Article

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# Behavior analysis of a hydraulic circuit through a low-cost data acquisition system

# Análisis del comportamiento de un circuito hidráulico a través de un sistema de adquisición de datos de bajo costo

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**Abstract**

In an industrial process exists several variables to be monitored, in particular, temperature is a main variable for many systems as a hydraulic circuit. Due to friction effects and recirculation of the fluid, a temperature increasing is noted causing some variations on physical properties of the oil. In this work, the design and implementation of a low-cost system is covered for data acquisition of the oil temperature and advance time of the final actuator. This system is composed by a minicomputer Raspberry Pi, a submersible digital sensor and programming code in Python; the hydraulic circuit is built with a hydraulic source equipment, a solenoid valve, a double-acting cylinder and two limit switches. The proposed approach is experimentally proved in a continuous process with 200 iterations for the cylinder to advance and retract, which results in a rising temperature. Furthermore, with available data from the advance time, the effect caused by the temperature on the advance velocity is observed by means of plots of temperature and velocity from the low-cost monitoring system.

**Raspberry Pi, Temperature Digital Sensor, Velocity of a Cylinder, Hydraulic Circuit**

**Resumen**

En un proceso industrial existen variables de interés para ser monitoreadas, particularmente la temperatura es fundamental para distintos sistemas como un circuito hidráulico. Debido a la fricción y la recirculación del fluido se nota un incremento de la temperatura, causando efectos sobre las propiedades físicas del aceite. En este trabajo se aborda el diseño e implementación de un sistema de bajo costo a través de una minicomputadora Raspberry Pi, un sensor digital sumergible y programación en Python para la adquisición de datos de la temperatura del aceite que es usado en un circuito hidráulico, el cual está compuesto por un equipo de suministro de potencia hidráulica, una electroválvula, un cilindro de doble efecto y dos sensores de límite de carrera. Se probó experimentalmente el esquema propuesto en un proceso continuo de 200 iteraciones de avance y retroceso del actuador final, en donde se manifiesta un incremento de temperatura del aceite. Más aún, con los datos obtenidos del tiempo de avance, se comprueba el efecto que causa la temperatura del fluido en la velocidad de avance del cilindro de doble efecto, como lo muestran las gráficas del comportamiento de la temperatura y velocidad a partir del sistema de monitoreo de bajo costo.

**Raspberry Pi, Sensor Digital de Temperatura, Velocidad de un Cilindro, Circuito Hidráulico**

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## Introduction

A hydraulic circuit is made up of various types of elements that handle pressurised oil. Generally speaking, we can identify those elements that supply the hydraulic power, those that capture information, control elements and, finally, the output elements, which are the actuators. Therefore, a hydraulic circuit can be described as a set of a motor-pump unit, filters, pressure regulating valve, relief valve, pressure gauge, stroke limit sensors, directional control valve, which depending on how it is activated, can be considered a solenoid valve if it uses an electromagnet to switch; finally, a double-acting cylinder as an actuator.

The design of hydraulic circuits is a task that allows the automation of industrial processes, based on the displacement-phase diagrams of the final actuators. However, it is important to know the behaviour of certain variables of interest such as oil temperature, due to a potential risk of explosion if the oil rises to a temperature that causes ignition in relation to the working pressure.

In the industrial components market there are sensors that allow temperature monitoring, which are relatively expensive at $2,500.00 MXN and require additional components, resulting in a system that is difficult to access for small and medium sized companies.

On the other hand, the use of frontier computing adds benefits of agility, real-time information processing and autonomy to create value to manufacturing intelligence (Moreno and Victoria, 2009). Thus, one of the most important fronts that has been highlighted in recent years within research and technological development focuses on the use of new low-cost technologies for industrial applications. For example, regarding monitoring through a commercially developed board, Othman *et al*. (2017) implements a low-cost monitoring system through a Raspberry Pi to understand the performance of a low-scale solar PV system. McBride and Courter (2019) use Raspberry Pi minicomputers to monitor a flock of birds and the environmental conditions of the site where they are growing. Sowmya *et al*. (2020) build a Raspberry Pi-based robotic car monitoring system.

Dupont *et al*. (2018) design and implement a photovoltaic water pumping equipment monitoring system, where the Raspberry Pi board is used to develop a Linux embedded system. Hasan (2020) uses the Raspberry Pi to monitor the variables of temperature, humidity, pH and water level of a crop field.

