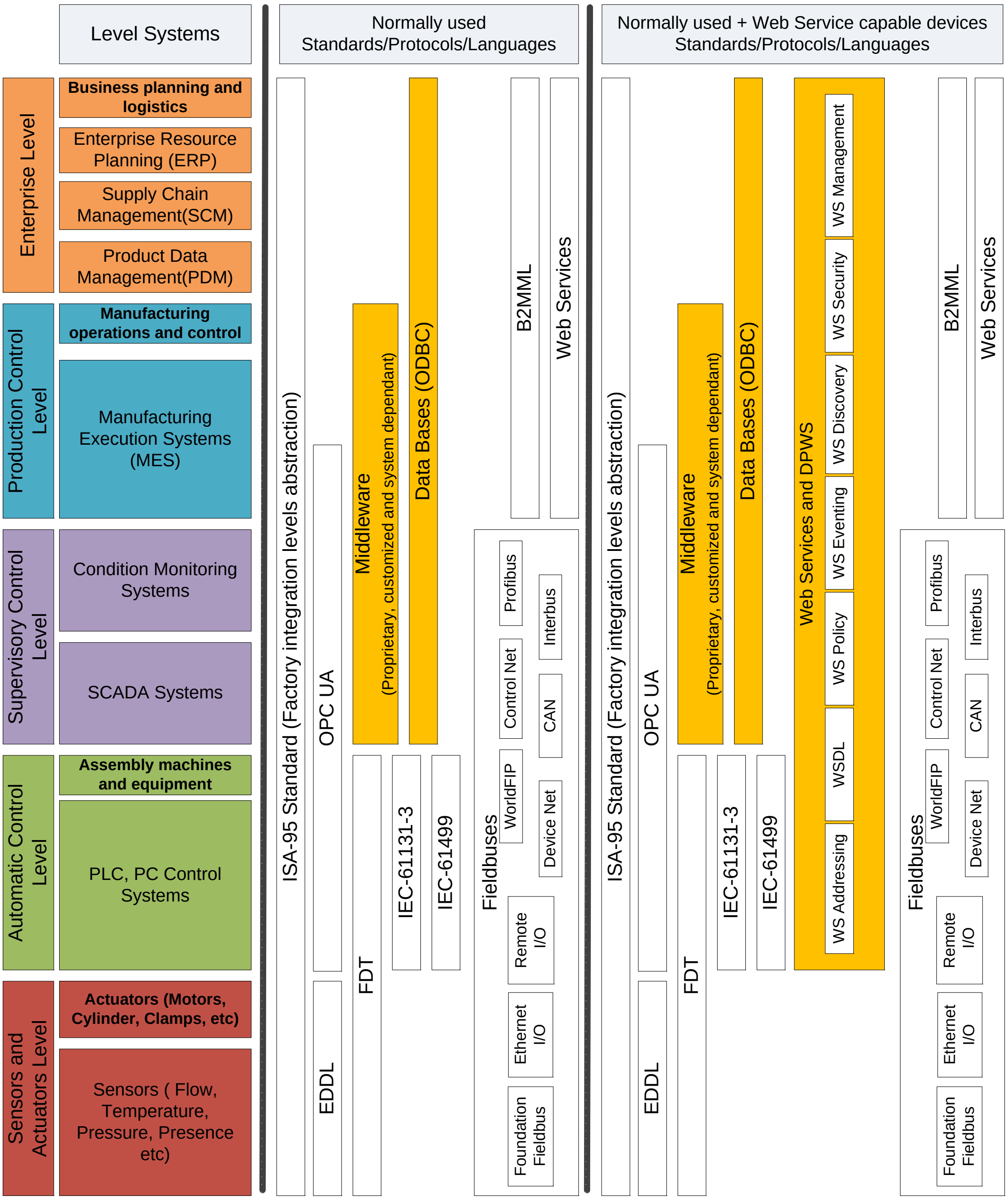


Figure 2.22: Communication integration components in automation.

As seen in Figure 2.22, there are actual level systems associated to each of the hierarchy levels. The *Enterprise Level* relies on Enterprise Resource Planning (ERP), Supply Chain Management (SCM) and Product Data Management (PDM) systems to accomplish the necessary tasks at this level [Huovinen 10]. ERP software systems are designed to improve and unify the components and functions of an enterprise. Namely, focus on tasks such as: handling, accepting and confirming customer orders, and forecasting sales, maintaining use of components and raw material, preparing accompanying documents for shipment, among many other functions. In some cases it is possible to find that some tasks of the SCM and PDM systems are as well carried out by the ERP [Delamer 08].

In a similar manner, the *Production Control Level* usually has a Manufacturing Execution System (MES) system. MESs are production floor control systems that are designed to tackle many different tasks, the Manufacturing Enterprise Solutions Association (MESA) defines these as systems that guide, initiate, respond to, and report on plant activities as they occur from order launch to finished goods. In addition to this, MESA has defined 11 functions that fall under a MES, these are:(1) Resource allocation and status, (2) Dispatching production units, (3) Data collection, (4) Quality management, (5) Maintenance management, (6) Performance analysis, (7) Operation/detail scheduling, (8) Document control, (9) Labor management, (10) Process management and (11) Product tracking and genealogy [Younus 10, Blanco 03, MESA 01, Qiu 04].

The following two levels, *Supervisory Control Level* and *Automatic Control Level* are considerably different to the previous MES and ERP systems. While they form an integral part of the manufacturing chain, the supervisory control level is mainly concerned with the condition monitoring and maintenance of the factory floor systems usually by means of SCADA systems. The automation control level, as its name implies, is composed of assembly machines and equipment, namely assembly machines and their controllers. While the top levels of the pyramid focus on enterprise administration, personnel, supply chain management and other things, these lower levels concern themselves with producing the sale product based on the instructions from the higher levels. It is therefore no surprise that good integration and data flow are necessary to accomplish the manufacturing of high quality products, while raising the competitive capacity of the enterprise [Meilin 10, Younus 10]. Lastly, the *Sensors and Actuators Level* refers to precisely the components that act as either information gatherers or actuators that inform and act on the orders given to them by the automation control level.

In order to accomplish the data integration of all these levels many things different components are necessary. The left part of Figure 2.22 shows some of the most commonly used standards, protocols and languages that enable the functioning and integration of manufacturing systems. At the lowest levels Electronic Device Description Language (EDDL) and Field Device Tool (FDT) device descriptions ease the integration to the upper automatic control level while fielbuses are used to collect sensor and actuator signals. Fieldbuses can simply be considered to describe channels that allow bidirectional flow of digital information between field devices and control systems, they can classified or divided into device buses (e.g. DeviceNet, Profibus DP), sensor buses (e.g. CAN, ASI), and process buses (e.g. FOUNDATION Fieldbus, Profibus PA) [Huovinen 10].

As far as languages, the IEC-61131-3 standard defines four different programming languages that are commonly used in PLCs: Structured Text (ST), Instruction List (IL), Ladder Diagram (LD), Function Block Diagram (FBD) and Sequential Function Chart (SFC) which is mostly considered a structuring tool for higher level programming [Otto 09]. The IEC-61499 is another standard for programming controllers, it is also based on blocks and is mainly used in distributed control applications.

Moving up the levels of the automation pyramid to the supervisory control level it is possible to realize that this is the main level of concern for this thesis. While fieldbuses have eased the transfer of low level information to process controlling devices, the transfer of this information to higher levels of the manufacturing chain, supervisory level included, has always been an issue of concern. OPC can be used together with EDDL, FDT and fieldbuses to integrate the information flow between the three lower levels of the automation pyramid [Huovinen 10]. The problem arises when trying to connect the three lower levels with the two higher levels. Every industry is different, and as a consequence uses different standards, fieldbuses, software and integration technologies to handle their processes and information at all the different levels. This is where *middleware* comes in; for lack of a better word, middleware is the name used for the custom integration systems used to facilitate the information flow between the low and high levels of any manufacturing industry. Whether the middleware is based on using intermediate databases to read/write data or using Association Connecting Electronic Industries (IPC) based standards that work with Extensible Markup Language (XML), the variations are vast [Delamer 08, Delamer 06]. In essence, middleware is a proprietary integration solution that ties any given manufacturer to a service provider. While middleware works well and is very common, it tends to marry the manufacturer to family of solutions. Not only that, but it tends to create upgrade, repair and reconfigurability problems in both manufacturing and monitoring systems. Web Services have also reached the manufacturing industry, while at the moment they are limited to the higher levels of the automation pyramid there are currently many attempts to push this technology to the lower levels. This and some of the previously mentioned integration components will be briefly explained in the following sections.

2.2.1 Databases

One of the first technologies that were introduced to solve the integration problem in the manufacturing industry was the use of databases. Databases basically store digital information in the form of records, these records can be read from and written to and are usually an integral part any enterprise network. It is therefore no surprise that one of the first attempts to accomplish inter-level integration was through existing network components. The main problem with the use of databases is the fact that the information formats of enterprise and factory levels are completely different. Not only that, but there are many different communication protocols, and different types of database systems. Some early attempts to accomplish this integration involved pre-processing information at the PLC level and arranging it in a way that was usable by a database, see [Russell 90]. Other attempts involved creating a Communication Description Database (CDDB) that accumulates all the information from a diversity of functions, such as business, administration, supervision, maintenance, etc. The relationship between these components was then analyzed and used accordingly by the connected relationships, see [Mammeri 91].

With the advent of ethernet networks, and their victory over other networks their introduction to the office domain became inevitable. This in turn reduced costs and devices for this sort of network soared, in turn causing the interest to introduce industrial devices capable of working on the same network [Neumann 05]. In turn, Microsoft developed the Open Database Connectivity (ODBC) interface, which allows the integration of data between different platforms, proprietary personal computer vendors and mainframe databases [Microsoft 10]. ODBC requires three components in order to work:

- ODBC Driver.- integral part of the ODBC Server, works as an interpreter between the the ODBC Client and Server.
- ODBC Client.- any Windows based application that is ODBC enabled.
- ODBC Server.- a server Database Management System (DBMS), like SQL Server, Oracle, Foxpro, Microsoft Access, etc.

The client usually uses a language that is unknown to the server, and therefore requires the existence of a driver to function as an interpreter between them. The advantage of ODBC resides in the fact that many different drivers may exist and allow the interconnection of many different types of systems regardless of the application, platform or database used [Microsoft 10]. An example of such system could be a SCADA system as shown in Figure 2.23. Database systems are also used to store Computer Aided Design (CAD) data that can be used by Computed Numerically Controlled (CNC) machines to produce mechanical parts, and are still very commonly used in manufacturing systems despise the rise of new technologies [Bernstein 96, Godavari 91, Lipnickas 09].

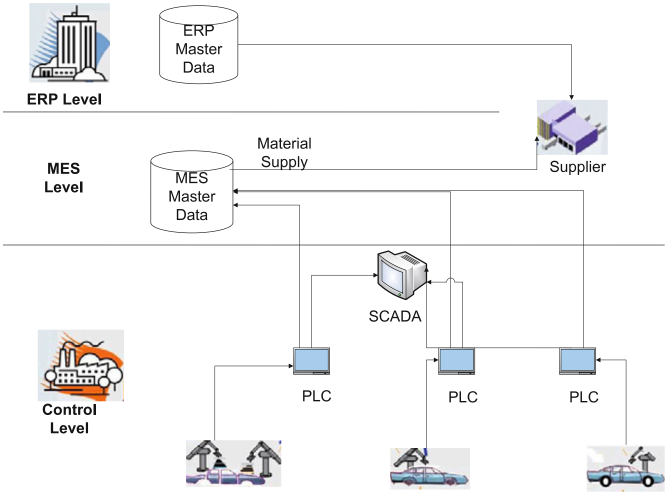


Figure 2.23: Computer distributed system. Adopted from [Kwiccicń 10].

2.2.2 OLE for Process Control (OPC)

OPC was created in the late 1990's with the objective of integrating the enterprise systems that support the industry by means of open connectivity based on open standards. It was originally based on Microsoft's OLE Component Object Model (COM) and Distributed Component Object Model (DCOM) technologies. This specification defined a set of objects, interfaces and methods that helped facilitate the interoperability of manufacturing systems and process control systems [OPC 10]. In turn, this allowed for OLE/COM compatible PLCs and intelligent field devices to connect via methods and properties to supervisory level software. Depending on the supervisory system however, the need for drivers that allowed the communication between different devices was necessary, much like the drivers used in ODBC systems. In a sense, it can be said that the OPC Foundation was, and still is, trying to eradicate the need for such drivers by developing a common method by which applications can access information and data regardless of the source, whether this be a device or a database [Blanco 03].

In simple terms, the objective of OPC seeks to determine the frontier between hardware devices and software components and generate a standard method for these to communicate with each other. This way the supplier creates a reusable server that is capable of communicating via an OPC interface with a piece of hardware that works as a source of information [Blanco 03]. To accomplish this, the OPC Foundation has created a series of specifications that address the different aspects of integration, some are shown below [OPC 10].

- OPC Data Access.- used to move real-time data from control devices to information display clients.

- OPC Alarms and Events.- provide alarms and event notifications on demand.
- OPC Historical Data Access.- opposed to OPC Data Access which provides real-time information, this specification provides historical data that has already been stored somewhere.
- OPC Commands.- a new set of interfaces that allow OPC clients and servers to send and monitor control commands which execute on devices.

Due to the fact that the OLE/COM model on which OPC is based on is beginning to be overrun by new rising technologies, not all devices and components support the technology. In order to deal with this evolution the OPC Foundation has developed the OPC Unified Architecture (UA) specification, which is not based on Microsoft COM and will provide standards based on cross-platform capability [OPC 10, Huovinen 10]. This transition towards a unified architecture started with the development of the OPC XML DA specification which introduces the use of XML, thus allowing the flow of information beyond the corporate firewalls and permitting cross-platform connectivity via Simple Object Access Protocol (SOAP) and Web Services through the internet [Huovinen 10, OPC 10, Blanco 03]. The limitations of OPC UA however, are mainly evident at the lower levels of the automation pyramid, namely in the device level. While OPC UA allows the integration of process control devices with supervisory control systems and even MES systems, the information offered by low level devices can only be accessed through process control systems. In order to further expand the reach and flow of information, device integrations standards such as FDT and EDDL can be used [Huovinen 10].

2.2.3 Field Device Tool (FDT)

The FDT concept, just as the OPC standard, is based on Microsoft's COM. It is therefore easy to integrate and to use as an extension of OPC that allows access to intelligent device data and information. As previously mentioned, while OPC allows both vertical and horizontal integration from the process control level upward, FDT extends that vertical integration to the lower device levels [Huovinen 10]. In a sense, FDT defines interfaces between device specific components and control systems, these interfaces are software components called Device Type Managers (DTMs) [Neumann 01].

A DTM runs inside the FDT frame application that manages and coordinates these DTMs. Given that a DTM is simply a software component, it can represent all the functionality of any given device [Feng 09]. DTMs in turn can be of three kinds [Huovinen 10]:

1. Communication DTMs.- a device class with direct access to a communication component.

2. Gateway DTMs.- used for routing between different types of protocols.
3. Device DTMs.- used to represent actual field devices. They interact with communication and gateway DTMs.

In short, FDT provides a Graphical User Interface (GUI) based on ActiveX that allows interaction with intelligent field devices by means of DTMs. In turn Communication DTMs allow inter-protocol communication and can support any communication topology when used in conjunction with Gateway DTMs. Lastly, FDT can be used with HART, FOUNDATION Fieldbus, Profibus DP, Profibus PA, Profibus IO, DeviceNet, Ethernet IP, Interbus, AS-Interface and ControlNet protocols [Feng 09, Neumann 01, Huovinen 10].

While FDT offers many advantages, and allows for easy integration with OPC a major shortcoming of FDT is its dependence on the Windows platform. Due to the fact that Windows technology is subject to constant updates and upgrades the same applies to FDT platforms, requiring certain amount of DTM regression testing [Huovinen 10]. Additionally, it relies on relatively old technology like ActiveX and COM, both which have already lost official support [Feng 09]. It is therefore no surprise that the FDT Group in conjunction with OPC UA and other companies have created a technical group named *Device Information Model for OPC UA*. This group seeks to allow OPC UA client applications to access device data through DTMs [FDT 06].

2.2.4 Electronic Device Description Language (EDDL)

In a similar fashion to FDT, EDDL is designed to describe intelligent field devices. Its origin dates back to 1990 when Highway Addressable Remote Transducer Protocol (HART) instruments appeared in the industrial market, when industrial fieldbuses came to be. It originally allowed an operator to connect to any HART instrument via a handheld device and calibrate said instrument [IAASIA 06, Yokogawa 06]. While FDT is based on different software components that work as translators between devices and Windows applications, EDDL is a simple text-based file that describes a device in terms of variables the instruments uses (e.g. flow, pressures, ambient temperatures, high and low limits, calibration settings, etc).

In 1992 the HART Communication Foundation (HCF) realized that users wanted to extend the configurability of devices from handheld devices to digital interfaces and so standardized EDDL to allow the description of devices in a programmable manner via control systems. Two years later, in 1994 the Fieldbus Foundation and Profibus adopted EDDL as a standard, though all three organizations implemented the technology independently and differently. It was not until 2003 that HCF, Foundation Fieldbus and Profibus Nutzerorganisation eV (PNO) submitted a unified version of EDDL to the International

Electrotechnical Commission (IEC) and later, in 2004 turned into the IEC-1804-2 standard [IAASIA 06].

It can be said that some of the disadvantages of FDT are overcome by EDDL due to the platform independent nature of EDDL. Since it is based on a simple text description file, setting it up requires copying a single file, there are no software components and therefore no version management required. The only version management required is linked to the device itself, in which case only the EDD file is changed [Feng 09]. It could be said that the limitation presented by EDDL is reduced to the complexity of the application required, simply because this technology was designed to facilitate device calibration [Huovinen 10, IAASIA 06].

Enhanced EDDL

Enhanced EDDL is an attempt to take this technology beyond simple intelligent device calibration. The Fieldbus Foundation, HART and PNO groups have worked together to accomplish this new and improved EDDL which supports device diagnostics, asset management,UI displays, bar charts, trends, etc. Additionally, in 2005 the OPC Foundation decided to adopt EDDL as the device description technology it would use in OPC UA [IAASIA 06].

Before the creation of enhanced EDDL, it could be said that FDT and EDDL could work as complementary technologies, as they both intended to have the same function, albeit in a different manner. While both these technologies have their advantages, one is limited by its scope and the other by old technology. Enhanced EDDL seeks to fill the gap by fulfilling platform and software independence whilst allowing complex applications that go beyond simple device calibration. This is accomplished by the text-based nature of EDDL which is tokenized and distributed in a unique format to the fieldbus that is using it. This code can then be identified by run-time software that interprets intelligent device information [IAASIA 06, Yokogawa 06]. In essence, facilitating the integration of data flow between the three lower automation levels.

