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Design and implementation of an energy monitoring cyber physical system in pneumatic automation

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Abstract

In manufacturing, pneumatic powered components provide a safe and reliable opportunity to automate a production line. However, compressed air systems are notoriously expensive to operate as a result of incorporated system losses and inefficiencies. For this reason, typical systems have an output efficiency of 10 – 12%. This offers a significant improvement opportunity to meet sustainable targets concerning energy consumption. Amongst various inefficiencies, leakages and excessive pressures are commonly identified as some of the major sources of waste. The scope of this project involved the use of a designed and constructed compressed air test bed that was capable of simulating various operating conditions found in industry. Experiments were carried out under experimental conditions to measure the additional energy consumption and air volume required for different leakages at specific input pressures.

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Keywords: Sustainability; Industry 4.0; Compressed Air

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1. Introduction

Industrial manufacturing companies are increasingly recognizing the financial and reputational benefits of meeting sustainable targets concerning waste and excessive energy consumption. Compressed Air Systems (CAS) provide a significant improvement opportunity in this regard. Typical CAS have an output efficiency of 10 – 12% [1] however, systems with an efficiency as a low as 5% [2] have also been identified in literature. For this reason, CAS comprise a growing field of research and innovation in both the academic and commercial sectors.

Meanwhile the 4th Industrial revolution is paving the way for the development and implementation of Cyber Physical Production Systems (CPPS). CPPS consist of autonomous and cooperative elements (e.g. Smart Actuators) and sub-systems (e.g. Smart Machines) that are connected with each other on and across all levels of production [1].

Nomenclature

CAS	Compressed Air Systems	
CATB	Compressed Air Test Bed	
Q_{Leak}	Air Volume lost due to leak	Litres
Q_{Total}	Total air volume required	Litres
$Q_{Actuator}$	Air volume supplied to actuator	Litres
$E_{Additional}$	Additional energy consumption	Wh
E_{leak}	Leakage energy consumption	Wh
$E_{Control}$	Control energy consumption	Wh

This technological drive is brought on by the development of technologies such as smart sensors [3], cloud manufacturing [4] and advanced communication protocols such as OPC/UA [5]. That said the 4th Industrial revolution is not only about technology development, but rather on how these technologies can be used to achieve breakthrough innovation in the design and management of our production systems.

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1.1. Research aim and motivation

Since CAS remain one of the main means for actuation within industrial automation, this research focuses on the end-use of pneumatically actuated devices. The aim of this research is therefore to apply Industry 4.0 technologies to the development of a cyber physical system for energy monitoring of CAS for use within industrial automation. The potential energy savings and sustainability improvements which may be gained by monitoring in real time a CAS being used within industrial automation acts as the motivation of this research.

1.2. Methodology

This paper is a record of the methodical approach and rationale adopted towards reaching the research objectives. Section 2 presents an in-depth analysis of the available literature in relation to energy monitoring in CAS. The design and implementation of a modular energy monitoring cyber physical system in pneumatic automation is then presented in Section 3. This functional configuration will be referred to in the following sections as the Compressed Air Test Bed (CATB) and is the main contribution of this research. Sections 4 and 5 present the testing and analyses of the initial results obtained based on a designed experiment in terms of sustainability.

2. Literature Review

2.1. Compressed Air Systems (CAS)

CAS are comprised from several elements that compress, distribute, filter and use the available compressed air. Each system is configured according to the production needs of a particular application and are typically divided in three different categories;

- Point-of-use systems: supply compressed air exclusively to a single piece of equipment,
- Local generation systems: supply compressed air to a group of machines,
- Plant air systems: distribute compressed air from a central air house to all or most of the pneumatic equipment in a factory.

Plant air systems are the most common form of CAS found in industry. However, these incur noteworthy limitations such as structural complexity, operational costs, low efficiencies and lack of system ownership.

2.2. Energy management in CAS

Dornfeld et al. [6] reported yearly savings of \$2,000 – \$3,200 from energy reductions of as much as 95,000 kWh when using local generation systems rather than plant air systems. In addition, Yuan et al. [7] compared the three aforementioned categories and similarly deduced that local generation systems were the most efficient, requiring 1.75 – 2.25 kWh per 28.3m^3 (62-80 Wh/m^3) of compressed air. In comparison, a point-of-use systems required 2.75 kWh and a plant air system require 3.25 kWh to generate the same 28.3m^3 of compressed air.