Therefore, in this work the main element for the implementation of monitoring and analysis is the minicomputer on Raspberry Pi (RPi) board, which has the characteristic of being low cost and small dimensions to be considered as a border computing device, in addition the DS18B20 temperature sensor is used, which is capable of immersing in fluids and stroke limit sensors. The Python programming language is used to build a real-time data acquisition system, which is stored in the Raspberry Pi itself, enabling the possibility of being analysed at a later stage of the experiment.

The rest of the article is presented as follows: section 1 details the methodology and the main characteristics of the Raspberry Pi used and the sensor; section 2 describes the procedure for the characterisation of the DS18B20 temperature sensor as well as the main characteristics of the sensor; section 3 shows the results obtained from the experimental tests; section 4 analyses the data and, finally, section 5 includes the conclusions of the work presented and future work.

## 1. Metodology

The test bench used for the characterisation of the temperature sensor is the one located at the University of Guanajuato, Engineering Division, Irapuato-Salamanca Campus, which is a hydraulic circuit with the typical components used in an industrial process, shown in Figure 1.

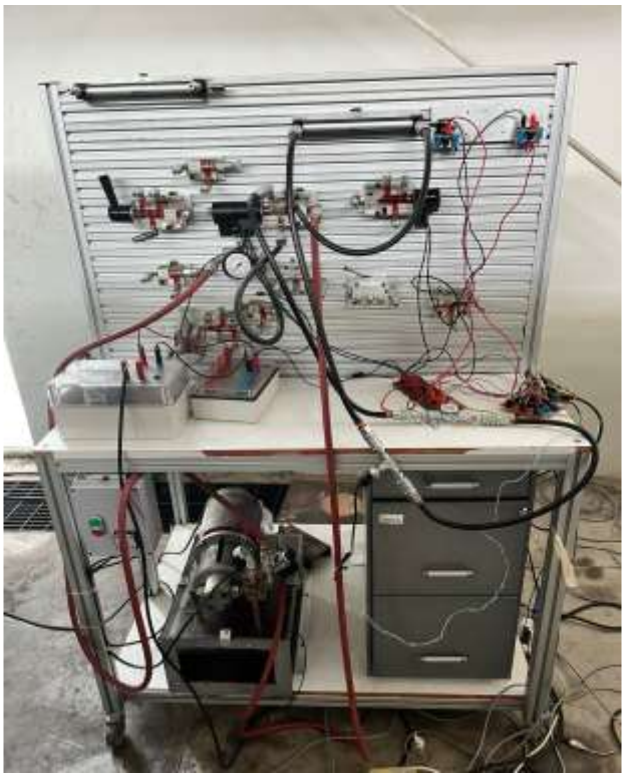

**Figure 1** Test bench
*Source Own Elaboration*

In this process, a Raspberry Pi is used as a means of data acquisition where the Python programming language is used to obtain the measurements made by the DS18B20 temperature sensor and the stroke limit sensors, in order to be able to analyse the results obtained. The main characteristics of both the Raspberry Pi and the DS18B20 temperature sensor are described below.

### 1.1 Raspberry Pi 2 model B

This model was launched in 2014 and is shown in Figure 2, with 1GB of RAM. It includes 40 GPIO pins and four USB ports.

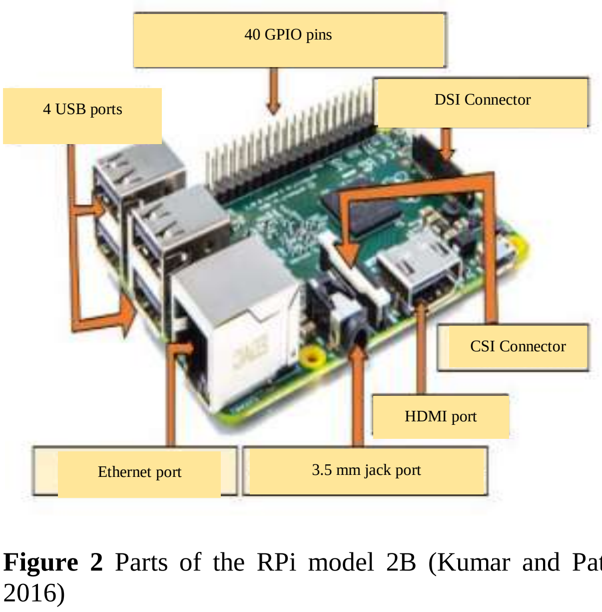


**Figure 2** Parts of the RPi model 2B (Kumar and Pati, 2016)

This model has the following specifications:

- Processor: 900 MHz Broadcom BCM2836 quad core ARM quad core Cortex-A7 quad core.
- GPU: Dual-core VideoCore IV with Open GL ES 2.0 support, hardware accelerated OpenVG up to 1080p30 H.264.
- RAM: 1GB SDRAM LPDDR2.
- WiFi connection: No WiFi connection.
- Serial communication ports: UART, RXD and TXD (support I2C and SPI protocols).
- ADC converter: It does not have its own converter, so it is necessary to implement an external one.
- Ethernet connection: This model reaches a maximum speed of 100 Mbit/s.
- Operating system: Raspbian.