2.2.5 Web Services

The previously addressed technologies mainly focus on either the lower levels or the higher levels of the automation pyramid. The various number of network protocols, fieldbuses, proprietary applications, integration standards and software platforms have forever complicated vertical and horizontal information integration in the manufacturing industry. While many different integration methods exist, some of which have already been explained, the result is often a customized, non-standardized system with poor to no scalability [Huovinen 10, Cândido 09].

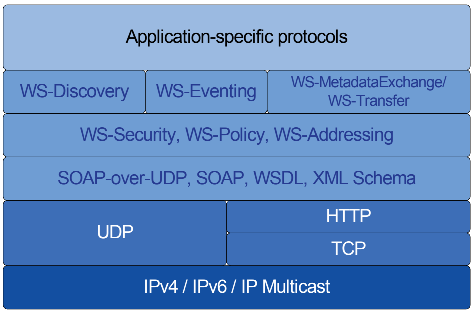


Figure 2.24: DPWS protocol stack. Adopted from [Zeeb 07].

Web Services allow the intercommunication between software components that offer, in essence, a *Service* in the form of a web application with a particular capability that a software web client can use or invoke. In turn, Web Services are based on the well understood Hypertext Transfer Protocol (HTTP) that is used in the Internet, it applies the request-response concept used in web pages and ports it to an application-to-application system [Feng 09]. The most common implementation of Web Services uses XML to send messages between applications, these messages are included in a SOAP envelope. In order to describe the interfaces provided by Web Services, the Web Service Description Language (WSDL) is used. A WSDL file defines the Web Service it is associated to in terms of its function and its input and output formats by means of an XML based description [Feng 09, W3C 01]. Lastly, Universal Description Discovery and Integration (UDDI) acts as a XML based registry where all the Web Services can be found and invoked according to the needs of the web client, in a sense, a UDDI registry works as WS yellow pages. This registry also uses the WSDL file to describe the Web Service and SOAP as the access means to the UDDI directory [Feng 09, W3C 10].

DPWS

The Device Profile for Web Services is the result of development done with the Web Service architecture protocol building blocks that allow the creation of different profiles, enabling the creation of protocols for specific applications. DPWS was originally developed to allow the use of Web Service technology in resource limited devices as it allows these devices to: (1) send and receive messages between Web Services, (2) dynamically discover Web Services, (3) describe Web Services, and (4) subscribe and publish events that can be sent/received by/from a Web Service [Zeeb 07]. Lastly, DPWS allows to encapsulate the functionality of any given device by means of Web Services, that if seen from the outside, present only one communication interface.

While DPWS is not the first attempt at this sort of device integration based on the SOA paradigm, it is the first that relies on Web Services. Other technologies that have attempted a similar approach to DPWS are the Open Service Gateway Initiative (OSGi), the Home Audio/Video Interoperability (HAVi), Java Intelligent Network Infrastructure (JINI) and Universal Plug and Play (UPnP) [Zeeb 07].

As seen in Figure 2.24 the previously mentioned components of Web Services are all used in the DPWS stack. In the particular case of this profile, it can be said that WSDL plays a similar role to EDDL and FDT as it represents the capabilities of the device in an XML description of its Web Services. The components on the top of the stack are further explained in the sections below.

WS Eventing

WS-Eventing defines a protocol that is part of the WS-Brokered Notification standard that implements publish and subscribe functionality. It allows both push and pull of events of interest that involve both the *Producer* and *Consumer* paradigm. In essence, subscribers request to receive notifications from an event source, namely a publisher. Lastly, there are also subscription managers that are responsible for holding the subscription between the publisher and the subscriptions. Subscriptions must be requested and can have an expiration time [Zeeb 07, Spiess 09].

WS Addressing

WS-Addressing is mainly concerned with providing an addressing mechanism for Web Services in a transport neutral manner. Namely, overcoming the dependence of SOAP to HTTP, by introducing the use of end-point references (EPR). These EPRs can be HTTP-based URLs, Unified Resource Identifiers (URI) or International Reference Identifiers (IRI) [Zeeb 07].

WS Discovery

As its name implies, WS-Discovery is a discovery protocol based on IP multicast that seeks to automate the discovery of services by introducing three different end-point types: target service, client and discovery proxy. Target services or services that are offering themselves to whoever may be in need of them. A client is the one looking for target services and the discovery proxy is the enabler of this discovery [Zeeb 07].

WS Security

WS-Security is mainly concerned with the confidentiality and integrity of SOAP messages. This specification defines SOAP headers and other additional components that ensure the signing of these messages [Zeeb 07].

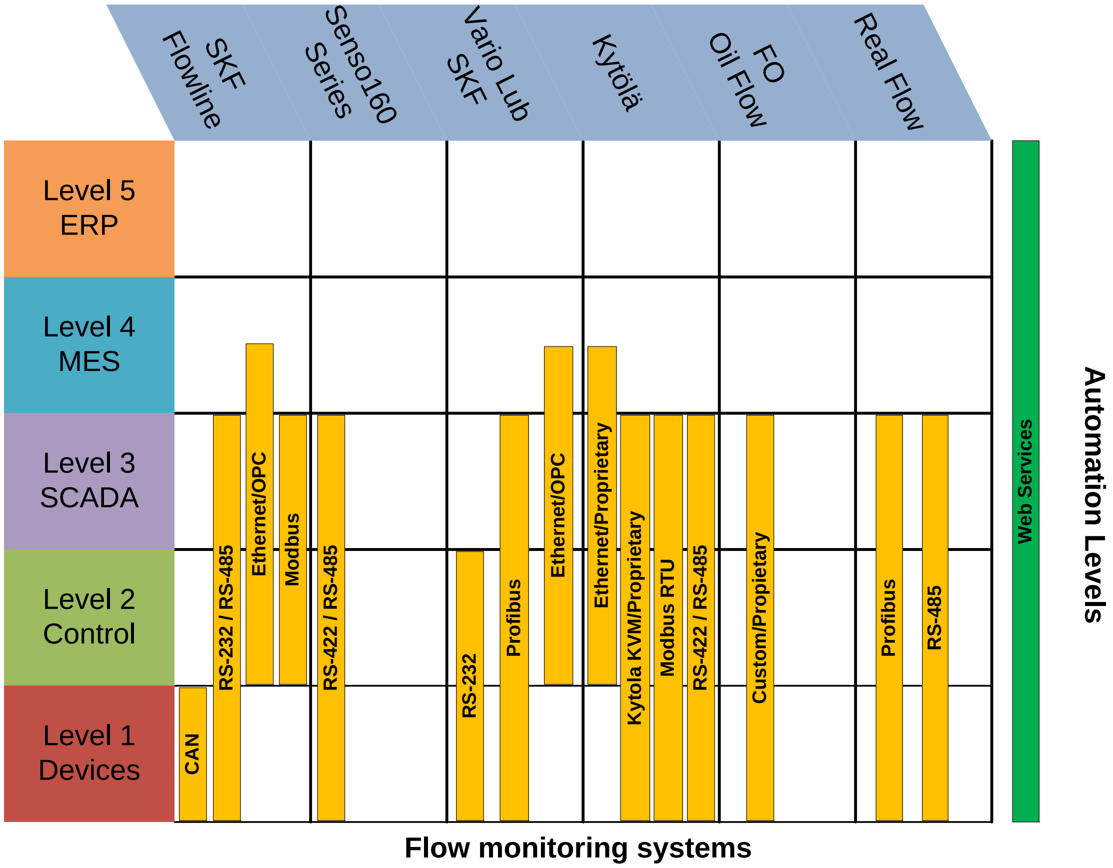


Figure 2.25: Flow monitoring systems mapped to integration technologies.

2.3 Summary

The previous sections have all relatively briefly explained the most important factors in flow monitoring systems. From the importance of condition monitoring, the theory behind flow and the parameters that affect it, to the state of the art flow monitoring systems and integration technologies.

Table 2.9 in Section 2.1.4 is a summary of features, components, and general capabilities of the six circulating oil flow monitoring systems that were studied. While there are many different areas of opportunity in the way these systems are designed, factors such as the type of flowmeters used affect aspects of precision, accuracy and repeatability, the amount of measurable variables can help generate additional information by means of data aggregation. Additionally, the number of flowmeters supported and the configurability of the stations that function as hubs for these flowmeters is of great importance due to the number of lubrication points in paper machines. User interfaces play a big role in configuration, setup and calibration, and are thus of great importance.

It is quite obvious however, that the main problem in these circulating oil monitoring systems is due to the same issue that has plagued the manufacturing industry for many years. The flow of information and data integrability at horizontal and vertical levels is becoming more important as quality standards continue to get more strict, and customers demand low cost and high customization. As can be observed from Figure 2.25, most of the systems offer a variation of fieldbus technologies that help the integration of the flowmeter stations they offer. It is possible to extend the reach and number of flowmeters by these means, but only a couple of these systems offer explicit data integration to the higher levels of the automation pyramid. And even if capable of extending to the MES level, they do so by means of proprietary technology and aging standards, such as OPC.

As Web Service technology becomes more popular among the manufacturing industry, and as the rise of intelligent field devices allow the extension of this technology to the lower automation levels, it is now possible to integrate all the levels in automation using the same technology, effectively reducing or potentially eliminating a lot of the current integration problems. There have already been many projects that have developed the idea of *Orchestration* and *Choreography*, in which whole manufacturing lines are controlled by means of Web Service invocation. [Cândido 09] provides an explanation of the work done so far in regards to the integration of SOA technology into the manufacturing industry. Other authors have also addressed the integration of Web Services with existing technologies, [Lipnickas 09] for example, addresses interoperability between SCADA systems and Web Services. [Walzer 08] mentions that by combining SOA with Even-Driven Architecture (EDA) it is possible to achieve truly flexible, re-configurable, and easily extensible systems.

While there is now an interest to extend the use of Web Services to condition monitoring, not many applications yet exist. This thesis will elaborate on an application for circulation oil flow systems based on Web Service technology.

3. USE CASE: WEB SERVICE BASED FLOW MONITORING SYSTEM

In this chapter the development of a use case for a circulating oil system will be presented. Section 3.1 will address and elaborate on the requirements of flow monitoring systems based on the industrial practices review presented in Chapter 2, and the needs of hydraulic service company that seeks to improve such systems. Based on said requirements, Section 3.2 will elaborate on the specifics of the use case and how said system was developed and tested. Finally, Section 3.3 will explain the capabilities of the system in regards to higher tier data integration by means of Web Services.

3.1 Circulating Oil Flow Monitoring System Requirements

In Chapter 2 the importance of condition monitoring and flow measurement was addressed and explained. Additionally, circulating oil flow monitoring systems were briefly evaluated in conjunction with the integration technologies that these monitoring systems use in order to integrate the flow of information, both horizontally and vertically. By observing Figure 2.25 it is possible to realize that the most important issue in these systems is not their capability to measure flow and allow its monitoring, but their capability to easily and seamlessly integrate to the higher levels of the automation pyramid.

While integration is probably the most important issue in these systems, it is not the only one. Table 2.9 shows that the measurable variables available to most of the systems is limited. Not only that, but the supported number of meters per station is also considerably reduced, not to mention that the user interfaces (UI) are, for lack of a better word, considerably basic and limited. Another important factor in this type of system is the configurability they allow in terms of alarm settings and notifications. Lastly, it is also worthy of note, that while each of the evaluated systems fulfill what they are designed and meant to do, there is still room for many improvements.

The Service-bAsed Monitoring for Industrial Ambients (SAMIA) Project, supported by the Finnish Funding Agency for Technology and Innovation (TEKES) is a joint effort made by three Finnish companies and the Tampere University of Technology to accomplish said improvements in monitoring technology as a whole. The objective of the SAMIA project is to “develop technologies for a service-based monitoring ambient, covering embedded and distributed data processing at source, event-based data gathering for minimizing the bandwidth requirements, and data aggregation and visualization for handling large amount of data" [SAMIA 09].

One of the companies involved in the SAMIA effort is FluidHouse, a Finnish company that can be said to be one of the leading suppliers of hydraulic and oil lubrication systems in Finland. It forms part of the FH-Group which is composed of FluidHouse Ltd. Finland, FluidHouse Shanghai Co. Ltd. and Prodatec Ltd. With more than 30 years of experience, it is currently seeking to introduce new technology into the manufacturing industry in the form of advanced condition monitoring systems. This is one of the main reason for its participation in the SAMIA project where parallel efforts, in the form of use cases were planned and implemented. These use cases focused on different ways to complete the objectives presented by the project, one of these use cases is the basis for this thesis.

As such, it can be said that the use case that will be presented in this chapter has as an objective to build and test a circulating oil flow monitoring system that avoids the pitfalls of the systems evaluated in Chapter 2, builds on the strengths of current monitoring systems while building itself over Web Service based technology. To accomplish the design of such a system the existing monitoring systems were broken down by further comparative analysis to conclude which are the strongest characteristics of each system. The following sub-sections do this in terms of the general specifications of these systems, and elaborate with more detail on the communication architecture and user interface components of flow monitoring systems, much as it was divided in the previous chapter.

3.1.1 Analysis of General Specifications

This section analyzes and compares the differences, advantages and disadvantages of the evaluated flow monitoring systems based on the same evaluation areas explained in Section 2.1.4. This is done by relying on the system features of each system and on Table 2.9.

Measurable variables

In this particular area of comparison it is quite easy to observe which system can offer the most types of measurements. The Senso 160 series 2 system is capable of measuring flow, temperature, pressure and water content of lubrication oil. This system is used and was designed for the paper and pulp industry and is therefore a very robust system. The use of this system in any other type of industry, however might result unnecessary or excessive capabilities, given that the system was designed for one specific purpose. The other systems mentioned only measure the flow of lubrication oil and can be used in both paper and pulp and other industries.

Flowmeter types

There are three different measurement principles being used in these flowmeters. The Turbine meter uses a propeller that is pushed and moved by means of the fluid flow, the flow rate is estimated by measuring the rotation speed of the propeller. Many methods can be employed to measure the speed in this type of meter, including the same method used by positive displacement meters. The turbine flowmeter in the SKF Flowline system uses an inductive method to calculate flow. This type of sensor has a repeatability of ±0.02% and a linearity of ±0.25% [Jamal 02].

The second type of measurement principle is positive displacement. The idea behind this principle is the counting of pulses generated by the flow of a fluid in a closed chamber that generates movement in a mechanical component, the concept is clearly explained in Section 2.1.3. These flowmeters can provide an accuracy of up to ±0.25% and a repeatability of ±0.05%. In the particular case of oval gear flow meters the measurement error can be as low as 0.1%, though at low flow rates it can increase to 0.5% due to "slip" leakage [Liptàk 03].

Lastly, the third type of flowmeters used, and only used by the FO-OilFlow system made by Flow Control. These flowmeters, are variable area flowmeters that measure flow based on differential pressures. These sensors have a repeatability ranging from ±0.25% to ±2% (full scale) depending on length of their scale, and a linearity rated at ±1% full scale [Fees 01].

All three flowmeters have a similar repeatability and are considerably accurate. Albeit, both the turbine and positive displacement meters can be said to be more accurate than the rotameter. Not only that, turbine and positive displacement meters are some of the easiest to use in industrial applications as the measurement calculation can be done in a relatively easy manner compared to other types of sensors. Additionally, given the nature of the flow calculation method, these pulse generating meters implicitly require a device to calculate the flow rate, thus inherently having the calculation registered in digital format. Since rotameters calculate flow rate based on physical phenomena, the flow rate is only visible on the rotameter scale. It is therefore safe to say that even if all the systems in evaluation use different flowmeters, and they are relatively on equal terms when it comes to repeatability, for the purpose of monitoring, horizontal and vertical integration turbine and positive displacement meters are the better option.

Supported amount of flowmeters

The number of supported sensors per/station is the system feature which is one of the most important factors to be reviewed. This is because one of the first things that is evaluated in a system is its capability of being able to monitor all the necessary lubrication points in any given machine. For example, SKF Flowline, VarioLub and FO-OilFlow systems are ideal for small amounts of lubrication points. Granted that these systems can be expanded by means of different communication protocols, the potential advantage of these systems will also depend on the amount of lubrication points needed in other areas of the machine to be monitored. On the other hand the Kytölä, Senso 160 and Real Flow systems are more obviously designed to cope with larger amounts of lubrication points.

Ideally, the best system is the one that can offer more variety, that is, the possibility to cover both small amounts and large amounts of lubrication points. All these systems, with the exception of the SKF Flowline and FO-OilFlow systems, can in theory cover thousands of lubrication points used in network. However, depending on the needs of the machine to be monitored a compromise needs to be made between many networked stations with a small amount of monitored points per station, and less networked stations with a larger amount of supported lubrication points per station. Ultimately, it all depends on the needs of the machine they are to be used on.

Signal types

All of the flow monitoring systems that are being evaluated are designed to use digital signals, with the exception of the Senso 160 system which also includes the possibility of supporting the use of analog signals. This feature can be advantageous if additional sensors, such as temperature or pressure are used to compliment flow rate measurements. It can therefore be concluded that while this feature is not completely necessary in this type of flow monitoring systems, they add value to the system if analogue signal measurement is also supported.

Station features

This sections focus is mainly to observe the stand-alone, modular and networking capabilities of the analyzed systems. Stand-alone means the system is capable of working on its own, without the need of any additional components. Modular evaluates whether the system is designed as a module and therefore easily integrated to either new or existing systems. Last but not least, interconnectivity evaluates whether or not the system is capable of forming a network with other stations by means of different communication protocols. Following these definitions it is easily deduced that all the systems are capable of good interconnectivity and are both modular and stand-alone.

Monitoring features

This is the last section that will be analyzed in this first component analysis. The UI features and the hardware architecture features will be studied in detail in their own section.

This section focuses on the typical features flow monitoring systems offer and how configurable they are. These features revolve, in general, around flow alarms, configurable measurement units and the act of monitoring itself. Flow alarms usually come in pairs, that is, low flow and high flow alarms. Having a low flow may result in bearing damage due to lack of lubrication while too much flow may also affect the way the system behaves and cause waste in lubrication fluids. It is also of interest for the system to be able to provide information in different units, may it be litres/min, pints/min, pulses/ min etc. Not only that, but the possibility of choosing in what unit to display this information is also important. Lastly, it is also important to note the importance of location. If the monitoring system offers the possibility of both local and remote monitoring it greatly increases the value and utility of the system. As can be observed from Table 2.9 all the studied systems, with the exception of the VarioLub system offer low flow alarms. Most systems also offer high flow alarms, except for the FO-OilFlow system which has it as an additional feature and the Variolub system which may or may not offer this. Another common feature are external output relays that allow for various options in the way alarms work, as they can be connected to indication lamps or horns that activate when alarms are present. Lastly, all systems offer both local and remote monitoring. The difference in the systems resides in the following:

- Zero flow alarms
- Configurable measurement units of representing flow
- By-passable alarms

Considering this, the systems that offer the most are the Senso 160, Kytölä systems. While not all these features are indispensable for flow monitoring, they all have value and should be considered as important features. It is also important to point out that, most of the systems presented here only obtain the flowmeter signals and send them to the processing unit to calculate flow. Whether these are process controllers or flow computers the information has to be process externally. The system that is proposed in the following sections has the capability to not only pre-process the information obtained from the flowmeters, but also allows for alarm configuration and customization.