Inefficiencies within a CAS are mostly attributed to the considerable number of stages required between electrical power and effective work output at the end-use. Studies by Taheri and Gadow [8] document that a significant portion of energy is dissipated at the compression generation stage or the supply side of the system. Losses result in significant energy costs that amount to around 78% of the total life cycle costs of a CAS, while the investment and maintenance costs of the system only amount to 16% and 5% respectively over the whole life cycle [9]. Saidur et al. [9] reported average savings of 30% for control systems such as variable speed drives (VSD) with a payback period of approximately eight months. The study also reviewed several efficiency improvement methods and indicated that payback periods of ten months or less are attainable even for relatively expensive improvements such as replacing an entire CAS.

Supply side inefficiencies originate from compressor losses and control deficiencies. McKane et al. [10] stated that maximum compressor efficiency is typically achieved during peak load conditions. McKane et al. employed various systems that utilize multiple compressors operating at partial load conditions. Such systems were designed to meet the maximum demand required for comparatively short periods of time resulting in substantial inefficiencies. Therefore, it was suggested that functional system controls and adequately sized air receivers should be installed at strategic locations around the CAS to meet maximum demand requirements and minimize losses [10].

2.3. Industry 4.0 and CAS

As explained by Francalanza et al. [11] the Industry 4.0 paradigm has brought about a new range of methods and technologies which can be applied to support industry in dealing with challenges such as energy performance improvement on the shopfloor. In CAS these technologies are allowing for the development of new service based business models such as those proposed by Bock et al. [12]. In this study the authors have applied Industry 4.0 technologies such as big data analytics together with predictive maintenance in order to monitor operational efficiencies resulting from compressor losses at the supply side. Similarly Bonfa' et al. [13] propose an approach in which compressor energy consumption data is measured in real time and compared to a baseline obtained through mathematical modelling to enable faults detection and energy accounting.

2.4. Research Gap

That said the applications of Industry 4.0 technologies reviewed deal with supply side inefficiencies and monitoring. An extensive research effort was employed to identify a CATB developed to analyse and understand the sustainability issues on the end-use side of a CAS. Following various attempts, such works could not be identified. This highlights a research gap for the design and implementation of an energy monitoring cyber physical system in pneumatic automation.

3. Design of a Cyber Physical Compressed Air Test Bed (CATB)

Various literature documenting the design and construction procedure of pneumatic and compressed air energy storage test beds were reviewed which provided valuable insight towards the design and construction procedure for the required CATB [14]. A sequential design methodology was adopted during the numerous design tasks involved to design and construct the CATB.

As explained by Francalanza et al. [15] a CPS design approach needs to be utilized which takes into consideration both the Physical and Cyber perspectives. The system was therefore to be comprised from a set of distinct elements which included:

- Physical Aspect:
  - Pneumatic system, including a compressed air generation, storage and distribution system;
  - Leakage simulations;
  - Simulated pneumatic actuation uses;
  - A frame module to provide structural support to the elements of the CAS within a single coherent unit;
- Cyber Aspect:
  - Data acquisition system;
  - Electrical control system.

Through the problem statement it was established that the designed pneumatic system had to represent a 'point-of-use' or 'local generation' system that was modular and capable of adapting to various pneumatic actuation uses. Furthermore, in order to reach the aim of this system, data had to be acquired for the variable parameters (air flow rate, pressure and electrical consumption). This data had to then be conveniently transmitted and logged in order to calculate the effects on system energy consumption.

3.1. Pneumatic system

The pneumatic system was designed to include a silent compressor that supplied compressed air to a number of drop off lines by means of an open loop compressed air distribution configuration. The silent compressor was chosen due to the low noise emissions making it ideal to be incorporated within a laboratory environment. A compressed air storage unit was also included to act as a reservoir for the system and ensure that sufficient stored air was available which allowed the compressor to switch on and off depending on the amount of end-use of the system.