### 1.2 RPi configuration

As it is a minicomputer, the first configuration carried out on the RPi was the installation of an operating system. For this work, the operating system recommended by the RPi organisation was installed, which is called Rasbian, which is a variation of Debian. This system works on the basis of Linux and is also free to use. For this, it was only necessary to boot a micro SD memory, which also acts as the main hard disk of the RPi. In this work, a 64 Gb SD memory is used. Once the operating system is installed, we proceed to install some tools that do not come by default in Raspbian, such as Phyton and its IDLE Thonny.

### 1.2 Characteristics of the Temperature Sensor DS18B20

To read the temperature of the system, we use the DS18B20 sensor which is low cost (about $45.50 MXN), capable of immersion in fluids and is shown in Figure 3.

The sensor has the following features:

- Requires only one port pin for communication
- Supply voltage range: 3.0V to 5.0VDC
- Measuring range: -55°C to 125°C
- 9 to 12 bit readings (configurable)
- Connection via One Wire protocol.

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**Figure 3** Temperature sensor DS18B20

### 1.4 Stroke limit sensor

Low-cost limit switches are also mechanical switches that are activated by means of a roller, which is actuated through contact with the cylinder. These limit switches can be positioned at the start or end of the stroke of a hydraulic cylinder or at any position the user deems appropriate. In such a way that the distance between the stroke limit sensors is considered constant, therefore, and taking into account the mathematical equation that defines the velocity, which relates the change in the displacement with respect to a change in the time in which it is made, it is possible to measure the advance speed of the cylinder if the reading of the activation time between the sensor at the start of the stroke and the one at the end of the stroke is obtained.

In this way, the sensors are fixedly positioned to keep the distance between them constant and thus the change in the advance displacement of the double-acting cylinder.

Validation of the DS18B20 sensor

The temperature sensor DS18B20 is immersed in the oil tank to determine its temperature during the process, while the stroke limit sensors are positioned within the range of the displacement of the double-acting cylinder, maintaining a constant distance between them, as shown in Figure 4.

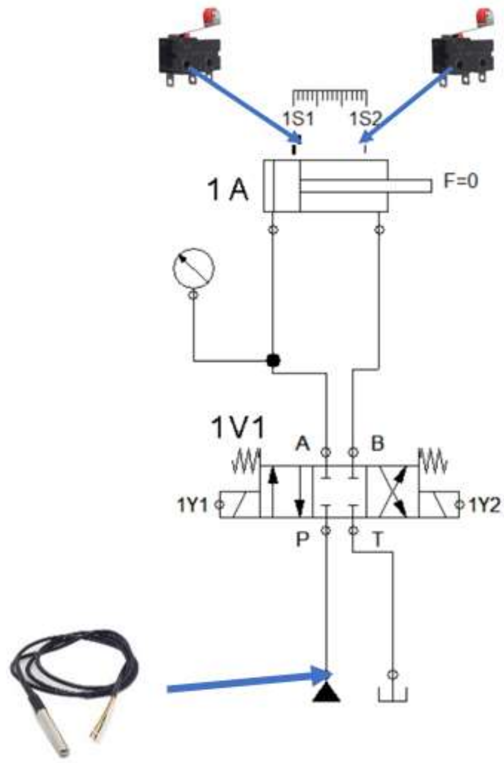


**Figure 4** Hydraulic circuit assembled with the DS18B20 temperature sensor and limit sensors
*Source: Own Elaboration*

For the validation of the temperature sensor, a Steren MUL-115 multimeter is used. This multimeter has the characteristics of measuring temperature in the range of -20 to 150°C±(3°C+1d)/150 to 1000°C±(3%+2d) according to the data sheet provided by the distributor.

For the measurement of the oil temperature it was decided to place the sensor inside the oil tank as well as the multimeter as shown in Figure 5.