3.1.2 Integration Architecture

The communication architecture is probably the most defining part of any given monitoring system, granted that most monitoring systems are simply “grown” out of existing control architecture and seamlessly horizontally and vertically integrated to transfer information to the necessary places. The particular case of oil flow monitoring systems is considerably different. Given that they do not control anything, and are only focused on monitoring certain behaviors, they are completely independent and not invasive in the sense that they do not affect the control system and they simply have to adapt to the existing communication network. This can be done by implementing different types of communication protocols, usually by using the one that is already compatible with the one that exists already on the factory floor. This section will analyze more thoroughly the communication architectures presented in each of the evaluated systems shown in Chapter 2.

Section 2.1.4 shows all the different monitoring system architectures that are being evaluated. Just by observing these different communication networks it is possible to observe the advantages and disadvantages of these systems. For example, the Flow Control systems focus mainly on local monitoring. The Real Flow system in Figure 2.19(a) only allows local configuration and RS-485 or Profibus to connect to a remote monitoring system. It is not specified whether there is any special software required for this integration or not. Figure 2.19(b) shows the second Flow Control system; FO-Oil. This system works with rotameters that already allow local monitoring given the type of flowmeters they are. Additionally, external inductive sensors can be installed to allow the connection of low flow alarms connected to a small concentrating hub that can later be connected to upper later monitoring systems.

The Senso 160 and Sensodec 10L shown in Figure 2.16, is one of the most complete monitoring systems, in the sense that it can monitor not only flow, but temperature, water content and pressure. However, the communication architecture it implements is one of the most complicated ones. It connects a series of positive displacement flowmeters to the Senso 160 system, which allows local monitoring and alarm configuration. It is then connected via RS-422 or RS-485 to a port interface that allows further integration to other stations. From the port interface there is a RS-422 or RS-485 connection to a monitoring computer that runs the Sensodec 10L. While this implementation allows the monitoring of up to 1600 lubrication points, an additional communication layer would be necessary to communicate to upper levels of the factory network.

Figure 2.17 shows the Variolub SKF system. This system is slightly more straight forward than the previous systems. It allows flowmeters so be installed in units of up to 12 lubrication points. These units are in turn connected to a pulse meter hub that calculates the flow of the connected sensors. Once the calculations are done this unit can be connected either to another master pulse counting unit that services as a hub, or directly to a higher layer interface. The following communication layer can be RS-232 or Profibus. The RS-232 interface is mainly used for local or semi remote monitoring via hand-held, laptops, or simple PGA-Displays, while Profibus is used to interface with monitoring stations. It is then possible to use Ethernet OPC to connect these stations to the SKF central monitoring system. The SKF Flowline system is the first of the evaluated

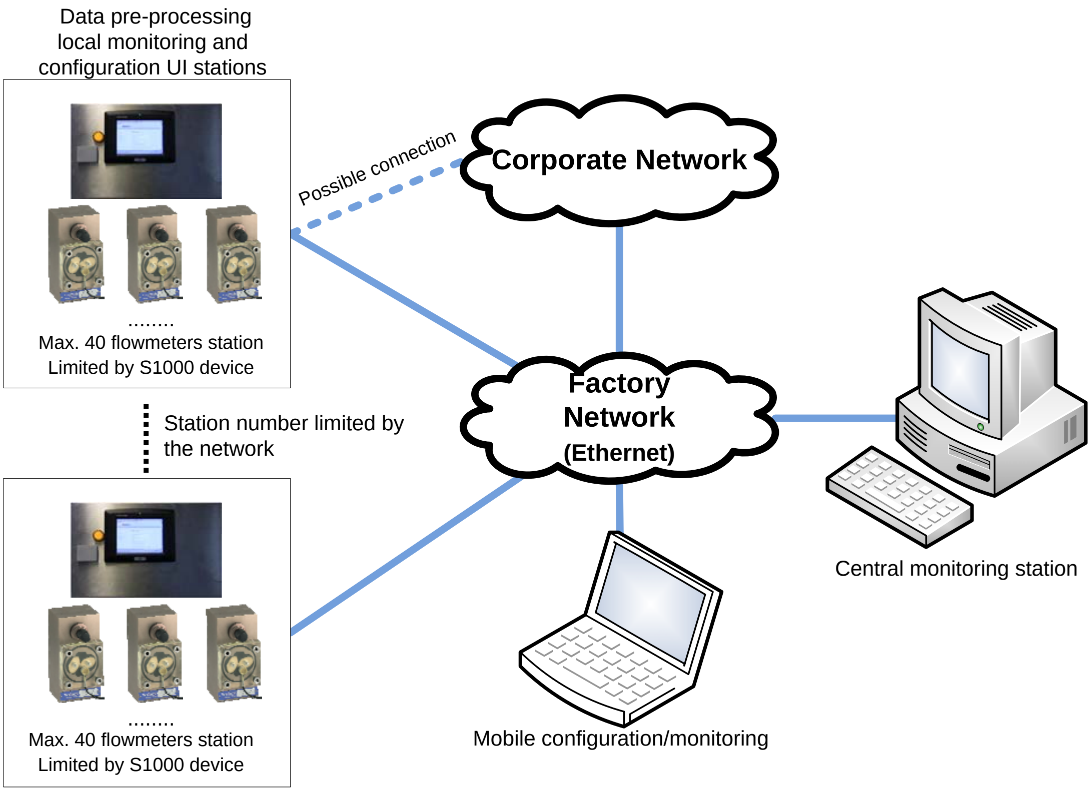


Figure 3.1: Proposed architecture.

systems that integrates the measurement monitoring and configuration system into one single unit. That is, flowmeter stations that can hold from 2 to 10 sensors allow local alarm configuring and monitoring. These stations in turn can be serially connected to each other via RS-485 and to a monitoring PC/Laptop via RS-232. It is also possible to use a multi-interface gateway that can connect to the RS-485 network and then transmit the corresponding measurements via USB, Modbus, RS-232, Ethernet or RS-485 to the corresponding monitoring workstation or upper level factory network.

The Kytölä system integrates the flowmeters with the local measurement, monitoring and alarm configuration unit, in a similar, albeit more friendly manner than the SKF Flowline system. The difference revolves around the network communication protocols implemented. The Kytölä system implements RS-422 and RS-485 to both interconnect flow measurement stations and remote monitoring centers. Once this is done it is possible to integrate to higher enterprise layers.

Lastly, the system proposed in this thesis is presented in Figure 3.1. This system integrates the flowmeters, data processing and UI in one single modular station that supports both, a small and large number of flowmeters. In addition to this, the main network communication it is based on is Ethernet; this allows for simple integration to any existing network. In turn, information is accessible both locally and remotely without going

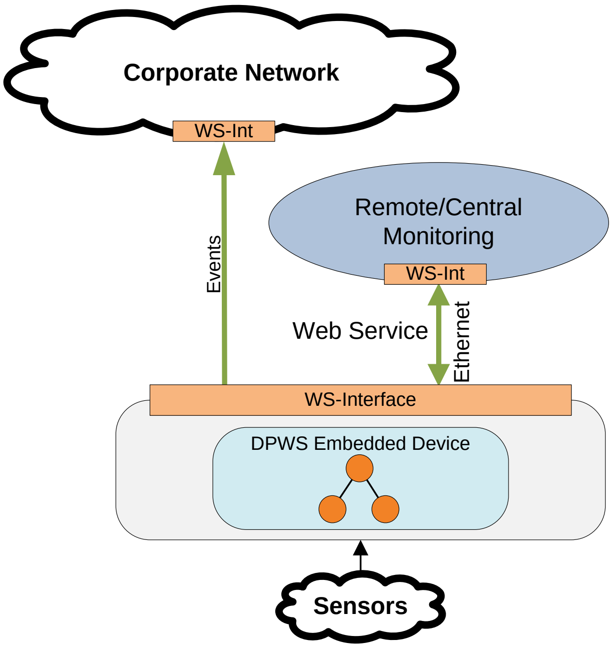


Figure 3.2: Web Service based architecture.

through additional network communication layers. Not only that, but the use of Web Service technology allows for seamless integration and scalability. Figure 3.2 shows a logical abstraction of the same architecture presented in Figure 3.1. As can be observed, the whole system is encapsulated in a Web Service that allows communication to the other components of the architecture by means of standard interfaces. This can further be expanded allowing a Web Service based communication architecture like the one shown in Figure 3.3.

It can be concluded, that while most of the systems implement commonly used communication protocols and can easily be integrated to practically any factory network. It is by far easier to integrate systems that implement less granularity and include all the required components one single integrated system. This can be accomplished by basing the interconnection architecture on Ethernet and using Web Services to seamlessly integrate the whole factory network, vertically, horizontally and with both DPWS embedded systems and Web Service Legacy monitoring systems.

3.1.3 User Interface

The HMI of any given monitoring system is one of the most important features that these systems offer. Some of the most prominent features they offer are parameter configuration, condition monitoring, alarm viewing and troubleshooting. Some HMIs may offer all of these features, while others may only offer the most basic of functionalities. While some simply display the configured information, others can also affect the way a system behaves

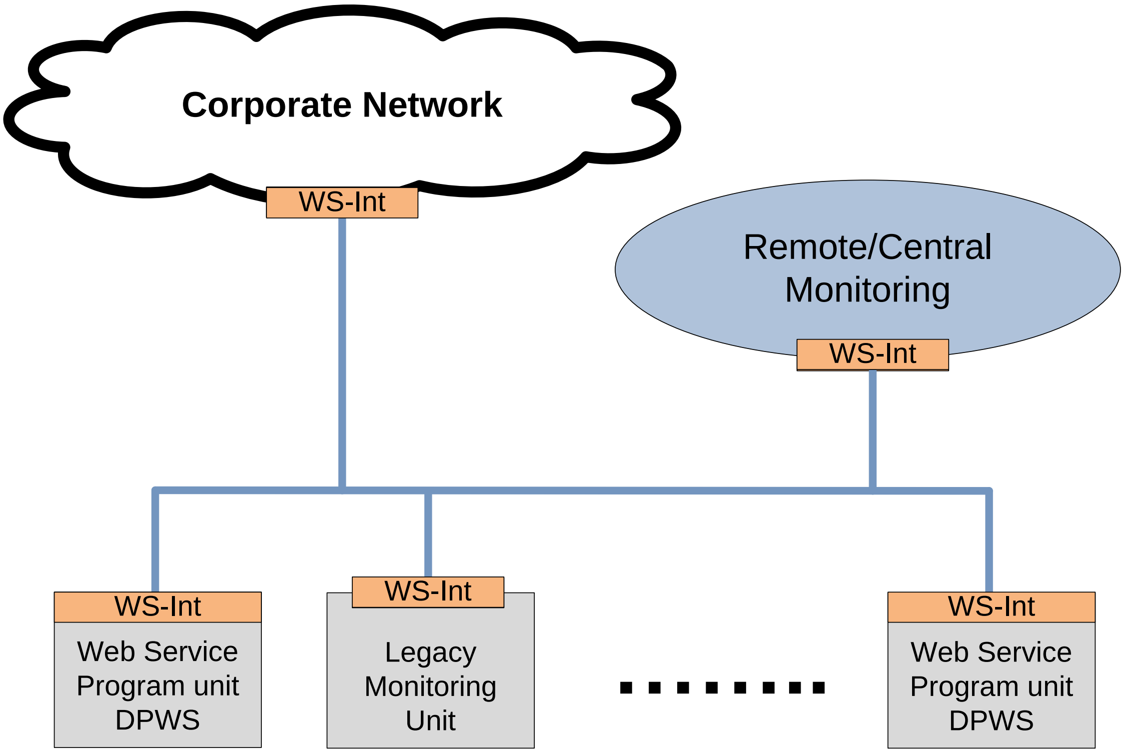


Figure 3.3: Web Service based network.

by changing and tuning certain parameters. Machine-Human interfaces can come in many different forms; they can be the most simple of button-light indicator types, or they can be computer like screens with key board compatibility or touch screen. At the same time, these interfaces can be localized or remote, and they can be set-up in a simple way, or installed and used in normal computers with special communication capabilities. This alone merits a different method of evaluating Industrial Human Interfaces. Many different methods exist to evaluate User Interfaces (UI) in Information Technology, in the manufacturing industry however, specific, context dependent evaluation methods are necessary [Queiroz 98]. In this particular case, it is not possible to evaluate the usability of the different systems. Given that the systems were not available for specific trials and testing the approach in this case is to simply evaluate the system based on offered features. The following aspects are verified based on the existing information:

- Type of UI
- Type of visualization
- Configurability
- Remote viewing

Table 3.1: User Interface features comparison table.

General specs	**SKF Flowline**	**Senso 160 Series 2**	**Vario Lub/SKF**	**Kytölä**	**FO-OilFlow**	**RealFlow**
UI Type						
Touch Screen	×	×	×	×	×	×
LCD+LEDs+Buttons	×	×	√	√	×	√
LEDs+Digital Display+Buttons	√	√	×	×	×	×
Local Visualization Type						
Monitor	×	×	×	×	×	×
LCD+LEDs	×	×	√	√	×	√
DD+LEDs	√	√	×	×	×	×
Rotameter	×	×	×	×	√	×
Remote viewing						
Possible	√	√	√	√	√	√
Additional Hardware Required	×	×	×	×	√	×
Configurable	×	√	√	√	√	√

Table 3.1 shows some of the same features mentioned in Table 2.9. It however, focuses more specifically on the features that compose the UI of the systems that are being compared. It is unfortunate that usability and more specific qualities cannot be measured. Even if some of these features would be given some sort of weight, the evaluation would be completely subjective. If, however, we base the comparison on the possible amount of information that can be displayed by the different UIs it is clear that a Monitor/Touch screen is the best option. Additionally, the possibility of local and remote viewing without the need of additional hardware adds an undeniable plus to the systems that offer it. Which, in this case, is not offered by any of the evaluated systems, making it a strong feature to include in any new system. It is important to note, in any case, that this component of monitoring systems, regardless of its importance, cannot be evaluated solely based on these features. Even if a modern touch screen system seems to be the best option, the only way to completely confirm this would be by means of a usability test comparing the strong and weak points of all the systems.

3.1.4 Improved Flow Monitoring System Requirements

The previous sections focused on thoroughly analyzing the flow monitoring systems presented in the previous chapter, based on this evaluation and comparison its easy to conclude the existing problems. Table 3.2 lists the existing areas of opportunity that these systems have and a possible way to address them.

Table 3.2: Improved requirements for flow monitoring systems.

Area of opportunity	**Solution**
Limited measurable variables	Additional sensor type capabilities (e.g. Temperature, Pressure, etc.)
Sensor amount flexibility	Multiple sized stations 1-20 flowmeters for stand-alone stations 1-45 flowmeters for networked stations
Configurable monitoring features	Configurable high, low and zero flow alarms Include output relay signals
Communication architecture	Build on the ethernet factory network Use Web Service capable devices
Unfriendly and limited UI	Touchscreen for maximum versability Extend the interface to remote monitoring units

3.2 System Development

The system requirements presented previously are the base and reason for the way things were designed and developed. It should be quite obvious at this point that most of the areas of opportunity that flow monitoring systems have can be addressed by improving the normal system capabilities (i.e. measurable variables, monitoring features, supported flowmeters). In the same manner, it is also easy to realize that the only improvable feature that cannot be easily addressed is the communication architecture available in these systems. The simple fact that these systems implement so many different communication protocols is an attempt to deal with this problem by being versatile. As such, it can be concluded that in order to accomplish a significative change in the communication architecture of these systems a hardware device capable of enabling this is necessary.

While a lot of industrial intelligent devices support Ethernet type connections and can form part of the factory communication network, many different integration technologies, some of which were mentioned in Section 2.2, are still required to obtain the information processed by these devices. At the same time, there is a strong effort to introduce Web Service capable devices into the manufacturing industry, but at the moment there is still a lack of commercially available devices that support this kind of technology.

Inico Technologies is one company that offers several devices that are capable of supporting Web Services. Founded in 2007 Inico seeks to innovate in the industrial manufacturing field by introducing intelligent devices that are capable of integrating to a SOA [Inico 10a]. One such device is the S1000, which is an RTU device that supports a considerable amount of Inputs and Outputs and is capable of implementing Web Services. The capabilities of this device, in addition to previous experience with other applications that used this device made it the most viable choice to complete the objectives presented by the SAMIA project.

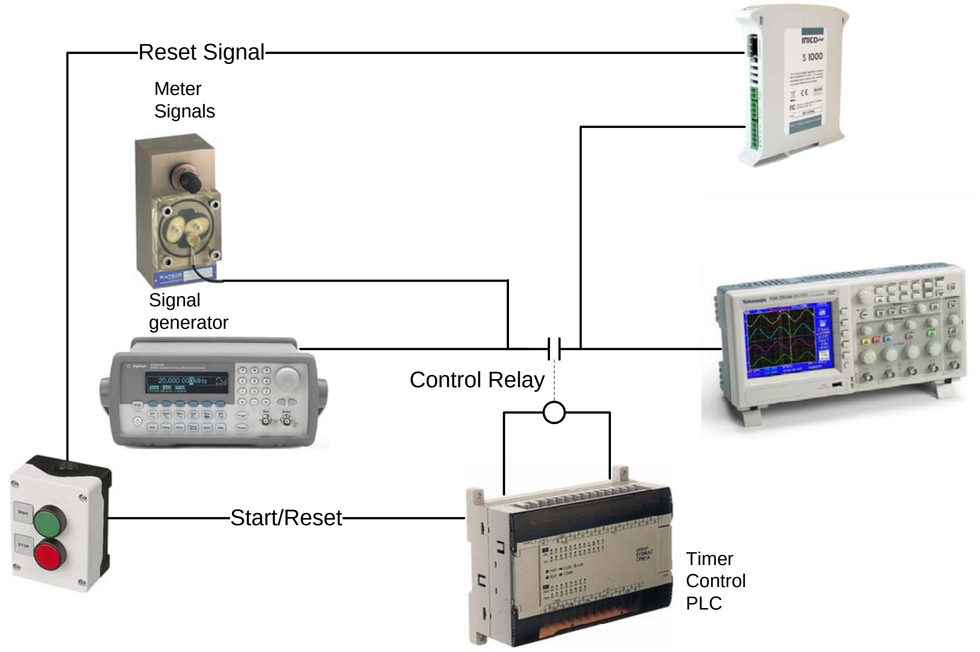


Figure 3.4: Test environment.