Furthermore, the components forming part of the pneumatic system had to be conveniently accessible and displayed on the designed frame module. Moreover, at the point of use, push-to-fit adapters were to be included for modularity and interchangeability of components.

3.2. Leakage simulations

In order to analyse the effects of various air leakage scenarios on energy performance, a mechanical means to simulate various leakage diameters in the CAS needed to be designed. This setup had to allow users to conveniently convert from a particular leakage diameter to another. Various design concepts were conceptualized. From the specifications of the selected compressor it was established that a range of leakage diameters up to a maximum of 1.5mm could be simulated. Moreover, the developed setup had to be conveniently interchanged between an ideal simulation containing no leakages and a controlled leakage simulation. Fig. 1 represents the computer aided design (CAD) model of the selected design following a qualitative comparison of various concepts.

The design provides for the simulation of various leakages by utilising interchangeable piping segments with a predrilled hole of a known diameter. To simulate a leak between 0.5 and 1.5 mm, the piping section (red) identified as S1 (Fig. 1) containing the specific leakage diameter was to be fitted between two push-to-fit connections for ease of assembly and disassembly. Through the inclusion of two three-way valves (T1 and T2), the air circuit could easily be altered between an ideal circuit containing no leakages (C1) and a pneumatic circuit containing a leakage diameter of known diameter (S1). After passing through T2, the compressed air is then directed to the installed end-use. This system therefore allows for the simulation of air leakage in the supply of pneumatic actuation devices.

3.3. Control and data acquisition in CPS design

The control and data acquisition system allows for the implementation of the cyber aspects of the system. As illustrated in Fig. 2, the CPS was designed to be capable of real-time data acquisition and transferring of information to allow for the automatic analysis of the system operation through various inputs and outputs, together with an electrical control system, to operate the end uses.

The main functional component of the control system is comprised of a programmable logic controller (PLC). This PLC is connected to a number of sensors which allows for the automatic logging of the system inputs such as compressed air flow rate in the CAS measured through a number of air flow sensors.

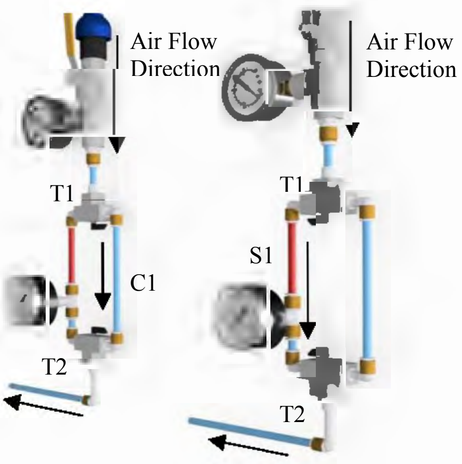

Fig. 1. T1 and T2 lever positions to direct air flow either through C1 or through S1.

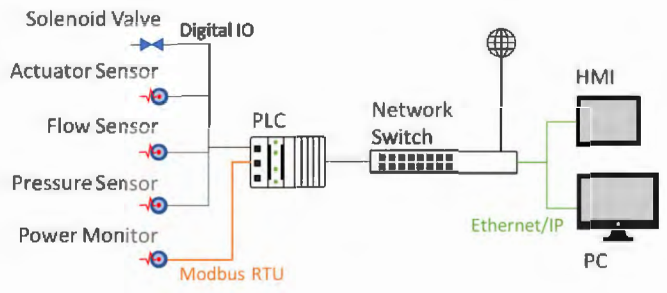

Fig. 2. Control and data acquisition system.

The electrical power of a CAS is measured by monitoring the voltage and current of the system. For adequate benchmarking, McKane et al. [10] suggested that the power to the compressor at full-load and no-load input should be established. For continuous motoring and data logging, digital power meters are normally connected to measure voltage, current, power, energy and power factor measurements.

The setup was designed to allow for the transmission of real-time information via an Ethernet/IP via the OPC/UA [5] communication protocol. The PLC was set-up as an OPC/UA server transmitting in real-time several variables being recorded from the sensors. Devices such as PC or HMIs could then be connected to the Ethernet/IP network in order to collect and analyse the information. The PC was set-up as OPC/UA client and using Node-RED data being streamed via the PLC could be analysed in real time. Finally, the PLC also allowed for the automatic actuation and control of the adopted end uses, such as a double acting cylinder via 5-way solenoid valves.

