A Service-Oriented Monitoring System of Pressurized Air in Industrial Systems for Energy Awareness

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Abstract— **This paper focuses on development of an independent system dedicated to monitoring of compressed-air systems. Main focus has been put on discovery of anomalies which influence energy efficiency of compressed-air systems. System is able to recognize anomalies in an automatic manner and notify the user if these are discovered. These improprieties are leakages, pressure drops and increased humidity in the system. Designed system consists of hardware device which can be connected to any desired point of compressed-air line and is responsible for data acquisition and processing. System offers two Human Machine Interfaces. Additionally one of HMIs exploits Web Service technology enabling major decrease in communication bandwidth usage.**

Keywords - monitoring; compressed-air; leakage; HMI; SOA

I. INTRODUCTION

It is estimated that around 90% of manufacturers worldwide use compressed-air systems (CAS). In EU, CAS use about 10% of produced electricity. The particular countries energy usage of compressed-air is around 10-15 TWh annually [12]. Therefore CAS are major contributors to electric power consumption. Kyoto Protocol obliges industrialized countries to significant reduction of greenhouse gasses. Key policy to achieve these norms is energy efficiency. According to [14] only 19% of the power used by a compressor can be transformed to usable air energy. However compressed-air possesses appealing advantages like: safety and simplicity of usage, reliability, easiness of distribution and storage capabilities [12]. Unfortunately many CAS lack energy efficiency due to many factors. The major one is said to be the leakage in the system, being responsible for wasting 20-50% of a compressor's output. The cost of leaks is the cost of energy required to balance the volume of lost air. As can be seen there is a huge potential of energy saving and at the same time cost reduction in that particular area. However most of the research in the field of leak detection focuses on pipe networks, transporting media like petroleum, gases, steam or water. Whereas on the plant level there is evident lack of means to detect compressed-air losses in a quick, continuous and effective manner. Additionally due to the stereotype that compressed-air is cheap and harmless in operation, many compressed air properties are not investigated enough, what may lead to malfunction or destruction of compressed-air powered equipment. Water condensation or pressure drop at particular points of CAS may prove to be essential to monitor in order to extend equipments life cycle and reduce the maintenance costs. Considering that compressed-air is a second after electricity energy source in most of the plants, there is evident shortage of methods to closely monitor its parameters to boost its energy efficiency. Therefore, proposed solution will target area of monitoring systems which use compressed-air energy. Main focus will be put on discovery of three improprieties: leakage, increased humidity and pressure abnormalities.

II. LITERATURE AND TECHNOLOGY REVIEW

During the CAS lifetime, operating energy costs may become five times higher than the initial investment [13]. The first step of saving process is to determine where the highest potential for saving is. As stated in [12], [13] in order to improve CAS performance, following measures might result in large savings: reduction of leaks, improved air treatment, avoiding over pressurizing. As can be seen there are many factors that can minimize the energy loss. Study in this paper will target three factors which can contribute to energy savings in CAS. System monitoring leaks, pressure deviations and dew point temperature will be developed.

A. Losses due to leaks, humidity and pressure changes

The biggest contributor to losses and the same time potential saving are leaks in the system. According to [12] leaks represent 42% of potential of energy savings in CAS. That figure makes it natural step to firstly tackle with leaks, whenever plans to decrease energy losses in CAS are undertaken. Based on equation presented in [3] losses due to leaks can be directly translated into money loss. For instance one leak of 6mm diameter will bring around 8000€ losses annually. Usually there are more leaks, which depicts a magnitude of possible losses. Apart from high energy losses and costs, leaks may contribute to fluctuations of system pressure - resulting in decreased efficiency or even destruction an air-operated equipment. Additionally the supply equipment may suffer due to unnecessary cycling and altered run time, resulting in shorten life cycle and extra maintenance.