The designed system is greatly based on the S1000 and its capabilities. The following sections address the hardware environment that was used to test the viability of using this device in the context of oil flow lubrication systems. The device used and its specifications will be briefly explained and the testbed used to test the system will be presented.

3.2.1 Hardware Environments

The hardware environments developed and used during the realization of this use case were designed with two purposes. The first purpose was to study the capability and limitations of the S1000 device to calculate flow rate moving through different types of flowmeters. The second purpose was to see how accurately this could be done. To accomplish this, two different testbeds were constructed; one designed and built by FluidHouse Ltd., the other designed and built in the Tampere University of Technology. Due to the nature of the application, namely the counting of pulses, one of the testbeds had to implement the use of a signal generator to simulate the pulses that would otherwise be generated by the flowmeters.

Even if both testbeds implemented considerably different hardware components the overall idea of the environment was the same. An oscilloscope that was used to verify the frequency generated by the pulses was used. Additionally an extra PLC was included in the testbed to function as an arbitration unit that allowed for a more controlled environment. This environment can be seen in Figure 3.4.

The additional PLC is CPM1A Omron controller that was connected to serve as an

Table 3.3: S1000 specifications.

S1000 Characteristics
32-bit CPU (ARM RISC 55 MHz)
8MB flash memory for programs and data storage
Web-based ST editor with built in compiler (IEC-61131-3)
Web-based HMI with configurable pages, graphics and automatic refresh
10/100 Mbit Ethernet (Web Services, compliant with DPWS specifications)
RS-232 serial port
CAN port
9-36 VDC digital inputs and outputs (8 in, 8 out built-in)
Analogue inputs
DIN rail mounting
16 input expansion card

independent start/stop timer. This was due to the fact that a defined number of pulses could not be generated by the flowmeters, therefore the testing was based on time windows controlled the Omron PLC. Different flow frequencies were adjusted on each individual flowmeter and the pulses they generated during a defined period of time were counted. By comparing the theoretical number of pulses that should be generated to the actual counted pulses in the allotted time it was possible to obtain a general perspective of the flowmeters behavior. The second testbed measured previously had exactly the same connections with the exception of utilizing pulse signals from a signal generator instead of flowmeters.

S1000

The S100 as defined by the manufacturer is “a programmable Remote Terminal Unit (Smart RTU) device which offers process capabilities, as well as a Web-based HMI, support for Web Services” [Inico 10b]. In essence, the S1000 can be considered to be a small PLC. The features of the device used for this test-case can be seen in Table 3.3.

As can be observed from Table 3.3 the S1000 while being relatively limited hardware wise, it is capable of supporting many different communication protocols, customized programming, and Web Services. One very important feature, and one that makes this device quite unique, is its capability to support web-based HMIs. Not only that, but everything is done on the device itself through a web browser-based interface that allows for configuration, programming and monitoring. While this has as a disadvantage the lack of debugging capabilities and off-line programming, it makes up for it by not requiring any additional software and being platform independent as it works from any browser that supports Vector Markup Language (VML).

Another important thing to note is the capability of the S1000 to allow ST program-

Table 3.4: FH testbed flowmeters.

Flowmeter	Make	Range	Conversion Parameter
SR10	Kytölä	1 - 10 l/min	126,8 pulses/l
SR30	Kytölä	3 - 30 l/min	49,8 pulses/l
SR2,5	Kytölä	0,2 - 0,25 l/min	1062 pulses/l
2-D rotameter	Vealdo	0,2 - 2,0 l/min	N/A
Honsberg rotameter	Honsberg	2 - 12 l/min	N/A
D58719	Kracht	1 - 65 l/min	500 pulses/l
RS3	Flow Control	1 - 10 l/min	145 pulses/l
SR-60	Kytölä	1 - 10 l/min	22,4 pulses/l
FO-Oil rotameter	Flow Control	N/A	N/A

ming according to the IEC-61131-3 standard, albeit in a limited manner. Limited because while it supports the standard it does not support the whole instruction set, this was a very important factor in the development of the application and will be more thoroughly explained in the following sections.

Testbed

The testbed manufactured by FluiHouse Ltd. was constructed with the purpose of studying the behavior of the S1000 as a flow calculating device, see Figure 3.5. As such, this testbed can be said to represent very closely a flow metering station for a circulating oil lubrication system. It has a total of nine flowmeters installed, mainly positive displacement and rotameter types. These meters are made by different manufacturers and have different specifications that can be seen from Table 3.4. The testbed had three lubrication oil input lines and three outputs, an oil pump moved the oil from a tank through the sensors and re-circulated back into the oil tank. The oil flow from the three input hoses could be adjusted at will, and each flowmeter could had a knob that allowed for individual adjustment.

From the control perspective the testbed also has a control box that has a mounted 5.7 inch panel PC which has a Windows CE operating system and supports the Internet Explorer Browser. The control device, as mentioned previously is an S1000 RTU unit with an I/O extension card that gives a total of 24 Inputs and 8 Outputs. There is also a lamp on the frontal panel that is used as an alarm indicator in conjunction with spare relays that be used as activators for low, high and zero flow alarms. The positive displacement flow meters had a standard inductive sensor that could be installed on each flowmeter. These sensors were connected to a concentration hub with M6 connectors, and this hub in turn transported all the signals to the S1000 inputs. In the case of the rotameters, inductive sensors were installed only to detect either low or high flow.

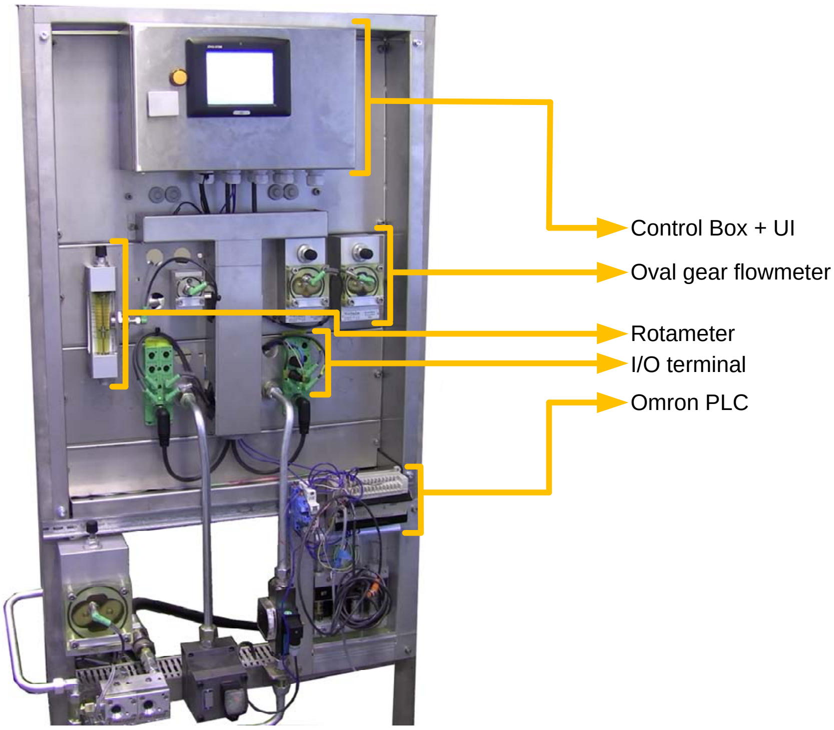


Figure 3.5: FluidHouse testbed.

3.2.2 Flow Calculation System

In order to calculate the flow passing through the flowmeters an algorithm was programmed into the S1000. As previously mentioned, this device supports the use of Structured Text programming according to the IEC-61131-3 standard, albeit with a limited set of instructions. Some of the lacking instructions, and highly required for this type of application, are the rising and falling edge detection instructions and the timer functions. Due to this, it was necessary to implement small custom programs that dedicated themselves to detect the rising/falling edge generated by the flowmeters, and other programs dedicated to create a time window during which pulses were counted.

Given the nature of the conversion factors in positive displacement flowmeters, namely the fact that they are in pulses per liter, or something similar, a time frame is required to convert this into a conventional flow rate measurements such as liters per minute, or pints per minute. As such, a time frame during which pulses are counted and flow rate is calculated was the most viable option. This time frame had to be of an appropriate duration, if it were to be too long the refresh rate of the calculation would be to slow, and if it were to be too small a greater error would be carried with the calculations necessary. As a solution for this, two different time frames were used depending on the frequency of the signal, if the signal was at a frequency smaller than 2 Hertz, the longer time window was used, if otherwise, the small time window was used. Figure 3.6 shows the algorithm that

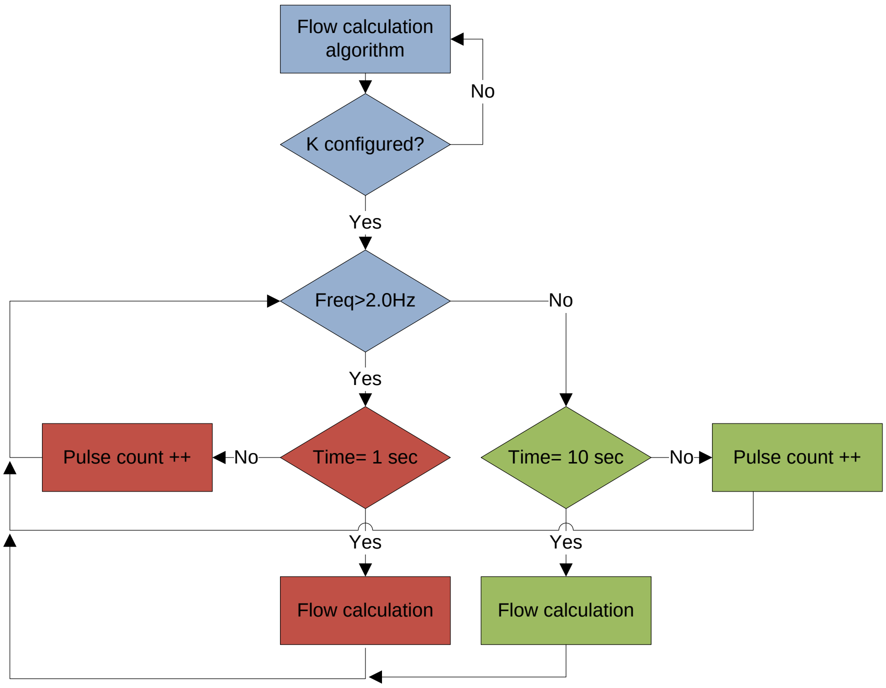


Figure 3.6: Flow calculation algorithm.

was programmed into the S1000. As can be observed, the algorithm does not execute until the constant for the flowmeter the program is linked is set. Once this constant is set, the calculation mathematics are executed depending on the calculated frequency generated by the pulses being sensed.

As previously mentioned, two different calculation formulas were used depending on the measured pulse frequency. Mathematically speaking the equations are exactly the same. The only difference is the time frame for which they are used for. Equation 3.1 calculates the flow for one second measurement windows, while Equation 3.2 is used to calculate flow for ten second measurement windows. Variable K represents the flowmeter conversion constant.

$$Flow(\frac{lts}{min}) = \frac{Pulses \times 60}{K} \tag{3.1}$$

$$Flow(\frac{lts}{min}) = \frac{Pulses \times 6}{K} \tag{3.2}$$

An important consideration in the flow calculation algorithm is the potential for error creation and dragging. Given that the counted pulses are multiplied by sixty in the one second window algorithm, an error may be created if the counted pulses are not the real pulses generated in the system. This makes the ten second algorithm much more accurate, albeit slow in for flow rate setting and data refreshing. To compensate for this, the

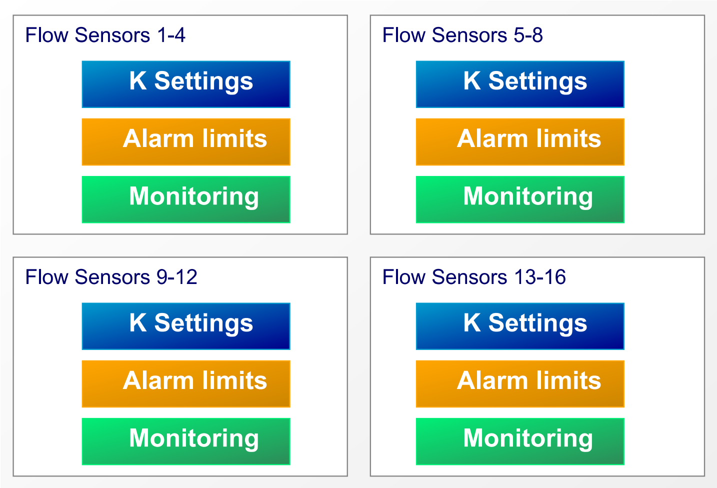


Figure 3.7: HMI main menu.

one second algorithm keeps historical data from the previous three calculated pulses and calculates the flow rate based on a square average of the current and historical values.

3.2.3 HMI Development

The HMI of the flow monitoring system was designed with the intention of being visually simple, helpful and easily configurable. In order to accomplish this, many measures were taken into consideration, both in the selection of hardware and in the design of the user interface. For ease of navigation and visual comfort, a touch screen was selected. This enables many advantages, given the nature of the S1000 software, and its platform independence, any panel PC capable of supporting a browser could be used. Lastly, to ease the configuration and personalization of the HMI applications created in the S1000, the application is straightforward and uses some naming conventions that relate the ST programs to the HMI applications of the system.

The S1000 allows the user to create many different types of applications. In the context of the S1000, these applications allow the use and customization of some of the S1000 features. They can be simple variable value display applications, parameter introduction applications, PID controller applications, graphical HMI applications and some others. In this particular case, however, the developed system uses the HMI graphics and parameter control applications.

There are two types of graphical applications and two types of parameter applications. The first of the HMI graphical applications can be seen in Figure 3.7. The *Main Menu* is a unique application that is meant to be the visual access point to the whole flow monitoring system. It contains links to the flow monitoring pages, flow constant configuration pages and alarm configuration pages.

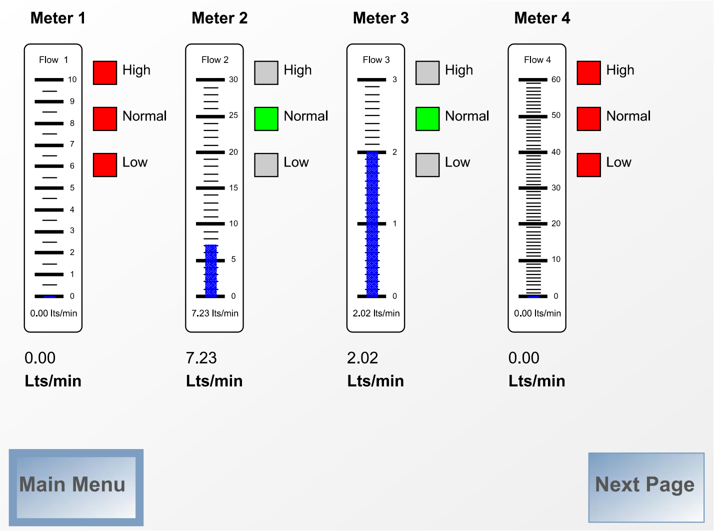
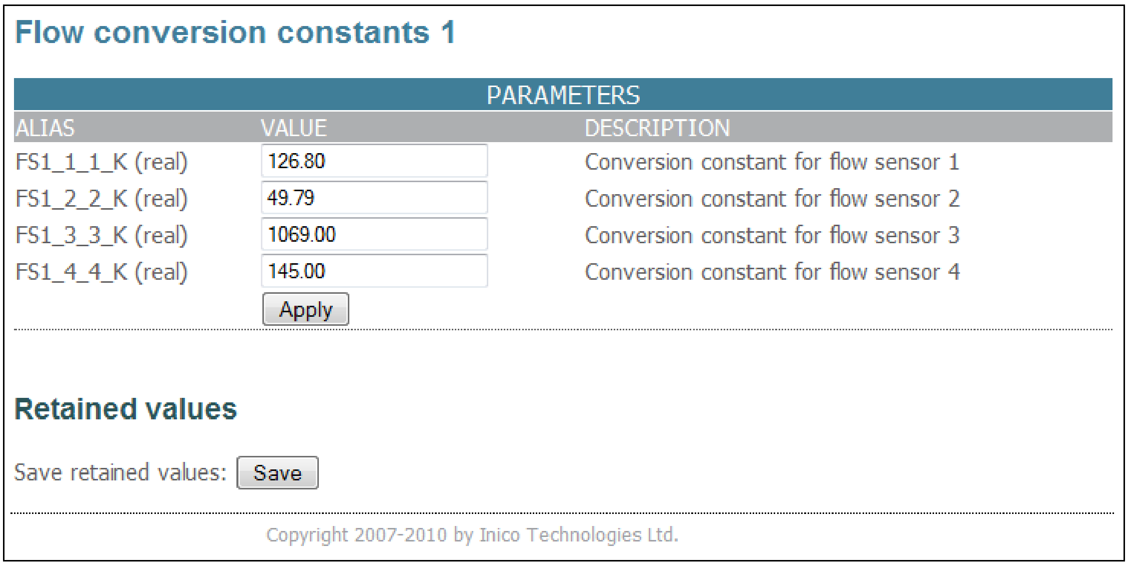


Figure 3.8: HMI flowmeters.

The second graphical application, and the most important one, is shown in Figure 3.8. Every flowmeter page displays a total of four meters, therefore there are more different pages of this applications, to make up more the amount of existing flowmeters. Figure 3.8 shows meters, two and three, calculating a flow rate and displaying it both numerically and visually by means of a vertical gauge. Meters one and four show no flow rate and their high, low and normal flow rate indicators are all in red. This means that the alarm limits for these meters are not yet configured, in contrast to meters two and three which have a flow rate calculation. While all the different components in this graphical interface may be personalized and configured, there are only two that would need to be customized to adapt to the system running the application. The flow rate gauges need to be adapted to the flowmeter which they represent, the high and low limits, the major and minor tick may all be changed in the configuration mode of the S1000. In a similar manner, the descriptive text above each gauge may be changed to something that identifies the flowmeter.

The other type of applications that were designed, the parameter control applications, can be seen in Figure 3.9. Figure 3.9(a) shows the parameters related to the K conversion values of each of the installed flowmeters, while Figure 3.9(b) displays the high and low alarm limits that are configurable for each flowmeter. In a similar fashion to the graphical HMI flowmeter gauge interface, these parameter setup applications are divided into groups of four. Each of these applications is linked to the main menu showed in Figure 3.7, therefore there are four instances of these applications, representing a total of 16 flowmeters. While most of the application features shown address the areas of opportunity presented in Table 3.2, the number of flowmeters supported by the S1000 is cut short, mainly due to its hardware limitations.