3.4. CATB detailed design and implementation

The components and elements described in the previous sections were used to synthesise various detailed design prototypes by means of CAD models. Fig. 3 portrays a rendered image of the developed CAD model for the frame module together with the elements of the pneumatic system. The inclusion of standard DIN rails facilitated the installation of the pneumatic components. Therefore, to install a particular actuator, the user would simply mount the component on the DIN rail and connect the required valves. Additional air circuit configurations were made viable through strategically placed ball valves in order to supply compressed air to supplementary drop off lines.

As a result of the limited space at the anterior side of the frame module, the control system and PLC were mounted to the posterior side of the CATB.

3.5. Test Bed Implementation and Verification

Following the completion of the design stage, the system was implemented using off the shelf industrial automation components. At the heart of the CATB is the NX1 modular machine controller by OMRON. A ladder diagram was utilised to program the PLC to acquire the sensor data and to operate the actuators. Preliminary testing and modifications were carried out to acquire optimum system performance.

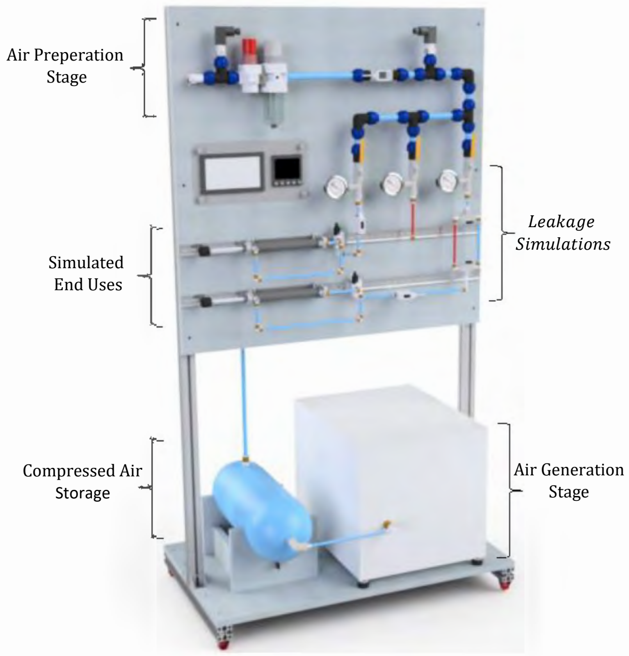

Fig. 3. 3D model of the developed CATB.

Fig. 4 depicts a representation of the air circuit configuration. Valves V1 to V3 identify the specific valves that engage explicit functions when triggered. Valves V1 and V2 were incorporated to provide additional drop off lines for future alterations and developments within the test bed configuration. When triggered, valve V1 supplied compressed air to ‘Actuator #2’, a double acting cylinder containing a leak of unknown size.

Finally, when valve V3 was activated, air was supplied to ‘Actuator #1’, a double acting cylinder with the same specifications as that of ‘Actuator #2’ but containing no irregularities.

4. Experimental Methodology

Following the completion of the construction and implementation of the CATB, an experimental procedure was designed to analyse the energy performance of various leakage diameter scenarios. The controllable input factors were established to be the leakage diameters which was set by changing the section of the pneumatic circuit (S1) while the measurable output responses were in terms of energy consumption of the compressor and air flow rates measured by air flow sensors 1 and 2.

The aim of the experimental setup was to investigate the relationship between the input factors (leakage diameter) and the output responses (additional air volume and energy consumption) through the execution of various single factor experiments. To simulate a condition, the required red piping segments containing a leakage of known diameter between 0.5mm and 1.5mm was fitted at the location marked ‘S1’ in Fig. 4, The pressure regulator was used to regulate the pressure between 3 – 6 bar.

The duration of each test was established to be 10 minutes long to calculate the average flow rate and power over that period of time.