Besides leaks, other functionality threatening factor is the humidity inside air distribution system. Depending on application of air, there is a need of diverse dryness. Air as general consists of mixture of nitrogen, oxygen and water vapour. Unlike nitrogen and oxygen, water vapour concentration is highly variable. According to the Dalton's law the total pressure of a gas is the sum of partial pressures of separate component gases. The maximum partial pressure of water vapour depends strictly on temperature. Adding more vapour will

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result in condensation of water. To determine the measure of how much water vapour is in the gas, dew point temperature is used. If the air temperature drops below the dew point temperature, it becomes saturated and some of water condenses. In CAS, changing gas pressure changes dew point temperature. The knowledge of dew point temperature has significant influence in CAS as any condensation of water may cause improprieties in the plant. Majority of compressed air distribution systems are made of steel, thus any contact with moisture results in corrosion, which may lead to creation of leaks. Moisture as well as rust blown with air may affect the air-powered equipment, making it sluggish or damaged. Any trace of moisture could be critical in the processes like: paint spraying, pharmacy, food industry causing adherence of hygroscopic products. Usually dew point is measured after the drying process, however possibility of measuring the humidity at different locations may be beneficial as it may happen that part of the distribution system is exposed to low outside temperatures, resulting in water condensation. Additionally accurate knowledge can improve energy efficiency of desiccant dryers which decrease the humidity level of compressed air. In that way savings up to 80% can be achieved in the process of air drying [4], [9].

Besides the previously mentioned issues also the pressure Affect the efficiency of the system. Pressure drops in the system occur mainly due to mechanical obstructions in distribution system or due to treatment of the air – in order to improve its quality. Usually the system should have a drop much smaller than 10% of compressor's output. Drops can result in performance decrease of the equipment and increased energy consumption [6]. While the drops due to mechanical constructions can be planned at the design stage, drops resulting from dirty and clogged filters may increase unnoticed. This can translate to energy and money loss. It is noted that pressure drop of 2 psi may result in 1% increase of energy costs [11]. As an example, annual cost of drop of 0.5 bar with compressor of 75kW performance can reach around 1300 €. More information regarding pressure drop and electricity dependency can be found in [11].

B. Condition monitoring

Main monitoring paradigm incorporated in that study is based on concept of condition monitoring. In industry, maintenance is considered to be an essential tool to provide reliable functioning. Maintenance can be divided into several categories, based on the methodologies [15]. These approaches are: breakdown, scheduled, condition monitoring, predictive. Condition monitoring fills the shortcomings of breakdown and scheduled approaches. Condition monitoring is a supplementary approach filling the drawbacks of scheduled approach and offering constant monitoring in order to avoid failures. It employs collection of data about certain part of equipment or system in order to assess if its state or performance is within or likely to remain in predefined limits. It mainly concerns with failures which may influence any kind of physical property and have evolutionary nature. That maintenance regime is existent in many fields ranging from machinery to fluid applications. According to International Foundation for Research in Maintenance it applies to more than 80% of maintenance [1].

C. Leak detection methodologies

The variety of mediums distributed in pipelines makes the discovery of improprieties like leakage, existent in a wide range of fields. Most of the focus in research is usually put in areas where any leakage may pose a threat to life to environment. These include big scale piping systems transporting petroleum or gas. In a smaller scale there are industrial systems which may use equipment powered by steam or compressed air. However methodologies dealing with CAS leaks usually limit to simple and not always fully reliable solutions. Although following methods deal with varied distributed mediums, the detection principles may be applied to all of them in most of cases. The division of leak detection methods can be found in [17]. Amongst the used methods are: negative pressure, acoustic, mass balance, flow or pressure change observation. Advantages of negative pressure are: useful for long distance distribution systems; offers possibility of localizing the leak as described in [8]. However that method requires computationally demanding processing. Acoustic method is usually conducted with the use of handheld, ultrasonic acoustic detectors [2]. Although widely used, it has significant drawbacks like: device needs to be in a close range from the piping system; checks are performed periodically which does give the opportunity for leak development between periods. Widely used leak detection method is based on mass balance equation. Despite simple principle, it requires constant measurements of other parameters which affect the gas mass. Interesting comparison of negative pressure and mass balance are shown in [8]. Flow or pressure change observation methods rely on principle that high change of flow or pressure signifies a leakage. It offers easiness of implementation. Based on one point of measurement the assessment of flow abnormalities can be performed. Research work presented in [10] utilizes that concept. Dynamic model methods are based on fundamental understanding of the underlying physics of the process. Extensive explanation can be found in [16]. Although some of the presented concepts have been used for monitoring leaks in CAS, most of them are utilized in applications which deal in transportation of fluids over long distances. That shows the need of a system monitoring compressed-air applications.