Flow conversion constants 1

PARAMETERS		
ALIAS	VALUE	DESCRIPTION
FS1_1_1_K (real)	126.80	Conversion constant for flow sensor 1
FS1_2_2_K (real)	49.79	Conversion constant for flow sensor 2
FS1_3_3_K (real)	1069.00	Conversion constant for flow sensor 3
FS1_4_4_K (real)	145.00	Conversion constant for flow sensor 4

Retained values

Save retained values:

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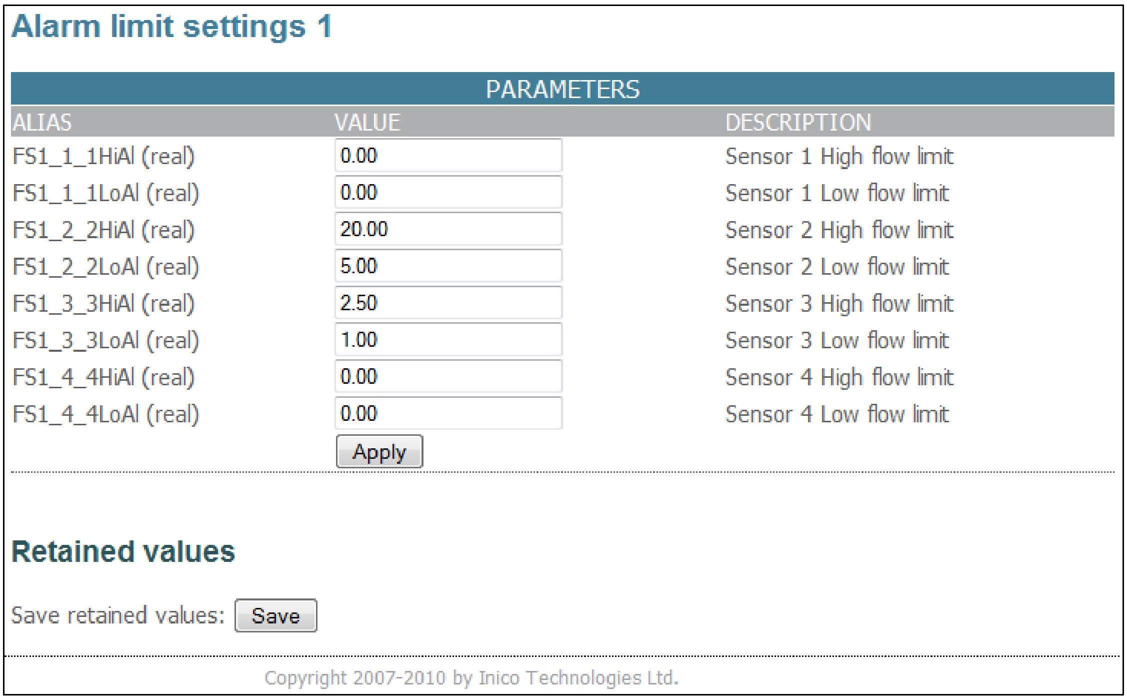
(a) K value configuration



Alarm limit settings 1

PARAMETERS		
ALIAS	VALUE	DESCRIPTION
FS1_1_1HiAl (real)	0.00	Sensor 1 High flow limit
FS1_1_1LoAl (real)	0.00	Sensor 1 Low flow limit
FS1_2_2HiAl (real)	20.00	Sensor 2 High flow limit
FS1_2_2LoAl (real)	5.00	Sensor 2 Low flow limit
FS1_3_3HiAl (real)	2.50	Sensor 3 High flow limit
FS1_3_3LoAl (real)	1.00	Sensor 3 Low flow limit
FS1_4_4HiAl (real)	0.00	Sensor 4 High flow limit
FS1_4_4LoAl (real)	0.00	Sensor 4 Low flow limit

Retained values

Save retained values:

Copyright 2007-2010 by Inico Technologies Ltd.

(b) Alarm limit configuration

Figure 3.9: HMI parameter control application screen captures.

3.3 Higher tier integration

The advantages of Web Service based devices has been already addressed in Chapter 2 and in Section 3.1.2. While designing a system that uses such devices bring some monitoring advantages inherently, as is the case of the S1000 through a browser-based HMI that is accessible from any point of the same network. The need for control rooms and supervision terminals still exists, this mainly due to the need of centralizing all the existing information. Not only that, but as communication technology has advanced management level personnel require access to factory floor level information from both office, and remote locations. In order to accomplish this kind of higher tier integration the Web Service capabilities of the S1000 had to be exploited. Although it is possible to configure two way messaging via Web Services, given the monitoring nature of the designed system, Web Service events were used.

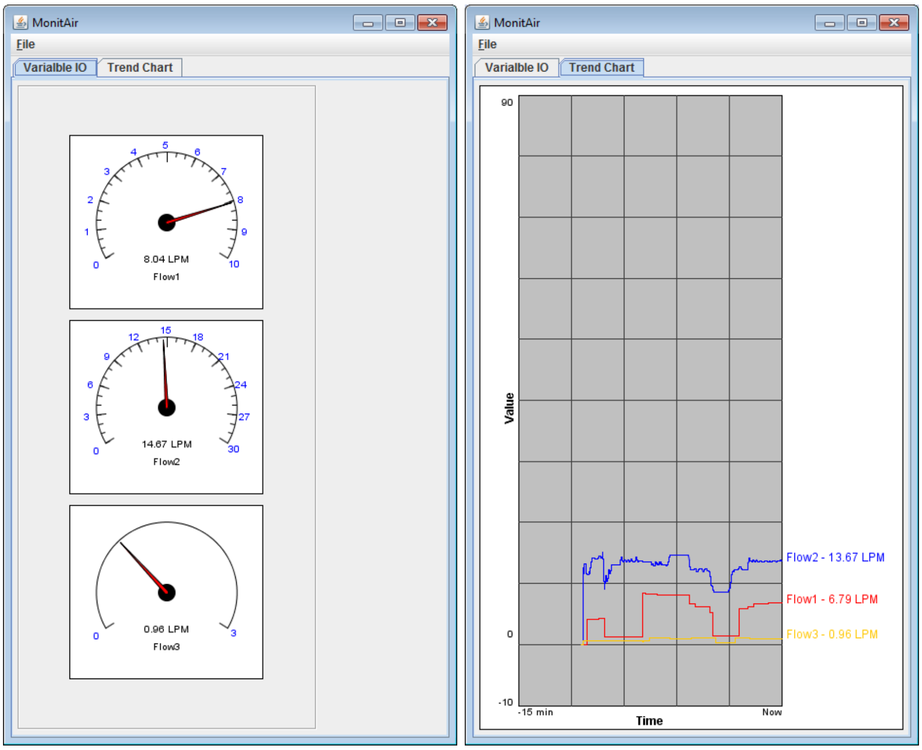
3.3.1 Web Service Eventing

Web Service eventing, as explained in Section 2.2.5, work based on the principle of publish and subscribe. As such, the device that collects and processes the data, in this case the S1000, encapsulates desired information in the form of publishable Web Services. This by itself, while an accomplishment, only makes the desired information available. To obtain this information, it is necessary to use clients that subscribe to the events published by the monitoring device. While this is not very different to what is currently being done in any given monitoring system, the advantage of Web Service technology comes from the standardized interface required to make this type of system work, and the fact that many current web applications work with the same principle. Additionally, the information made available may already be pre-processed and may be made easily available to qualified personnel.

Three events were created in the S1000 to prove this concept. All three events were flow rate values that were calculated by the algorithm programmed into the S1000. Given the nature of this device, the only necessary steps were:

- To create a WSDL file that described the desired events and upload it to the S1000.
- Create the messages in the S1000 Web-based interface and link them to the correct variables.
- Add the logic necessary to send the events each time a change was detected in the flow rate.

In order to subscribe to these events two different methods were attempted. The first

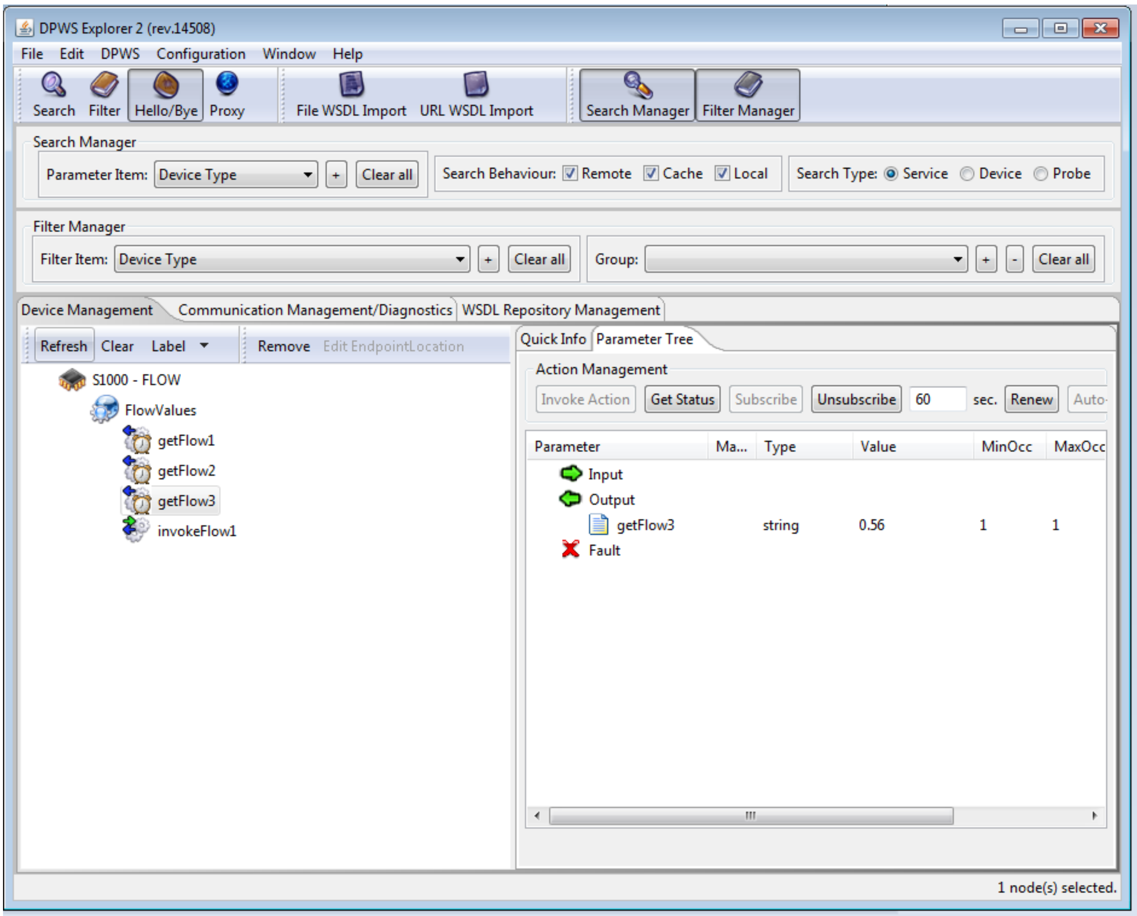


(a) Flow rate gauges (b) Historical trending plot

Figure 3.10: HMI monitor.

implied using a DPWS Explorer designed by the University of Rostock, and the University of Dortmund. This explorer was created for the ITEA (Information Technology for European Advancement) project SIRENA (Service Infrastructure for Real time Embedded Networked Applications), and is used to discover DPWS embedded devices. Additionally, it allows the invocation of operation services and event subscription [Materna]. The second method implied modifying an in-house designed client HMI, that could invoke and subscribe to DPWS compliant devices.

Figure 3.10 shows two tabs from the same simple application. While the original application from which this version was modified allowed the invocation of Web Service operations, this simple version only subscribes to the flow measuring device of the designed system, namely the S1000. Figure 3.10(a) shows a three different gauges indicating different flow rates. Those flow rates are calculated by the S1000, and sent to the monitoring HMI every time a change in the flow rate is detected. In a similar manner, the trending graph in Figure 3.10(b) allows to view present and past values in an historical manner. While this is a very simple HMI application, the implications behind this are great. Simple stand-alone HMI applications that subscribe to all the existing events in any given system, web-based applications accessible from any point in the network, data aggregation and prediction maintenance can all branch out from this. Even if these things



Parameter Item: Device Type

Search Behaviour: ☑ Remote ☑ Cache ☑ Local

Search Type: ● Service ○ Device ○ Probe

Filter Item: Device Type

Group:

60 sec.

Parameter	Ma...	Type	Value	MinOcc	MaxOcc
Input					
Output					
getFlow3		string	0.56	1	1
Fault					

1 node(s) selected.

Figure 3.11: Materna DPWS Explorer.

are already being done, Web Services allow for seamless, loosely coupled, easily scalable horizontal and vertical integration.

As mentioned previously, two different tests were made regarding Web Service implementations. One revolved around the use of the Materna DPWS explorer which discovers Web Service capable devices and allows for event subscription and event invocation. Figure 3.11 shows the discovery of a web service called *Flow Values*. This service has three events that allow for subscription and one operation that may be invoked. The events are unidirectional and trigger every time the flow rate changes and send the flow rate to the subscribed clients, while the invocation is a bidirectional *request/response* operation.

The services that can be created in the S1000 can vary greatly and the way they are designed can be configured as desired. In the particular case of the use case presented in this thesis, only one service that encapsulates three events and one operation was created. This purpose behind this was simply to evaluate the general performance of Web Services in the S1000. The S1000 only requires that the variable that wishes to be sent via event is configured. Then the S1000 encapsulates variable in a SOAP message that is sent to the client which is subscribed to the event. An example of these generated messages can be

```
<?xml version='1.0' encoding='UTF-8' ?>
<s12:Envelope xmlns:s12="http://www.w3.org/2003/05/soap-envelope"
xmlns:wsa="http://schemas.xmlsoap.org/ws/2004/08/addressing">
  <s12:Header>
<wsa:Action>http://www.inicotech.com/schemas/FlowSensorPortType/getFlow3
  </wsa:Action>
    <wsa:MessageID>urn:uuid:e58478d5-9adb-48c9-7b61-0050c289908f
    </wsa:MessageID>
       <wsa:To>http://192.168.2.59:28606/DPWSExplorer2/OngetFlow2-3
       </wsa:To>
       <wsa:From>
          <wsa:Address>http://192.168.2.43:80/dpws/ws01</wsa:Address>
       </wsa:From>
  </s12:Header>
  <s12:Body>
    <getFlow3 xmlns="http://www.inicotech.com/schemas">0.56 </getFlow3>
  </s12:Body>
</s12:Envelope>
```

Figure 3.12: SOAP message for *getFlow* events

seen Figure 3.12.

A very important thing to consider, is the way these services may be defined, that is, their granularity. It could be that the desire is to obtain all the flow rates in one pull. This could be possible if an event sent all the flow rates at certain intervals, or every time an important change in the flow rates happened. The problem with this approach is that it is possible that not all the flowmeters carry the same importance, or that a lot of traffic could be created on the network due to the interval event generation. On the other hand, if each event represents an individual flowmeter it is possible to generate the events in a customized manner depending on the importance of the flowmeter linked to said event. In a similar manner, if certain variable is not of much importance it would be possible to use a traditional polling method by means of bidirectional operations. This explains the reason behind the naming convention used in the events and operation, while one implies getting a constant flow of events from the device, the other implies a necessary invocation to be made.

Lastly, if other variables were to be included in the system, such as temperature and pressure. The services created would require a very different configuration. Perhaps it would be necessary to have an individual Web Service per flowmeter and allow it to have one event for measured variable. If this were the case, perhaps events such as *getFlow*, *getTemperature* and *getPressure* would be appropriate. Alternatively, it could be possible to encapsulate all three variables in one single event. However, this would cause a similar scenario as the one explained above. In essence, the possible Web Service definitions in this type of system can vary greatly and should be considered as an important part of system design, as they may affect the performance of the system in more than one way.

3.4 System Performance

The previous sections have explained the design and implementation of an circulating oil flow monitoring system based on web services. While the implemented web services implemented in the system are limited to the subscription of events that publish a given flow rate, the improvements behind the systems architecture, and its potential expansion are the main merits behind it. In order to further evaluate the viability of this system many different tests were made. Section 3.4.1 briefly elaborates on the performance parameters that were considered to be of importance, and the reasoning behind it. Additionally, Section 3.4.2 explains the different tests that were designed and performed to evaluate the defined parameters.

3.4.1 Defining Performance Parameters

There are many performance tests that can be performed in this kind of system, some of them pertaining to the capabilities and behavior of the communication network and web services. Additionally, performance tests that are limited to the evaluate the use of the S1000 as as a flow measuring and calculation device. As mentioned previously in 3.2.1, it is to the latter that the scope of this thesis is limited to. As such, the parameters that were evaluated are related to the accuracy, precision and repeatability of the calculated values. In addition to this, the limits of the S1000 were tested, as well as its performance under different conditions and behaviors that are common in positive displacement flowmeters.

Maximum frequency

Most flow monitoring systems work with a flow computer especially designed to detect the whole spectrum of frequencies that any given positive displacement flowmeter may generate. These frequencies can vary greatly depending on the flowmeter used. Given that the S1000 is a device which has the generic purpose of an RTU controller, its hardware and software capabilities are limited in this aspect. While its discrete inputs are capable of detecting a reasonable amount of pulse frequencies, the limit had to be defined.