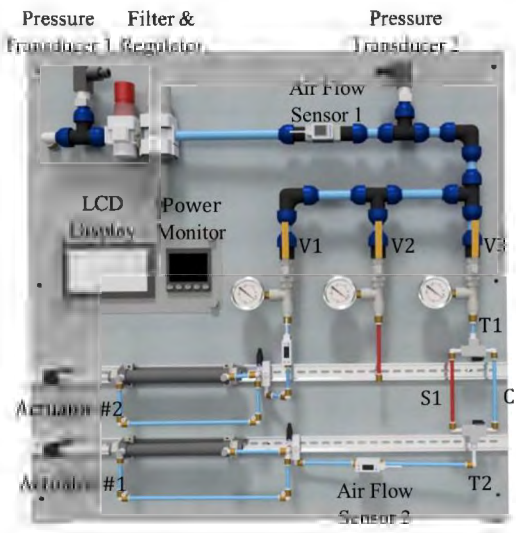

Fig. 4. CAD representation of the air circuit interface.

Initially, positive control experiments were conducted to determine the benchmark results for energy consumption and air flow rate required at each pressure between 3 to 6 bar increasing in increments of 1 bar. The simulated leakage experiments were conducted by repeating the same procedure of the control experiments for the leakage diameters; 0.5mm, 1.0mm, 1.5mm.

An uncertainty analysis was conducted on the measured output parameters. Through preliminary testing it was determined that the highest uncertainty attributable to each of the output parameters was at the lowest measurable output responses i.e. during the control experiment at 3bar pressure. The total energy consumption and air flow rate (from Sensor 1 and Sensor 2) under such conditions were determined to be 33.3Wh, 17.1 litres per minute and 17.2 litres per minute respectively. Due to the lack of leaks within the control experiment, Sensor 1 and Sensor 2 measured the same flow rate that was later converted into the total air volume used in 10 minutes (the duration of each test). Therefore, the uncertainty associated with each of these values at the worst-case scenario were calculated to be 33.3Wh ±0.49Wh (±1.5%), 171 litres ±8.7litres (±5.1%) and 172 litres ±3.5litres (±2%).

5. Results and Analysis

In this section, the results recorded are reviewed in relation to the objectives of the experiment discussed in Section 4 and to various statements reviewed in the literature. Fig. 5 highlights the operating pattern of the compressor, comprised from a number of active and idle cycles. The compressor was factory set to automatically deactivate when the pressure within the 6-litre receiver tank of the compressor exceeded 8bar. Once this pressure decreased to a value lower than 6bar, the compressor automatically triggered until the initial 8 bar of pressure was regained before repeating the cycle.

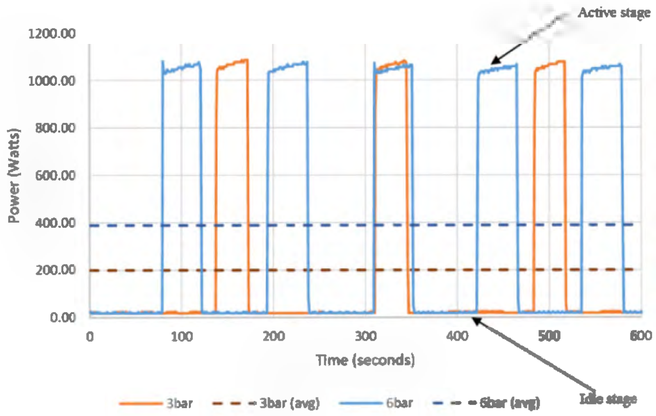

Fig. 5. Energy reading comparison of the logged powered values associated with the control tests running at 3 and 6bar.

The cycle pattern differed according to the parameters. As can be viewed in Fig. 5, during identical 10-minute (600s) test durations, at 6 bar pressure the compressor activated a total of five times (depicted by the peaks in the graph) while at 3 bar, the compressor was activated for three times. This resulted from the fact that during the 6 bar test, the compressor remained active for an extended period of time and idle for a smaller period when compared to the 3 bar test.

The logged values for each test extrapolated from the digital power meter were then used to calculate the average power (WAvg) of each condition and the subsequent energy consumption (Wh per 10 minutes) required during the test. To determine the additional air volume and energy consumption required due the introduction of each leak, the following relationships were then implemented:

$$Q_{Leak} = Q_{Sensor1} - Q_{Sensor2} \tag{1}$$

$$E_{Additional} = E_{Leak} - E_{control} \tag{2}$$

Sensor 1 and Sensor 2 were positioned such that the drop in air flow rate due to the leakage under test is measured. On the other hand, from Equation (2), the energy consumption for the positive control experiment at each pressure was considered as a datum and this value was subtracted from the energy consumption values measured from each subsequent leakage test resulting in the additional energy required due to a specific leakage diameter.