III. METHODOLOGY

A. Sensor selection

Discovery of leak can be performed having the knowledge of actual flow of air in the CAS. Therefore appropriate flow sensors had to be selected. It has been quite challenging task due to varied operational principles. Each of them has their pros and cons depending on the application. The first division results from measured value type. There are mainly two types: mass and volumetric flow sensors. Besides indicating different units, their operating principles are different. Under the volumetric group, there can be found sensors based on differential pressure, positive displacement and velocity principle. The mass flow meter group differentiates

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two operating principles: Coriolis and thermal. The advantage of volume flow meters is its low cost, big versatility on the market, applicability varied fluids. Although the volume flow devices are a common choice in industry, they possess unwanted property - temperature and pressure dependency. Fluctuation of these parameters results in changing gas density and viscosity. When that occurs, the previously set calibration point will no longer be valid and the measurement will not be accurate. As the designed system is supposed to be applicable in varied environments, selected sensor is based on mass flow measurement principle. Mass flow meters in contrast to volume flow meters are relatively immune to changes in inlet temperature and pressure – which is the biggest advantage. Mass flow meters based on thermal principle are more available on the market and at cheaper cost. Sensor has been chosen from Festo offer. Important factors that influenced the selection were: wide selection of ranges, price and freedom of installation. Quite often flow sensors have a restriction of place of installation. They had to be placed in laminar-flow regions, making installation demanding. Festo sensors due to their construction let the flow go through the bypass channel that generates laminar flow, where the sensing element is located. Considering required applicability of designed system in different scenarios, sensor should cover widest range possible. Festo sensors discover flow from 0.1 up to 5000 l/min. Best solution would be to choose one sensor that covers big range. However each of offered sensor covers some portion of 0-5000 l/min range. In order to cover widest range possible, two sensors have been selected: model SFAB covering range from 0.5–50 l/min and SFAM with range of 50-5000 l/min. Due to the big difference in sensors channels diameter, they were connected in a parallel connection. Series connection would result in significant obstruction of flow. However that decision resulted in additional signal processing. In parallel connection total flow is sum of two sensors outputs. Due to varied diameters there are differences in proportion of flow that is coming through sensors channels. Thus when either one of the sensors falls out of the range, other one needs a measurement correlation factor to compensate particular constant proportion of flow that is coming through the other channel. Otherwise, when both sensors cover the range, total flow is a sum of SFAB and SFAM sensors. Correlation factor has been found with help of Matlab tool – curve fitting. Quadratic equations appeared to be accurate enough.

Main objectives while choosing humidity sensor were: measurement range, accuracy, long-term stability, operating pressure and cost. In terms of precision, sensors based on chilled mirror principle are considered to be most accurate. However the cost is several times higher than sensors based on other principles. Therefore sensor based on capacitive measurement principle has been chosen. Although capacitive sensors cannot be compared in their performance to chilled mirror ones, they offer measurements accurate enough for industrial needs. Selected sensor, SF52 model is offered by Michell Instruments. It measures relative humidity. In order to obtain dew point temperature the values of relative humidity are correlated to reference dew points confirmed with a NIST-traceable (National Institute of Standards and Technology) chilled mirror hygrometer. The biggest advantage of this method is that the cost of such a sensor is several times lower than the one based on the chilled mirror methodology.

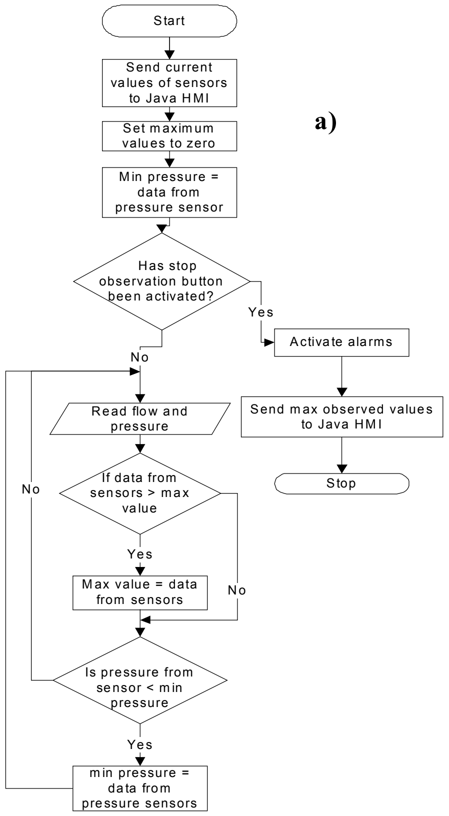
The selection of pressure sensor has been mainly motivated by cost and accuracy. There is very rich offer of pressure sensors on the market. Decision has been taken to find the pressure sensor from the same vendor that flow sensors were obtained, i.e. Festo. Selected sensor is a SDET type and offers maximum range measurement up to 10 bars.