Duty cycle

A very particular characteristic of some positive displacement flowmeters is duty cycle that their rotating gears or rotors generate. Given the physical design of the sensor, and their varying sizes - which depend on the tolerated flow rates - the pulse signal generated by these meters does not have a 50%-50% duty cycle. In other words, the positive width of the pulse these meters generate is smaller than the negative width. Figure 3.13 shows a

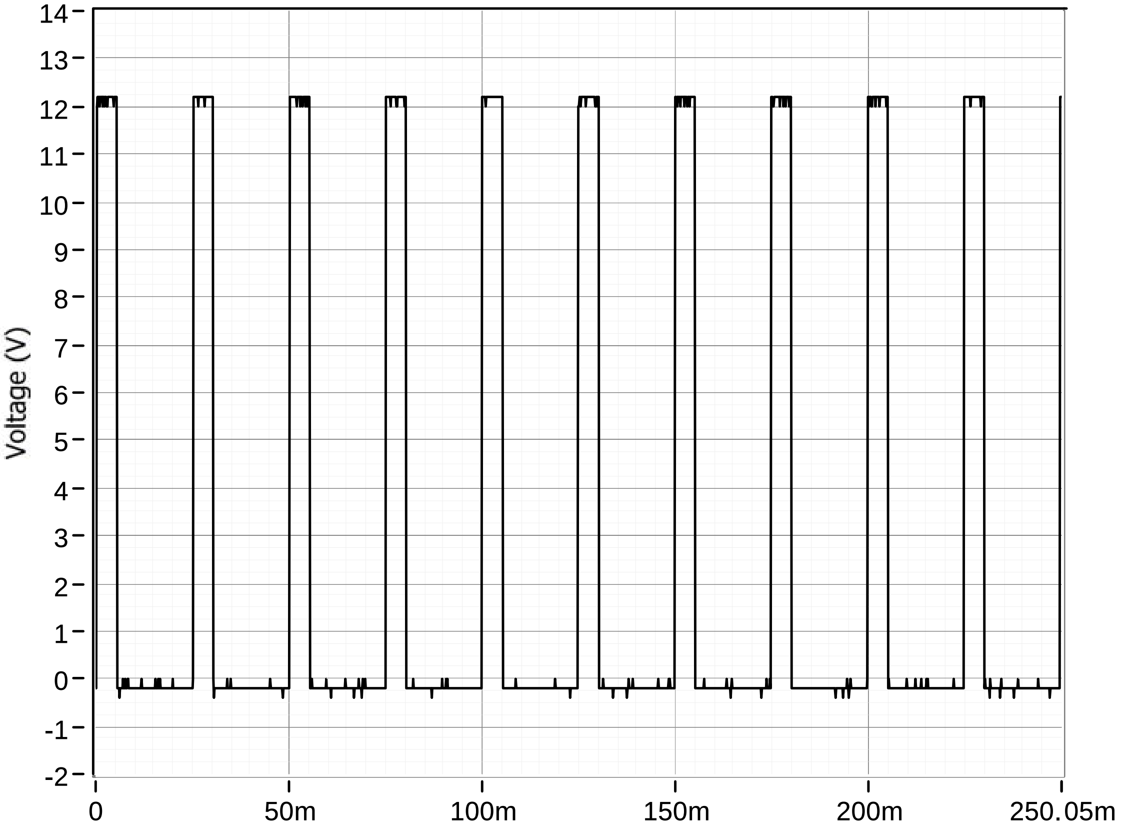


Figure 3.13: 40Hz Square signal with small pulse width.

40Hz square pulse signal much like the ones generated by positive displacement flowmeters. The shape of this type of signal affects the maximum frequency detectable by the S1000, making this a very important performance parameter.

Overall accuracy and precision

The previously defined performance parameters are merely indicators of the limitations of the S1000 as a measurement device. In order to appropriately evaluate the S1000, measurable parameters that give an estimation of the device capabilities had to be obtained. Therefore, error percentage, standard deviation, bias error, accuracy and precision, which are some of the most common performance parameters were estimated. The importance and principles behind this parameters, and their relation to flow measurement were previously addressed in Section 2.1.2.

3.4.2 Performance Tests

The performance tests done mainly served the purpose of verifying the behavior of different types and brands of positive displacement flowmeters while testing the capabilities

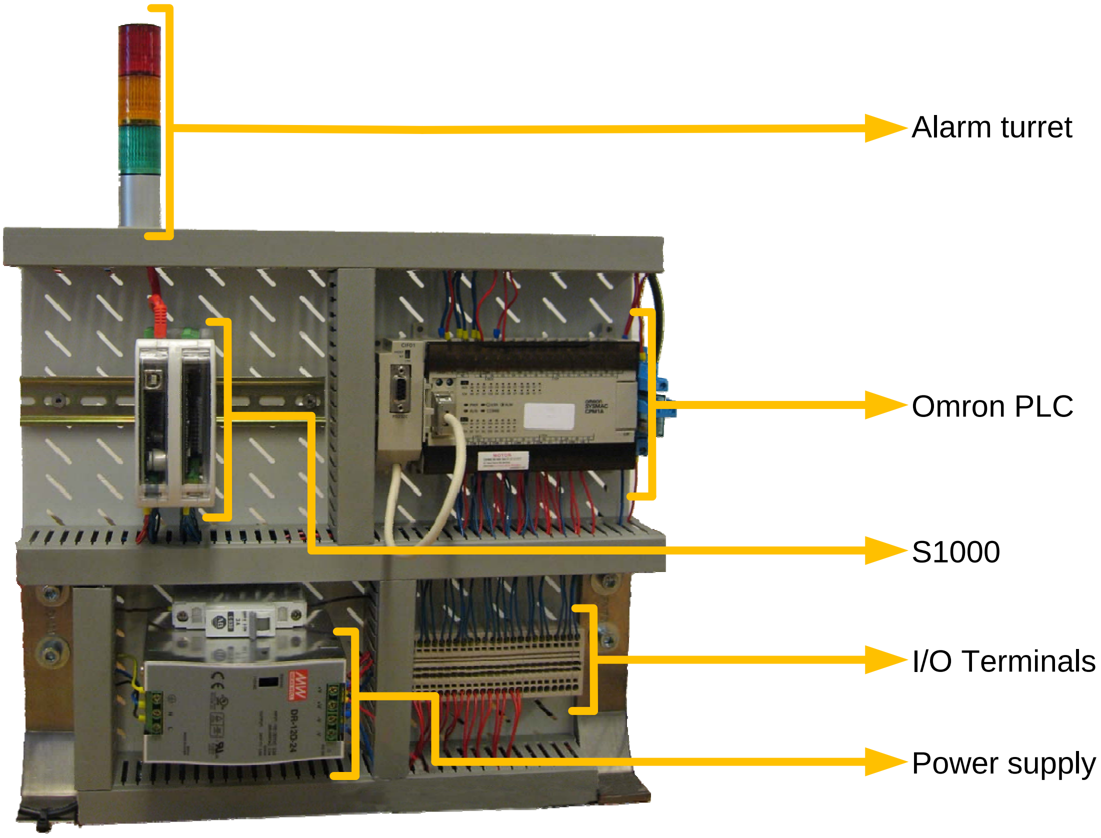


Figure 3.14: TUT testbed.

of the S1000 as a measurement device. Additional tests were made in a more controlled environment, using signal generators to simulate the pulses generated by the flowmeters. Although two different environments were used, the setups used were the same, Figure 3.4 shows the general idea behind the setup used. While some of the testing was made in the testbed shown in Figure 3.5, most of the tests that yielded measurable and reliable results were done with the testbed presented in Figure 3.14.

In general, it can be said that all the test revolved around the pulse counting capabilities of the S1000. Many repetitions of these tests were made under two different scenarios and the two different testbeds that have already been shown. For the sake of simplicity the tests will be classified in the same manner as the parameters they were designed to obtain. The results will be shown in the same manner in the Chapter 4.

Obtaining the maximum detectable frequency

In order to obtain the maximum detectable frequency three different tests were made. All three tests worked with the same principle, but by different means. The basic idea was to send a controlled number a pulses to the S1000 at different frequencies and verify the amount of pulses that were detected by the pulse counting routine. These tests are briefly explained in the list below:

1. **External PLC generated pulses.-** A defined number of pulses at different frequencies, controlled by internal timers, were generated by an Omron CPM1A PLC. Some of the outputs of this PLC were connected to the S1000 inputs, the counted pulses were then compared to the sent number.
2. **Timer controlled pulses.-** Different pulse frequencies generated by a signal generator were sent to the S1000 inputs. Time windows regulated by the Omron CPM1A PLC were programmed. The theoretical number of pulses generated at the input frequency, at the allotted time were compared to the actual counted pulses.
3. **Signal generator bursts.-** A high-end signal generator was used to send a defined number of pulses in the form of bursts. This number was then compared to the counted pulses.

An additional test, performed in the testbed shown in Figure 3.5 using the principle number two mentioned above was also done. This particular test served to obtain the maximum detectable frequency per/flowmeter. While it used the same principle already mentioned, the time windows used were only 5 minute and 1 minute windows. In this particular case the flowmeter generated frequencies were adjusted, as possible, by veryfing the generated frequency with an oscilloscope.

Verifying the performance at different duty cycles.

In order to verify the performance of the S1000 at different duty cycles the same principle behind the maximum frequency test was used. Given that the most reliable of the maximum frequency tests is the test that relies on the high-end signal generator, this was the only method used to calculate the behavior at different duty cycles. Twenty bursts of 10,000 pulses were sent at different duty cycles ranging from 50%-50% to 20%-80% with a spacing a 10% between each tests. The percentage change was only one sided, that is, only the reduction of the positive width of the duty cycle was tested.

Accuracy, precision, bias error, and overall performance parameters

The tests that were made to obtain these performance parameters were done using two of the same principles used to calculate the maximum detectable frequency. The first test used the external PLC controlled timer; twenty iterations of 5 minutes each were made per/frequency from 5Hz to 55Hz. From this amount of data, averages and standard deviations were used to calculate bias error, uncertainty, accuracy and precision.

The second test used the high-end signal generator and with the same principle. Twenty bursts of 10,000 pulses were sent to the S1000, the counted pulses were registered. In the same manner as the first test, the averages and standard deviations calculated were used to estimate performance parameters. In other words, these were the same tests as the duty cycle tests, except that they were done at 50%-50% duty cycle.

4. RESULTS

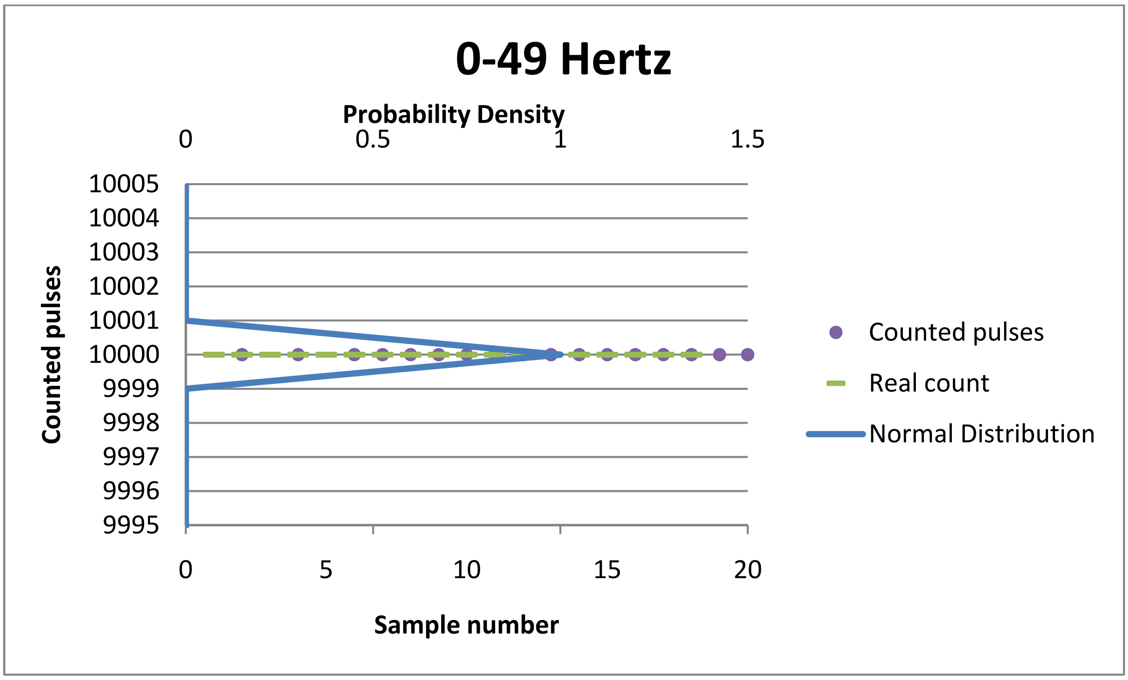
In Section 3.4 of Chapter 3 the performance parameters that needed to be evaluated were defined. In a similar manner, the tests that were designed in order to obtain these parameters were described and explained. This chapter shows the results obtained in each of those steps and briefly elaborate on the interpretation given to the results. It is important to note, as was done in the previous chapter, that two rounds of tests were made. Some using the external PLC timer control, the other using the high-end signal generator bursts. This chapter mostly presents the high-end signal generator tests, as they are the most reliable. The other tests results are referenced, and can be seen in Appendix B.

4.1 Maximum Frequency

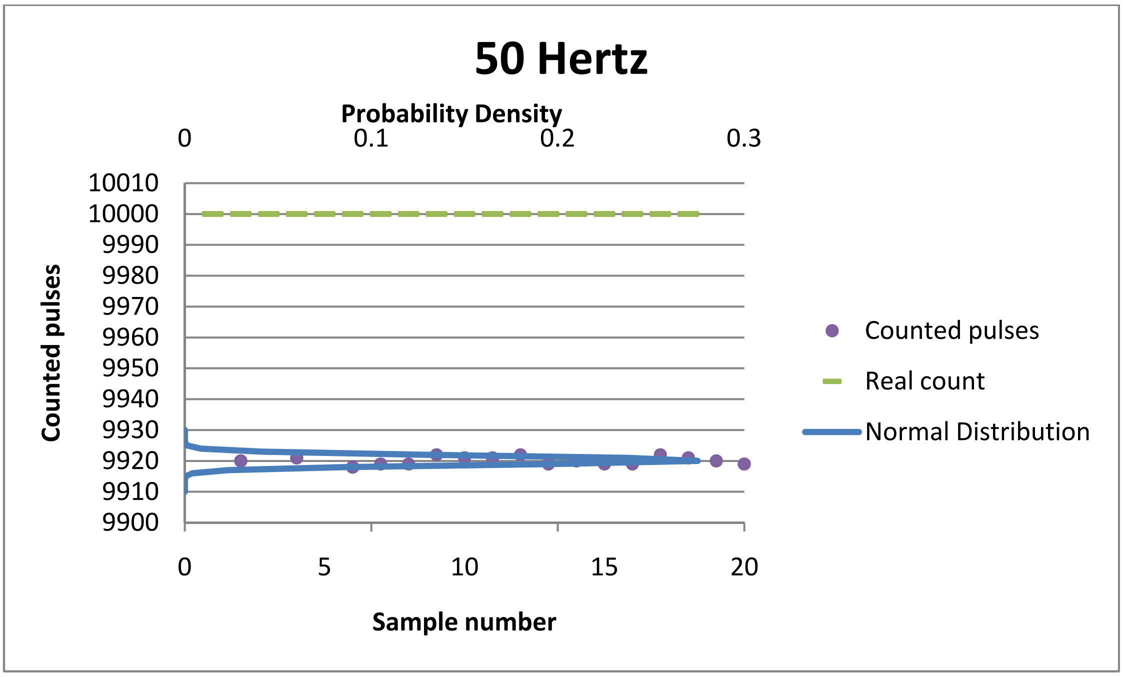
As said in the previous chapter, the maximum frequency detectable by the S1000 is one of the most important parameters. While simple pulse counting tests were initially made to obtain this frequency, this parameter is evident in all the tests that were made. The results presented here can be attributed to both of the testbeds used, see Figures 3.5 and 3.14.

The first test to evaluate the maximum detectable frequency was a simple observation test based on the external PLC generated pulses. A simple routine that counted the pulses in the S1000 counted a defined number of pulses generated by the Omron CPM1A PLC was used. The maximum reliably detectable frequency that resulted was 50 Hz. This test was discarded however, since the capability of the CPM1A PLC to generate high frequency pulses was limited.

To more accurately calculate the maximum frequency, the other two tests that relied on the use of signal generators were done. Out of these tests, the ones that relied on the high-end signal generator yielded the most reliable tests. Figure 4.1(a) shows the behavior of the system between 0 Hz and 49 Hz. This figure represents three different things; the first is the probability distribution that the system presented from 0 Hz to 49 Hz, the second is the number of counted pulses in each of the 20 test repetitions of 10,000 pulse bursts, lastly the real count is represented. As can be seen, the results in this frequency range were perfect, no error in the count occurred in any of the tests. In contrast to this, the firsts test that relied on the PLC timer system yielded less accurate results, this can be seen in Figures B.3 and B.5, in Appendix B. The former shows the behavior of the system at 45 Hz, and the latter shows a comparative graph of the different calculated probability



(a) 0Hz-49Hz Standard deviation; second test



(b) 50 Hz Standard deviation; second test

Figure 4.1: 0Hz-50Hz Standard deviation.

Table 4.1: Flowmeter testbed maximum frequency testing.

Flowmeter	Frequencies	Time window	Avg. error %	Theoretical range	Real range
SR-2,5	5Hz	1 min	0.13%	1-44.25Hz	1-16Hz
	10Hz	1 min	0.16%		
	15Hz	1 min	0.48%		
	20Hz	1 min	14.75%		
RS3	5Hz	1 min	0.22%	1-12.083Hz	1-14Hz
	10Hz	1 min	0.55%		
	15Hz	1 min	5.85%		
	20Hz	1 min	30.97%		
SR-10	5Hz	1 min	1.667%	0-21Hz	0-21Hz
	10Hz	1 min	0.07%		
	15Hz	1 min	0.622%		
	20Hz	1 min	0.883%		

distributions.

It was found that the system begins to show erratic behavior at the 49.5 Hz frequency. While at this frequency the system is only missing one or two pulses at most, the system becomes completely unreliable at the 50 Hz frequency. Figure 4.1(b) shows the drastic change in the reliability of the system. While the counted pulses seem to be relatively consistent, the mean value of the counted pulses is completely of the mark by around 80 pulses. The results for the PLC timer based tests can be seen in Figure B.4, in Appendix B.

In order to execute these same tests with the flowmeters themselves, the PLC timer based approach had to be used. While at this point it is known that this timer based approach is not very reliable, there was no other way to accomplish these tests. Another factor that affected the flowmeter tests was the oil flow rate fluctuations that occurred in the system. While the pulse frequency generated by the flowmeters was verified with an oscilloscope and adjusted with the flowmeter knobs, these fluctuations still added some errors to the results obtained. Nonetheless, the results shown in 4.1 give an appropriate estimation of the system behavior.