The results were calculated for each 10-minute single factor experiment and the resulting relationship of energy values against the leakage diameter and pressure can be viewed in Fig. 6 and Fig. 7 respectively.

These figures depict a significant increase in additional air volume requirements and hence energy consumption in relation to leak diameter. This occurred as a result of the quadratic increase in leakage area when compared to an increase in leakage diameter due to the following relationship;

$$A = \pi d^2/4. \tag{3}$$

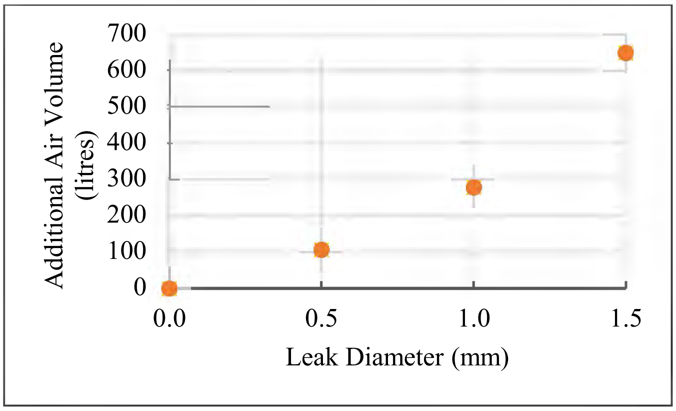

Fig. 6. Additional air volume required against each leakage diameter at 6 Bar.

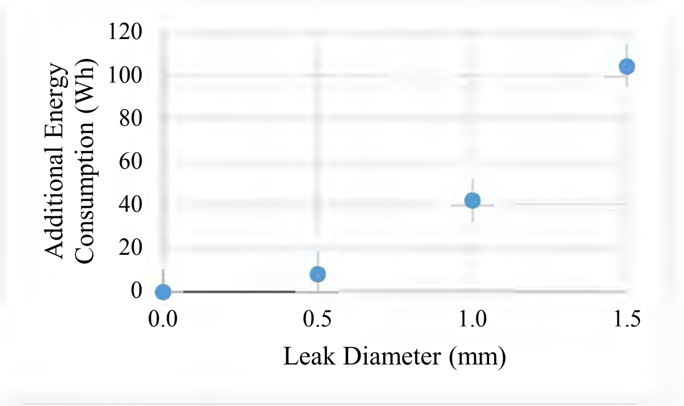

Fig. 7. Additional energy required against each leakage diameter at 6 Bar.

To analyse the effects of the extrapolated results on the sustainability of the CAS, the measured energy consumptions for each 10-minute test were then considered over a period of a whole year to acquire more tangible values. The compressor was assumed to operate for 6,240 hours a year. To determine the incurred expenses associated with the financial pillar of sustainability, the average electricity tariff rate on the Maltese Islands for a non-residential building (e.g. production site) that utilises a maximum of 5 million kWh of energy a year was calculated to be 0.1199 €/kWh. Therefore, the additional costs incurred due to a 1.5mm leak at 6 bar would be of € 469.53.

6. Conclusions

This research has contributed towards the design and implementation of an energy monitoring cyber physical system in pneumatic automation. The developed system allows for real-time monitoring of various measurement sensors (energy, pressure, air flow rate) and transmission of this data via the OPC/UA communication protocol for remote processing.

On the other hand when considering that readings from the PLC can be recorded and transmitted every 10ms, for the currently implemented 6 sensors over a period of 10 minutes, this results in a total of more than 60,000 data points being streamed in real-time. This exposes one of the challenges when dealing with CPS which is the creation of big data. Hence future work on this system will not only continue to explore the relationships between different factors affecting the energy performance of CAS but will also investigate the use of the CATB together with artificial intelligence approaches such as unsupervised learning algorithms to analyse the real time data stream.

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