B. Data acquisition – event driven model

Traditional approach in industrial monitoring applications is based on the pull paradigm. This communication scheme is based on the periodical polling of relevant data from hardware I/O devices. Drawback of that approach is high bandwidth usage as unnecessary requests are made in a short time interval in order to keep high accuracy. On the other hand, increasing the interval to relieve the communication link load, results in increase of update latency. Polling approach is thus inefficient as it may happen that observed data is at constant level for long period but data is polled anyway. Solution for decreasing the bandwidth usage could be using a contrasting approach - push paradigm. In that approach information is sent in form of event from the controller to other endpoints (for instance HMI). Event can be defined as occurrence of a happening of interest, which could be change of input value. Event-driven paradigm is much more efficient in terms of bandwidth usage as only relevant data is transmitted. Additional benefit of using event model is that neither the event nor the subscriptions to them are dedicated for specific endpoints. Such a design increases the interoperability, making the separation of communication from computational part more evident. Due to that, integration of low level devices into higher level system is easier and no additional drivers are needed to communicate. Eventing functionality is part of Service Oriented Architecture (SOA) and particularly its implementation – Web Services (WS). Used controller enables usage of WS through DPWS (Device Profile for Web Services) specification.

C. Discovering compressed-air anomalies

Following the main concept of condition monitoring, system is supposed to perform constant observation and announce any abnormalities in CAS, before their magnitude grows to level generating major energy losses or endangering equipment or process. After reviewing common practices in leak detection most of them include usage of distributed sensors in order to perform mass balance calculation. Additionally quite many of them incorporate computationally demanding algorithms. Due to requirement of mobility, system designed for this thesis is able to give one point of measurement thus distributed sensor approach cannot be considered. All data processing is planned to be done at the controller level thus any computationally demanding algorithms are restricted. Therefore the leakage discovery methods implemented in that project will base on flow observation, relying on principle that change of flow value from previously obtained reference band will signify a leakage.