Table 4.1 shows the results of the frequency behavior tests done on three of the pulse generating positive displacement flowmeters. It shows one minute tests done at different frequencies and compares the theoretical frequency range of the flowmeter to the frequency that is actually detected by the S1000, namely the real range. Different time windows were used, but it was concluded that regardless of the time window size the behavior was the same, one minute was chosen out of practicality. The theoretical range frequency is obtained by taking into consideration the Maximum Flow Rate (MFR) that the flowmeter is designed for, and multiplying it for the K conversion factor of the flowmeter. This amount is then divided by sixty to obtain the maximum theoretical frequency the flowmeter will generate once its maximum flow rate is reached. In essence, it can be said that

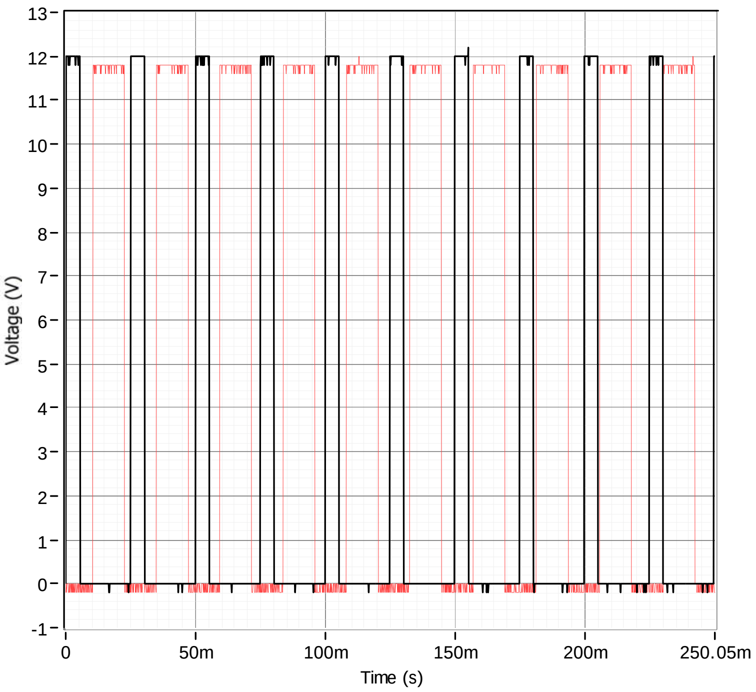


Figure 4.2: Two 40 Hz signals with different duty cycles.

the S1000 is capable of capturing the pulses generated by flowmeters that respect either Equation 4.1 or 4.2.

$$K \times MFR < 3000\, pulses \tag{4.1}$$

$$\frac{K \times MFR}{60} < 50Hz \tag{4.2}$$

It is important to note that these equations are only valid if the duty cycle of the generated signal is 50%-50%. The reason behind this can be attributed to the fact that the S1000 works as a PLC. That is, it has a scan cycle during which the inputs are taken in, the logic is processed and the outputs are activated according this logic. In this particular case the scan time is aproximately 10 ms, which just to happens to be half the period of a 50 Hz square pulse signal. It was previously mentioned, in Section 3.4.2 that the signal generated by these flowmeters presents a smaller positive width, or an unequal duty cycle otherwise interpreted.

Figure 4.2 shows an example of two signals with the same frequency, but different duty cycles. If one considers the 50%-50% duty cycle signal (in red) to be the scan cycle of the S1000 it becomes clear that each cycle does not manage to detect all the signals. While it is possible to somewhat syncronize both signals, and improve the count, all the pulses will still not be detected. This is the reason why the real frequency range of the SR2,5

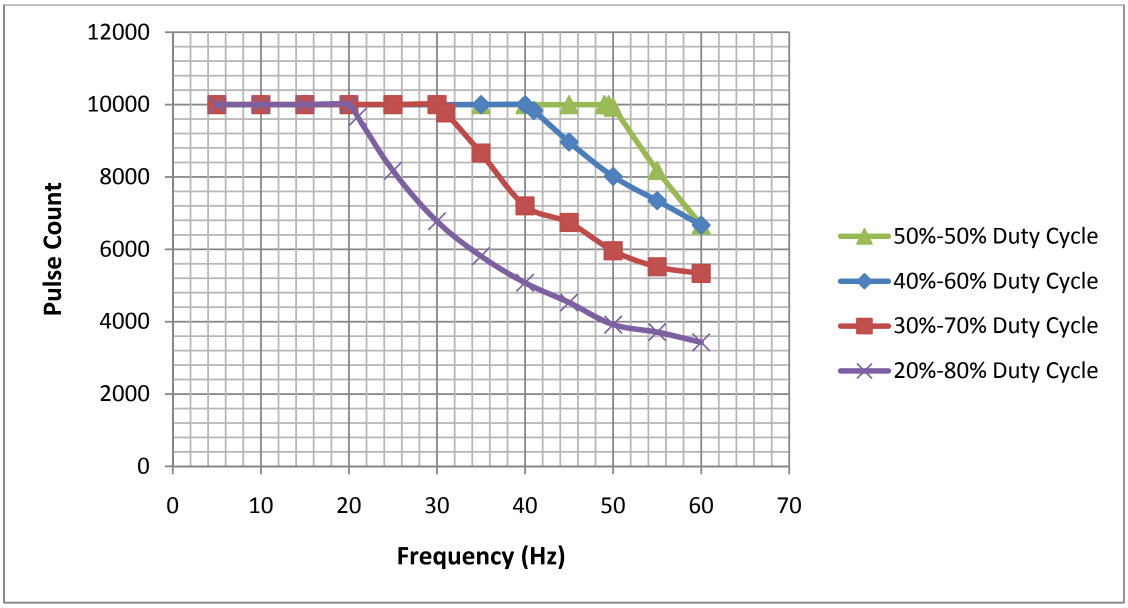


Figure 4.3: Pulse count vs. Frequency; Behavior with varying duty cycle.

flowmeter is nowhere near the theoretical frequency range. It is therefore more accurate to say that the capability of the S1000 to reliably capture the pulses generated by any given flowmeter if, and only if, Equation 4.3 is validated.

$$\frac{K \times MFR}{60} < 50\ Hz\ AND\ Positive\ Width > 10ms \tag{4.3}$$

4.2 Duty Cycle Tests

It can be said that the duty cycle tests are a continuation of the previous tests. Whereas the reliability of the system at a normal duty cycle reaches a frequency of 50 Hz, it has been proven that the this behavior changes in relation to the positive width of the pulse signal generated by the flowmeters. This adds to the importance of the duty cycle tests made to the system.

Figure 4.3 shows the behavior of the system at four different duty cycles. As can be seen, the maximum reliably detectable pulse signal is greatly affected by the duty cycle of the pulse signal. This is quite obvious as the duty cycle is directly related to the positive and negative with of any given square frequency signal. At the same time, this reinforces the findings made when the real flowmeters were tested, and it reinforces Equation 4.3. The lowest tested duty cycle was 20%-80% due to the limitations presented by the high-end signal generator used in the tests.

Table 4.2: Obtained performance parameter values.

Parameter	0-49Hz	49.5 Hz	50 Hz	60 Hz
Average error%	0	-0.007	-0.798	-33.34
Standard deviation (σ)	0	-0.007	-0.798	0.3244
Uncertainty(95%)	0	0.7326	1.4363	0.1518
Uncertainty(98%)	0	0.3429	0.6722	0.2575
Precision 95% confidence	0	0.4687	0.9188	0.6767
Precision 98% confidence	0	1.5283	2.9962	0.9231
Directional bias error %	0	-0.007	-0.798	-33.34
Bias error range ±95%	0	0.3417	0.6699	1.1630
Bias error range ±98%	0	0.46616	0.9138	1.5864
Accuracy 95%	0	1.5661	3.0702	0.6934
Accuracy 98%	0	2.1362	4.1878	0.9445

4.3 Overall Accuracy and Precision

All the information obtained in the previous tests was used to estimate the general performance parameters that could approximate the capabilities of the S1000 as a measurement device. The theory behind the calculation of flow measurement performance parameters was explained in Section 2.1.2 of Chapter 2. These equations were utilized to obtain the average error percentage, the standard deviation, uncertainties, precision, bias error, and accuracy. Only the most important results will be presented in this section, other obtained results can be seen in Appendix B, and will be referenced accordingly.

Table 4.2 shows the obtained performance parameters obtained for a 50%-50% duty cycle. Given the standard deviation for the 0 - 49 Hz range is zero, all the calculations return 0, which can be interpreted as a perfect behavior, namely, 100% accurate and precise in that range. However, since the tests realized only consisted of 20 repetitions and does not account for external noise and other possible factors it is safer to say that the system precision and accuracy are those of the 49.5 Hz rather than the ones from the 0 - 49 Hz range. It is also important to note that while the accuracy and precision above 50 Hz does not appear to be bad, the important parameter to observe is the directional bias error which indicates that the system at 50Hz is 0.7% of the count. That is, 0.7% of 10,000 pulses were not detected at all. This can be also observed in Figure 4.1(b). It is important to consider that these results refer to a normal square pulse signal, and differ greatly from the actual signals generated by positive displacement flowmeters.

For this reason, it was also important to obtain the performance parameters of the system at different duty cycles. Observing Table 4.3 it is possible to realize that the behavior changes drastically the more the duty cycle is reduced. Figure 4.3 shows more clearly the degradation in the pulse count when reducing the duty cycle. It is important to remember

Table 4.3: Performance parameters at different duty cycles.

Duty cycle	**Standard deviation (σ)**	**Uncertainty(95%)**	**Uncertainty(98%)**	**Precision 95% confidence**	**Precision 98% confidence**	**Directional bias error**	**Bias error range ±95%**	**Bias error range ±98%**	**Accuracy 95%**	**Accuracy 98%**
40%-60%										
0Hz - 30Hz	0	0	0	0	0	0	0	0	0	0
41Hz	1.507	0.705	0.964	3.145	4.290	-1.628	0.703	0.959	3.22	4.396
30%-70%										
0Hz - 30Hz	0	0	0	0	0	0	0	0	0	0
31Hz	2.446	1.145	1.565	5.103	6.961	-2.282	1.141	1.556	5.229	7.133
20%-80%										
0Hz - 20Hz	0	0	0	0	0	0	0	0	0	0
21	3.069	1.436	1.963	6.402	8.733	-3.425	1.431	1.952	6.560	8.949

that the values presented in Table 4.3 might not reflect completely the deterioration of the pulse count as those calculations are limited to the break-point frequency at which the deterioration starts. The directional bias error however, reflects more accurately the beginning of the deterioration as up to 3% of the pulses start to be lost in the 20%-80% duty cycle tests, the negative sign accounts for the fact that the pulse count was always lower than the real count.

As shown in Tables 4.2 and 4.3 the measured parameters show a great drop in performance once they reach the 50 Hz mark. While this was already said to be the maximum reliably detectable frequency, these tables greatly reinforce the initial findings. Figure 4.4 shows a plot that represents the accuracy at 95% and 98% confidence, versus frequency. This clearly shows the sudden change in accuracy that the system presents. One might argue that when the system is again at 60 Hz the accuracy improves once again, while this is a wrong statement, it also has some truth. A consistent behavior in the pulse count tests is that the general accuracy at all frequencies is constant, regardless of these being above 50 Hz in the normal duty, or above the threshold frequency of different duty cycles. This is because the S1000 detects roughly the same amount of pulses at most frequencies, this is why it is so important to take into consideration de directional bias error. Table 4.2 tells us that the this error is as high as 33.34%, that is, 1/3 of the 10,000 pulses sent to the device were not even detected. In spite of this, both Figure 4.4 and Table 4.2 may give an incorrect impression if other parameters are not taken into account. For the figures that represent the results obtained in the PLC based timer tests, see Figures B.1 and B.2 in Appendix B.

The change in the bias error percentage mentioned above can be more clearly observed

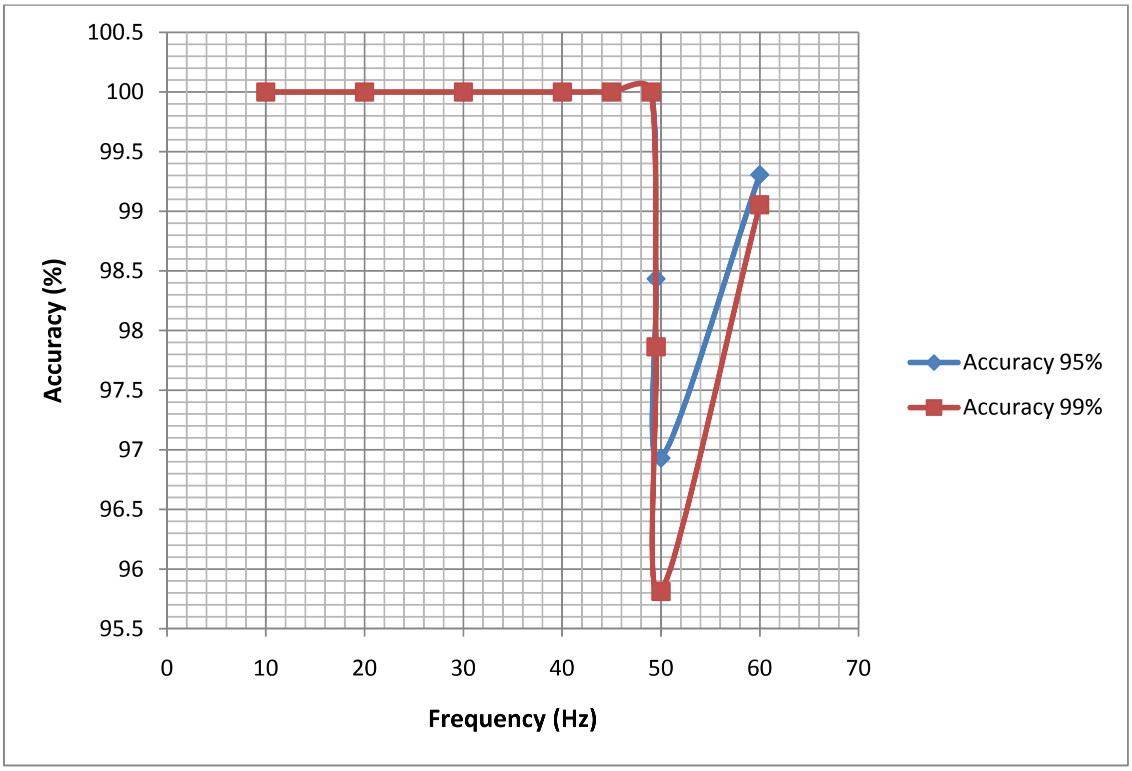


Figure 4.4: Overall Accuracy VS Frequency; second test.

in Figure B.7. Figures B.6 and B.8 show other plots that allow the visualization of the behavior of the system. The former shows a the bias error versus frequency, while the latter the error percentage versus frequency. Both show a drastic change in the capabilities of the S1000 after the 50 hz boundary is reached.

5. CONCLUSIONS

This chapter elaborates on the conclusions reached at the end of the work presented in this thesis. It answers the questions presented in the introduction of this work and discusses on the obtained results. Lastly, potential new directions and future work possibilities are mentioned.

5.1 System Architecture

While there has been many different approaches to the development of SOA in many different fields of the manufacturing industry, few have addressed the use of this technology in condition monitoring oriented systems. The late improvements in SOA technology however, have enabled the possibility to create smart devices that embed DPWS and allow an easier implementation of Web Services in many different fields. One of these potential areas is the oil lubrication monitoring systems used in the paper industry. As presented in this thesis the need of thousands of lubrication points in any given paper machine merit the need of distributed scalable monitoring systems. These systems must enable the communication of data from factory floor to central monitoring stations, and in some instances all the way to the corporate network.

This thesis has shown that Web Service capable devices can be easily integrated to create a reliable communication network that allows for data integration at all levels. Chapter 2 described many different flow monitoring systems and analyzed different system integration technologies, while at the same time relating both of them. While Chapter 3 thoroughly evaluated the advantages and disadvantages of the current flow monitoring systems. Areas of opportunity in these systems were addressed with the design of a new flow monitoring system based on intelligent devices capable of encapsulating themselves as Web Services. Not only that, but the capability of these devices to pre-process raw data in the form of pulse trains generated by flowmeters was also proved. In addition to this, HMIs that allowed both local and remote monitoring were shown and explained.

Based on the previous arguments the question: "*Is it possible to completely solve the network integrability problem in flow monitoring systems by means of DPWS embedded devices and Web Services?*" may be answered with a partial yes. Although a lot of the communication integration problems may be solved by using these types of devices there are still factors that limit this type of system to solve all the existing problems. Some of these limitations are due to the capabilities of Web Service capable devices, as it is a relatively new technology. Other limitations pertain to the existing communication network architectures implemented in the manufacturing system. While these systems may be seamlessly integrated to existing legacy systems, and they follow powerfully established standards, they require changes in the existing systems that may be costly.

In addition to the network architecture integrability improvement that Web Service based systems enable, it can also be said that another of their greatest strengths is the availability of information. While in traditional systems may be configured and customized in a way that allows information to reach the necessary peers, Web Service based technology facilitates this and may even appear to make it in a more transparent and simple way.

5.2 Performance

The performance tests explained in Section 3.4.2, which results were presented in the previous chapter gave a very clear idea of the capabilities of the S1000 as flow measurement device. Generally speaking, this particular Web Service capable device is quite capable of obtaining accurate flow rate measurements. It showed and exceptionally good behavior between the 0 - 49 Hz frequencies, but an unreliable behavior above 50 Hz. Not only that, but given the nature of the pulses generated by positive displacement flowmeters, which have a short positive width the 50 Hz frequency limit is only valid for normal duty cycles. As such, the frequency range that is supported by the S1000 is flowmeter dependent.

In regards to Web Service eventing, the behaviour of the S1000 was good. Given the limited size of the testbed, and the limited amount of available flowmeters more elaborate tests could not be planned. It is therefore yet to be verified if the S1000 is capable of processing all the signals generated by flowmeters, if all the inputs available in the device were to be occupied the performance might change greatly. Nonetheless, the tests that were made with the special purpose event subscription client that was programmed were satisfactory. Lastly, it is important to note that while the S1000 is a highly capable device it still lacks the necessary hardware that would allow the system to work on a wider frequency range, and the memory to allow it to support a greater number of flowmeters. This by itself, may answer the second question presented in the introduction of this thesis; "*Are DPWS embedded devices capable of pre-processing and composing flowmeter data correctly and reliably and, at the same time handle the necessary Services and Events needed to monitor lubrication flow monitoring systems?*".

While the answer to the previous answer has already been given, it is important to consider that there may be other intelligent DPWS embedded devices with higher capabilities that may perform better for this type of oil lubrication flow monitoring systems.

5.3 Future Work

This thesis has shown the high potential that Web Service embedded devices have. Not only in the communication architecture sense, but also in the pre-processing and transportation of information by means of standardized interfaces. While this technology has still not reached its full maturity, great promise has been seen in it, and as such, manufacturing and monitoring systems may continue to evolve in this direction.

The particular case presented in this thesis can be taken further in many ways. The first and most obvious is by introducing a more powerful device capable of detecting high frequencies, and capable of supporting a greater number of flowmeters. Additionally, full installations in actual paper machines could be made to test the event and service performance and reliability in a real manufacturing environment. This would allow, in turn, the implementation of Complex Event Processing (CEP) systems that work based on the aggregation of data from different sources. In the case of circulating oil flow monitoring systems, additional temperature and pressure sensors can compliment the flow rate measurements, resulting in a more complete perception of how a system is behaving overall. This would greatly improve the existing flow monitoring systems, reduce maintenance costs and increase the product quality.

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A. APPENDIX

Table A.1: Student's *t* distribution for 95% and 98% confidence.