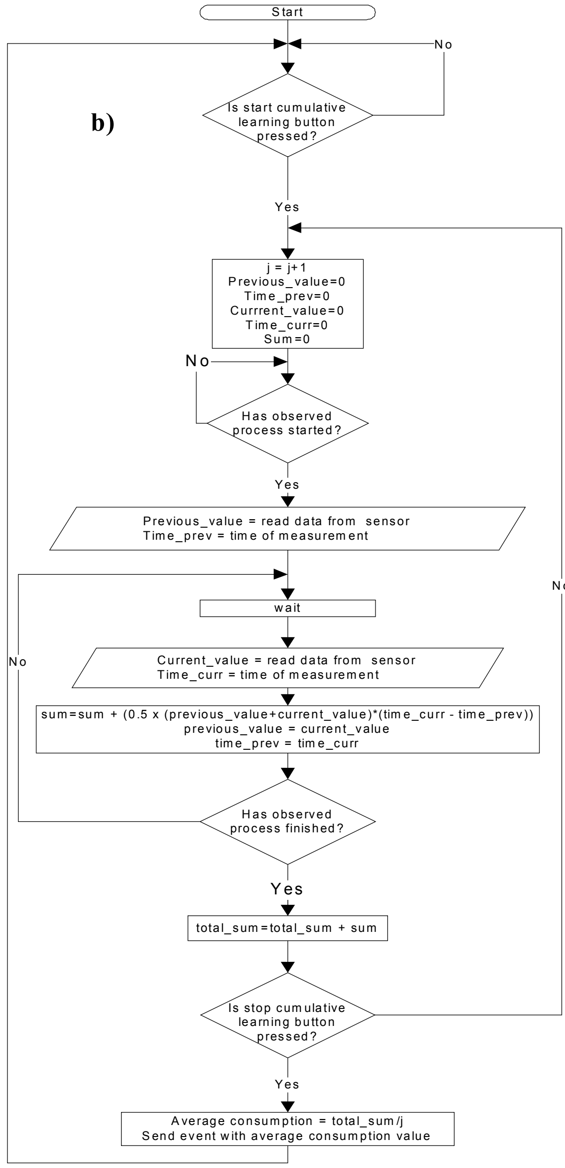


Figure 1. a) Range observation and b) process observation algorithm

Same principle will be applied for detecting abnormalities in pressure and humidity level. First step of monitoring is to collect healthy conditions of the observed system. After that, system will monitor any deviations from obtained data. First of applied approaches for monitoring is based on observation operating ranges. This approach is not process based, thus does not need any additional signals from observed system. More details related to the algorithm can be found in Figure 1a. The method of obtaining reference value of the dew point temperature has been decided to be put manually by the user. Motivation of that decision was fact that in order to discover dangerous level of humidity in CAS, there is a need of measurement of ambient temperature. System at current stage of development does not have a temperature sensor included, thus value of surrounding temperature is put by the user. If dew point temperature of compressed-air will approach set reference point, alarm will be set. Based on obtained normal operating conditions, alarms are set. System has two types of adjustable alarms: low and high. Algorithm defined for alarms is a loop constantly comparing current data from sensors with calculated thresholds. Each alarm indicates one of the anomalies. If flow alarm is triggered it indicates higher than usual consumption of air - which announces leakage in observed system. Any deviation from pressure normal working conditions notifies either about pressure drop - which could result in air-operated device malfunction - or notify about over pressurizing equipment - which could result in devices destruction. In case when dew point temperature reaches set point, alarm will inform about serious possibility of condensation of water in the air distribution system. Second monitoring approach is process oriented and mainly focuses on observation of flow. In industry, many operations are repetitive due to automation of the processes. It could be pick and place performed by robot or work performed by cylinder. Taking under account repetitiveness of certain operations, particular amount of air is consumed during such an operation. This value can be a ground for monitoring possible leakages in the CAS. Any deviation would indicate higher consumption of air during the process which is result of leakage. After observation is started from Java HMI level, system waits for trigger indicating beginning of the observed process. After that, two consecutive measurements of flow are done with a predefined

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delay between them. By knowing the values of flow at those particular instances, integration can be performed in order to obtain consumption value in liters. Due to controller limitation, trapezoidal rule has been used to approximate definite integral. It is particularly accurate when integrating periodic functions over their periods, which is the case. Algorithm on which process oriented observation is based can be found in Figure 1b. Monitoring system is informed when the observed process starts and ends by means of messages send from controller responsible for observed process. More details on that operation will be presented in implementation section. After the average consumption value for process is calculated, observation is performed. Leakage is discovered by comparing the previously calculated average consumption with current process consumption. User similarly to normal operating range method specifies the thresholds of two alarms. Any deviation from usual consumption reaching the alarm zone will be notified to the user and considered as leakage in CAS. Additional features, helpful in monitoring process are total consumption information and leakage diameter estimation value. Former one accumulates each, calculated process consumption together. Leakage diameter approximation is based on transformation of equation for volumetric flow escaping through the leaks described in [7].

IV. Implementation

A. Hardware implementation

All the components i.e. four sensors, controller, in order to constitute one unified, independent system, have been placed in a cabinet. From the user perspective such a system should be in a sense a “black box” with an interface to connect to it.

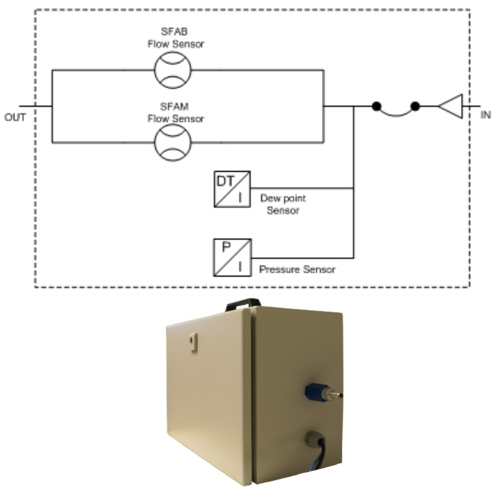

Figure 2. Hardware part of the system

As can be seen in Figure 2 that aim has been achieved. System can become part of compressed distribution line in an easy manner thanks to two push-in 10mm pneumatic connections .Thanks to its Ethernet based communication it can also very easily become either part of underlying communication layer or be connected directly to PC to gather process information in a straight forward manner.

B. Software implementation

All processing of the data gathered from the sensors is done at the controller level. Due to that and the implementation of Web Service (WS) technology, bandwidth usage can be reduced. S1000 (by Inicotech) controller which has been selected for that project offers Web browser interface, as well as WS capabilities. Web based access enables implementation of the logic as well as all necessary configurations independent of any additional software. There were two stages related to programming and configuration of the controller. First one included logic programming in Structured Text (IEC 61131-3) and is responsible for processing sensors data. Second one focused on configuration of the WS in order to properly communicate with external applications – in this case Java HMI. Configuration required definition of eight events and six input messages. Events are generated asynchronously, depending on the predefined rules and send to interested parties. Inputs are dedicated for HMI to communicate with controller. Each message is actually an XML message including specific data and appended as SOAP Body content when transferred to interested subscribers. Some events have been grouped together in order to decrease the bandwidth usage. For instance, alarm values and sensor measurement is encapsulated in one event instead of two separate ones. Next step included creation of a WSDL (Web Services Description Language) file. WSDL file is a language providing description on how to interact with particular service. Next and final step included implementation of HMIs. Decision has been taken to develop two independent HMIs. First one would be controller based, accessed through Web browser. Motivation for that approach has been: firstly exploiting HMI creation capabilities of the controller, secondly allowing easy access to monitoring system through Web browser. Second HMI has been developed as a Java standalone application. Its aim was to investigate SOA approach. Moreover it enabled development of additional functions which would not be possible at the controller HMI. As depicted in Figure 3, controller-based HMI consists of several graphical elements. There are three gauge components enabling live preview of current readout from sensors. Next to them there are alarm lights indicating two types of alarm: green - normal working condition and red -alarm. After specified period of observation has elapsed, normal working conditions in terms of operating ranges as well as proper process oriented consumption of air, are calculated. User can see those limits in form of two tables. They represents normal condition range observation results, values obtained in process oriented observation. Average value depicts average consumption after observation stage. Current value informs about consumption in latest process. Total value represents total consumption of air start-up monitoring system. In case

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any leak is discovered its approximated size will be displayed in the leak parameter.

Figure 3. Controller based HMI

The main core of Java HMI is based on open source Java API for developing HMIs. However it has been highly modified in order to implement SOA and specific functions. Controller has already defined service thus in order to use it, HMI needs to be able to comply with Devices Profile for Web Services (DPWS). Thus the HMI has been built on top of Java Multi Edition DPWS Stack (ver.0.9.7) which implements the DPWS specification [5]. JMEDS enables creation of the client which can discover and use services available in the network. Application discovers specific services available on the network on the start-up. Application offers several functions which are accessed through the tabs. First of all, two types of observation and learning normal working conditions: range and process oriented approach.

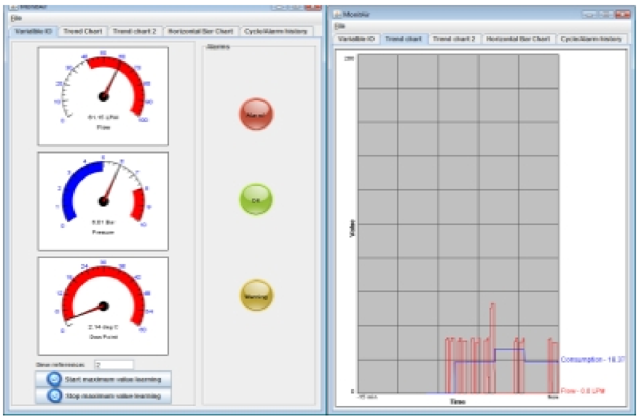

Figure 4. Java HMI

Two alarm states: low and high. Two real-time visualization of the parameters: gauge and bar chart types. Trend charts offering historic preview of parameters like: flow, pressure dew point and consumption. Parameters like average, last cycle and total consumption as well as leak diameter estimation. Additionally HMI offers alarm log as well as data recording to spreadsheets. All of information is exchanged by means of events. Both presented HMIs are independent.

V. RESULTS

Monitoring system has been tested at automatic manufacturing line. Main operation performed on one of cells, was loading and unloading products on the pallets by a robot, using suction grippers. This gave the opportunity to monitor transient conditions of the compressed air.