Degrees of Freedom	***t*(95%)**	***t*(98%)**
1	12.7062	68.6567
2	4.3026	9.9248
3	3.1824	5.8409
4	2.7764	4.6040
5	2.5705	4.0321
6	2.4469	3.7074
7	2.3646	3.4994
8	2.3060	3.3553
9	2.2621	3.2498
10	2.2281	3.1692
11	2.2009	3.1058
12	2.1788	3.0545
13	2.1603	3.0122
14	2.1447	2.9768
15	2.1314	2.9467
16	2.1199	2.9207
17	2.1098	2.8982
18	2.1009	2.8784
19	2.0930	2.8609
20	2.0859	2.8453

B. APPENDIX

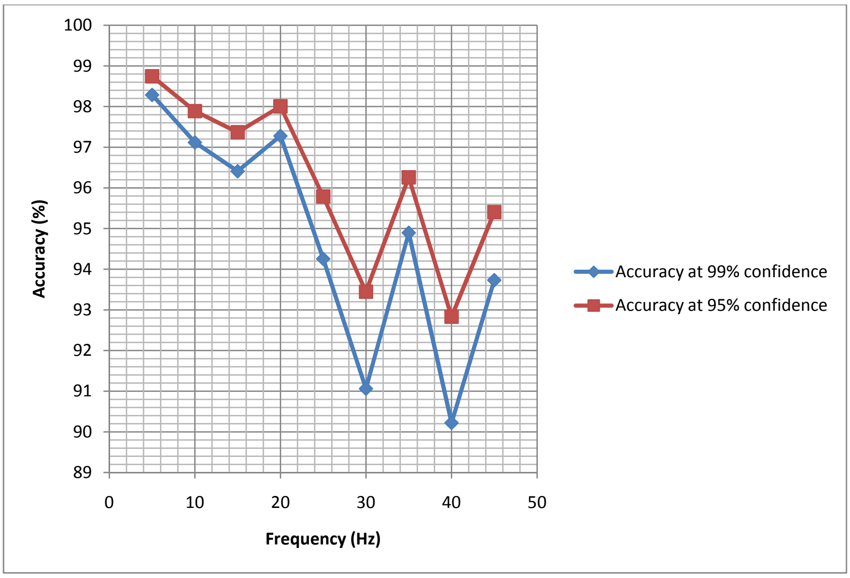

Figure B.1: 5Hz-45Hz Accuracy VS Frequency; first test.

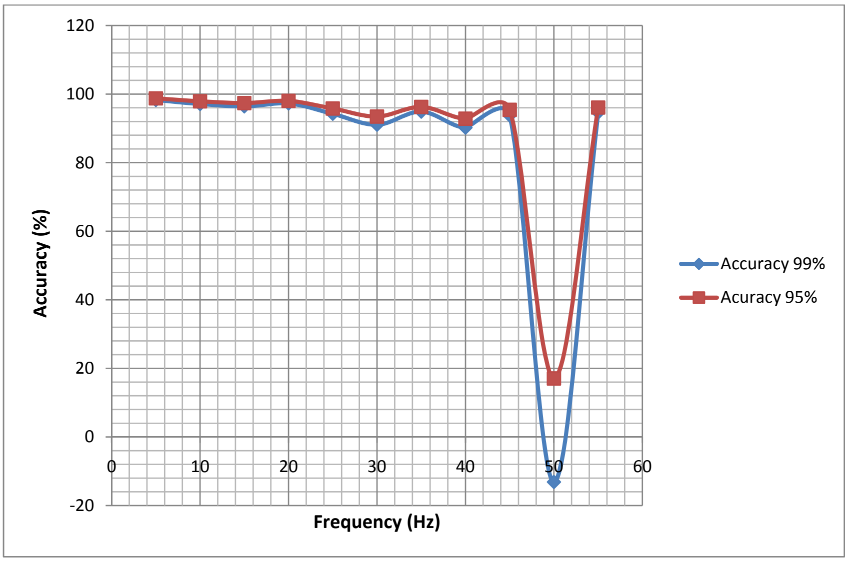

Figure B.2: Overall Accuracy VS Frequency; first test.

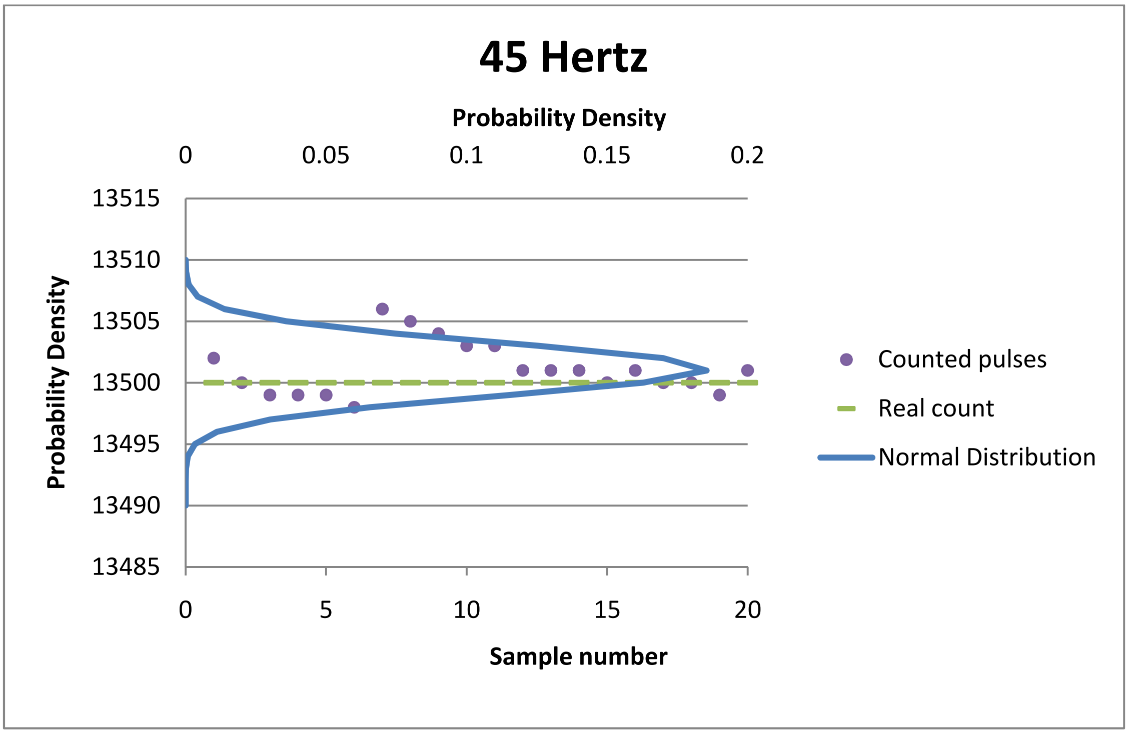

Figure B.3: 45Hz probability distribution; first test.

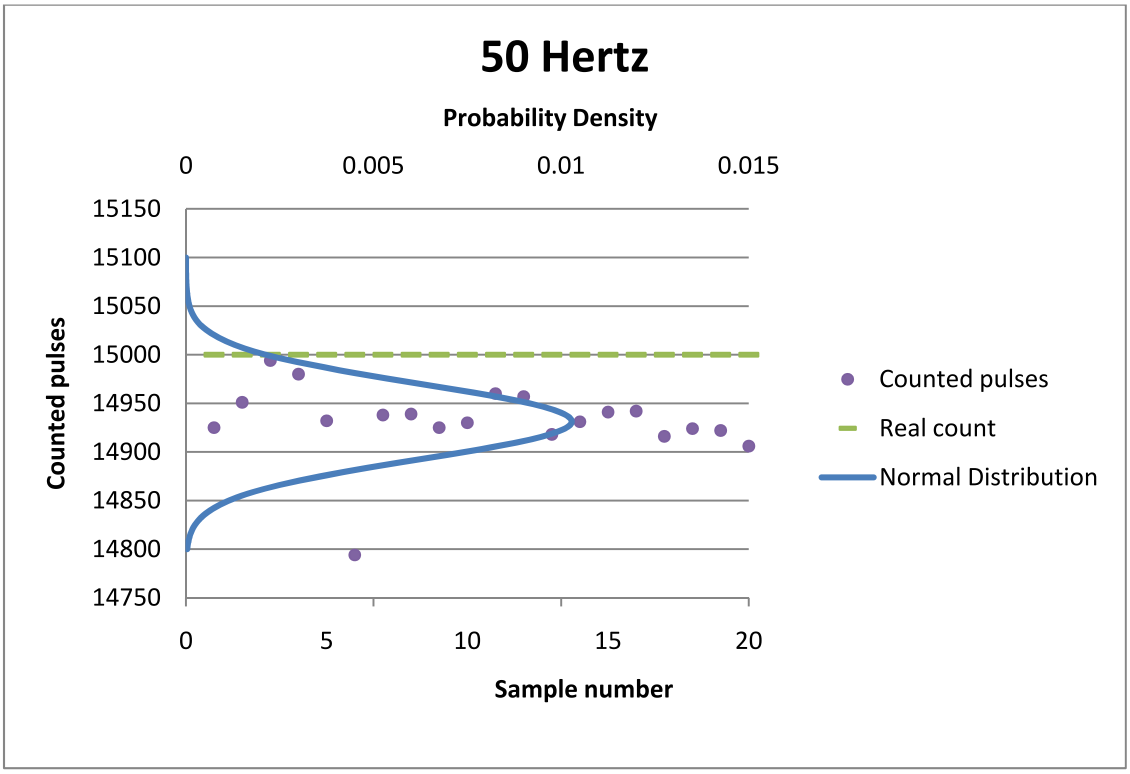

Figure B.4: 50Hz probability distribution; first test.

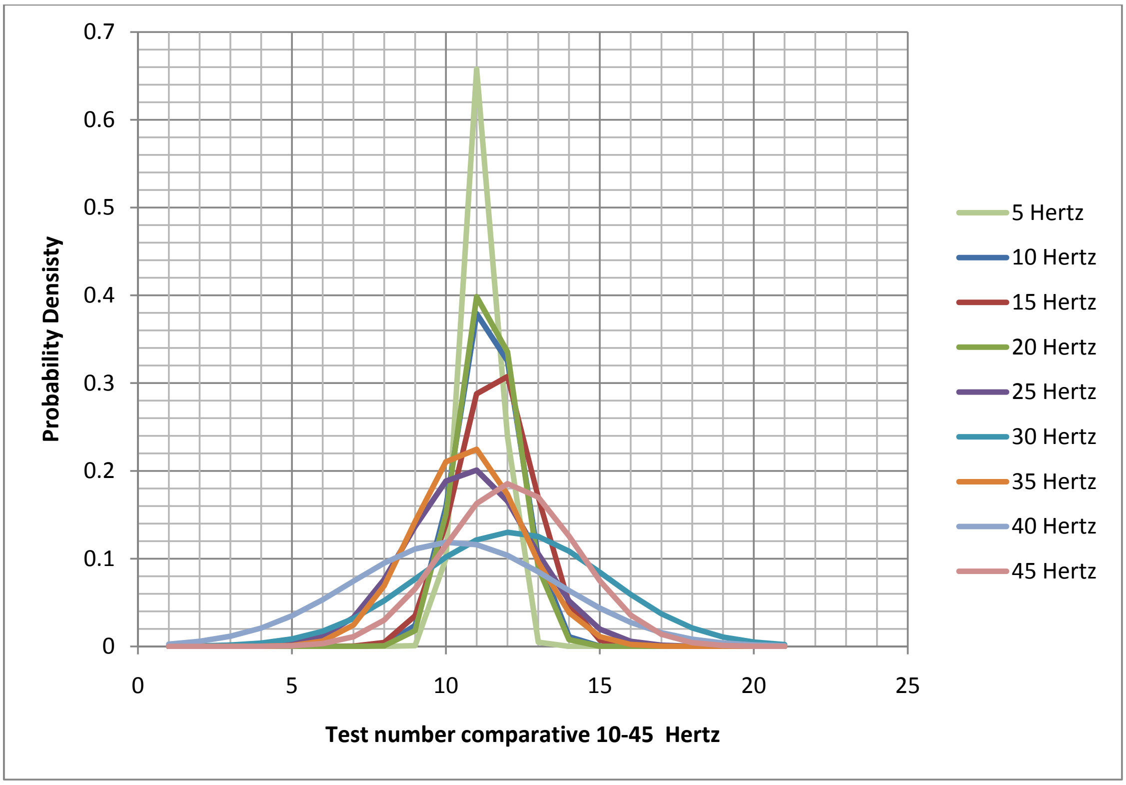

Figure B.5: Standard deviation comparison; first test.

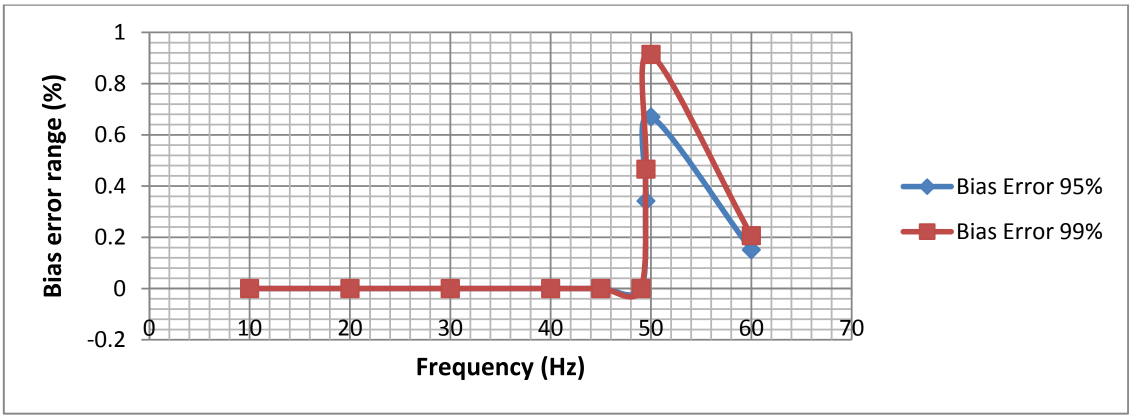

Figure B.6: Bias error VS Frequency; second test.

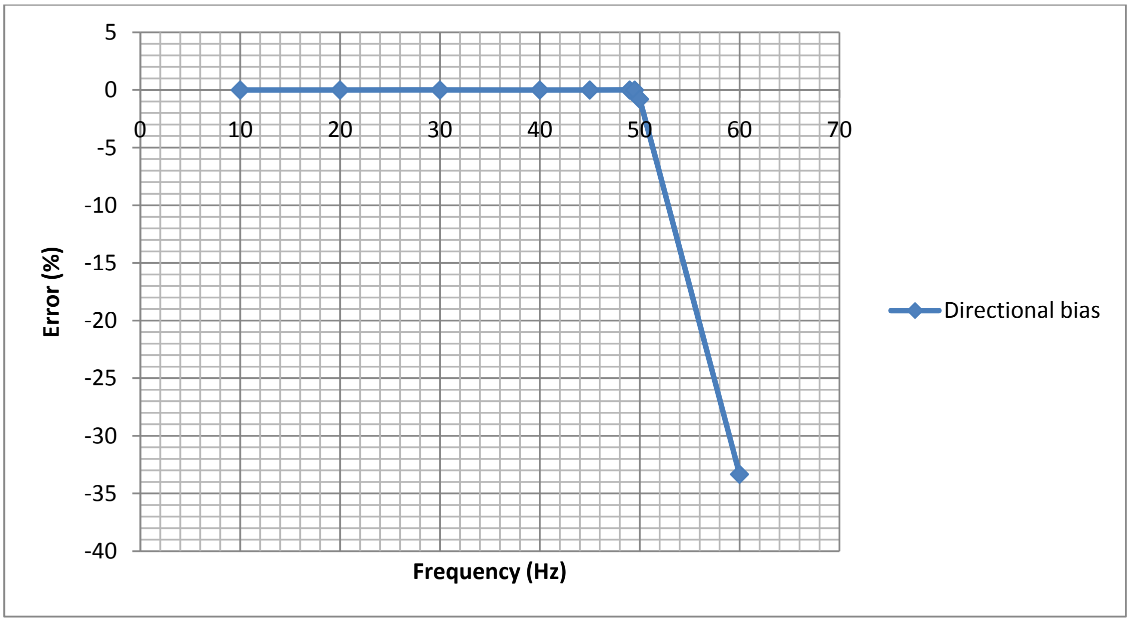

Figure B.7: Directional bias error %; second test.

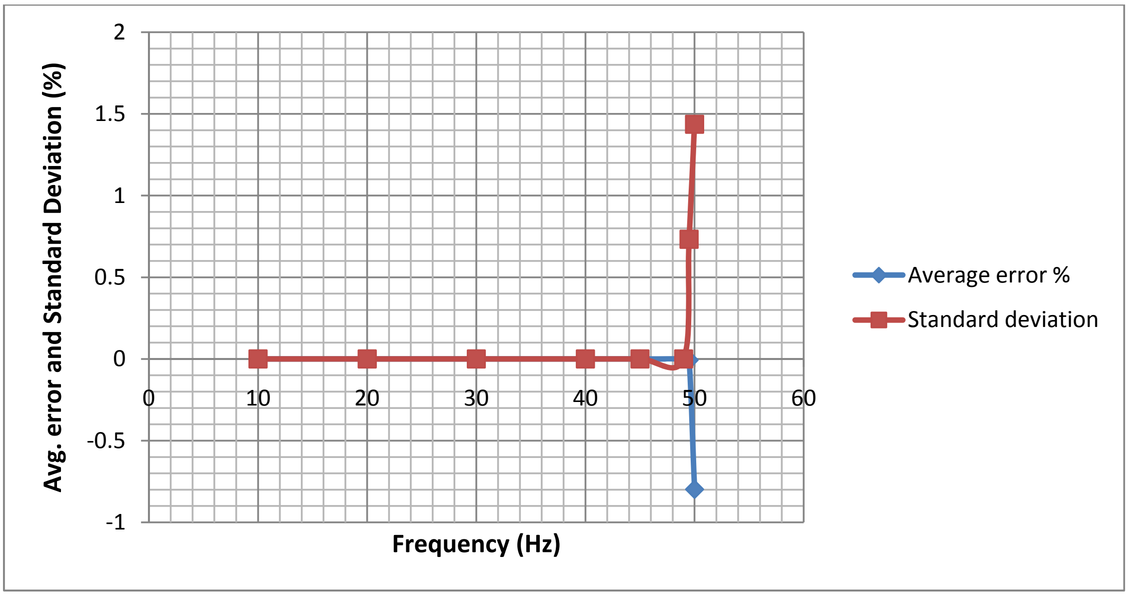

Figure B.8: Error and standard deviation VS Frequency; second test.