A. *Event-based communication*

System uses eight different event types. Some events are more frequent than the others. These are particularly events including real-time information. Events are generated by sampling two consecutive values with predefined delay. If the deviation at these time instances is bigger than predefined threshold, event is published. During the tests it appeared that changes of delay and threshold affect the amount of generated events quite significantly. First approach assumed short sampling interval and small deviation. However what occurred during tests was high amount of unnecessarily published events increasing the load of the network. Secondly this approach did not work with slow, long term changes of parameter where deviation was not rapid. In order not to overload network with high event rate and at the same time make system sensitive for long term changes (where the function of change over time is not steep) additional program has been added which samples the sensors inputs with much longer time interval. Manipulation of the deviation threshold between two time samples in both programs highly affects the number of events as well as sensitivity. In case of short sampling program, threshold has been set to higher values – in this case rapid and significant changes will be discovered. In case of long term sampling, small deviation threshold has been set to ensure that less significant changes are reported to the HMI. Proposed approach reduces amount of events, increasing the bandwidth and at the same time notifies user of system status in a reliable manner. Table 2 presents results related to bandwidth.

Table 2. Bandwidth usage results

	Download	Upload
Max rate	108.8 KB/s	25.2KB/s
Average	3KB/s	700 B/s
One event	20.4 KB/s	4.6 KB/s

B. *Compressed-air anomalies discovery*

First test phase focused on how well method for obtaining normal working conditions by assessment of operational ranges, will succeed in case of simulated anomalies.

Primary test concentrated on discovery of the leakage in CAS. Leak has been simulated by installing a valve with 4mm tubing at several different locations. Leakage discovery resolution is dependent on value of set thresholds for alarms – and especially the low alarm. Tests have shown that leakage of less than 1 mm in diameter will be detected with threshold of 5 % deviation from obtained reference range. Setting the value of warning alarm less than 5% may result in creation of sporadic false alarms. Repeatability of detection was very high. As leaks in industrial environments are never completely unavoidable it may be reasonable to set higher alarm thresholds – when repair due to magnitude of leak will be profitable. In case of pressure drop discovery this method's approach also proved to be successful. In case of tested environment, robot's pick and place operation created drop of around 0.6 bars. Thus the normal range has been at level from 6.2-7.4 bars. After obtaining the range, pressure has been decreased at the cell compressed-air inlet. Simulated decrease has been around 0.1 bars from usual conditions. Setting the low alarm threshold to 2%, reported the loss of pressure accurately. Due to the nature of compressed air, pressure drops may vary with time thus at least 5% threshold should be set for low alarm in order to avoid false alarms. Both sudden and long term pressure drops were discovered. For instance, high deviations have been discovered over a week observation in pressure level, which resulted in improper functioning of one of robot grippers. Similar successful results have been obtained with notification of high humidity level of the compressed-air. Due to the difficulty of adding extra humidity in to the compressed air or moving the testbed into much colder environment other approach have been conducted. Firstly the dew point reference value has been set when the compressed-air pressure was low. After that line pressure has been steadily increased – causing the dew point to steadily rise, according to Dalton's law. Alarms have been correctly triggered whenever humidity has reached alarm threshold.

Process oriented method observed pick and place robot operation using suction gripper. To notify monitoring system where the process starts and stops, controller responsible for observed process sends SOAP messages. After many process cycles, average consumption standard deviation has been at level of 0.178, which proves that measurement accuracy is high. System detected leaks of diameter around 0.5mm. This approach gives more accurate results than the previously described method, mainly due to the fact that is based on accumulated consumption during period of time and not on direct reading of flow measurement. Previous approach might periodically produce false alarms for instance when the thresholds are inappropriately set.

VI. CONCLUSIONS

Created system proved to be reliable tool in monitoring of compressed air anomalies. System announces deterioration before it affects functionality. Due to that, CAS is kept at high energy efficiency level. As the system monitors in an autonomous manner, supervision can be performed from remote location. System exhibits high accuracy, thus even small improprieties can be detected. Monitoring methods give possibility to monitor with and without knowledge of any process. Due to its design system is easy to connect to existing compressed-air and communication network – making it independent from underlying infrastructures. SOA model reduces amount of transferred data.

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