**Figure 5** Measurement of the fluid inside the tank with the multimeter
*Source: Own Elaboration*

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It allows the temperature of the fluid to be analysed before it is pumped into the system, measuring the thermal equilibrium that is reached when the oil re-enters the tank after the process has been completed. The multimeter is used to measure the temperature within the same point in the tank as the temperature sensor, however, the measurement obtained by the multimeter only has integer values within the range specified by the distributor data sheet. In order to increase the fluid temperature more rapidly, an electrical resistor is introduced into the tank to heat the oil and take measurements every 15 seconds for 5 minutes and thus, with a total of 30 measurements, calibrate the DS18B20 sensor through a linear regression model.

Using the least squares regression methodology, the following equations are obtained:

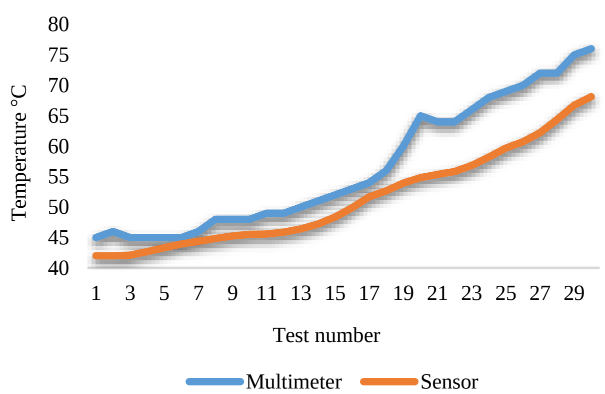
$$\hat{b} = \frac{\sum x_i y_i - n x_m y_m}{\sum x_i^2 - n x_m^2} \quad (1)$$

$$\hat{a} = \frac{\sum y_i - \hat{b}\sum x_i}{n} = y_m - \hat{b} x_m \quad (2)$$

where $x_i$ are the values obtained from the multimeter, $y_i$ are the values obtained from the sensor, n is the number of data, $x_m$, $y_m$ are the averages of the multimeter and sensor data, respectively. This gives the linear regression model described in equation:

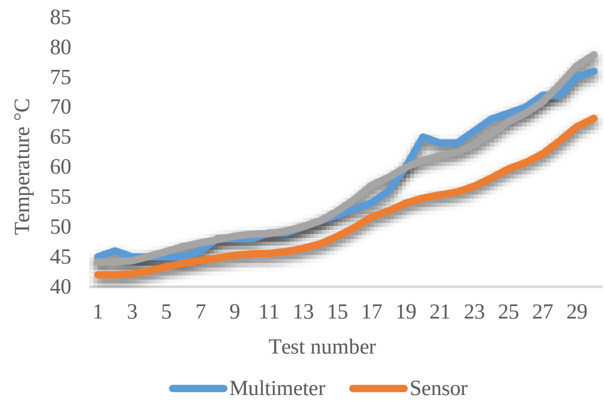
$$y = \hat{a} + \hat{b}x \quad (3)$$

The results obtained by the DS18B20 temperature sensor and the Steren MUL-115 multimeter, before applying the linear regression, are presented in Figure 1.




**Graph 1** Temperature measurements, comparison between multimeter and sensor
*Source: Own Elaboration*

The results obtained with the implementation of the linear regression equation are shown in Figure 2.




**Graph 2** Regression model on sensor measurements
*Source: Own Elaboration*

### 1.5 Circuit assembly RPi

For the assembly of the circuit with the RPi, the pins shown in Table 1 were selected.

| Pin | Description |
|---|---|
| 3V3 | Power supply used throughout the RPi circuit at 3.3 Volts DC |
| PIN GROUND | Grounding throughout the RPi circuit |
| GPIO 2 | Connection to temperature sensor data cable DS18B20 |
| GPIO 6 | Connection to the start of stroke sensor |
| GPIO 12 | Connection to end-of-stroke sensor |

**Table 1** Description of the connections of the RPi

## 2. Experimental results

In the manufacturing laboratory of the Division of Engineering of the Irapuato Salamanca Campus of the University of Guanajuato there is a hydraulic circuit test bench with which the physical implementation of the proposed approach was carried out in order to obtain experimental results.

Hydraulic power supply equipment, a double solenoid solenoid valve and a double acting cylinder were used, interconnecting each of the components through hydraulic hoses. As part of the instrumentation, the DS18B20 sensor submerged in the oil tank or reservoir and the start and end of stroke roller sensors in the cylinder stroke were used; all of them connected to the RPi for the data acquisition system.

The experimentation was done in a continuous process with 200 iterations of forward and reverse of the double-acting cylinder. In addition, 4 temperature measurements were considered for each advance. In total, 800 measurements were taken. At each advance an average of the 4 respective measurements was taken. The results of the oil temperature during the 200 iterations are shown in Figure 6.

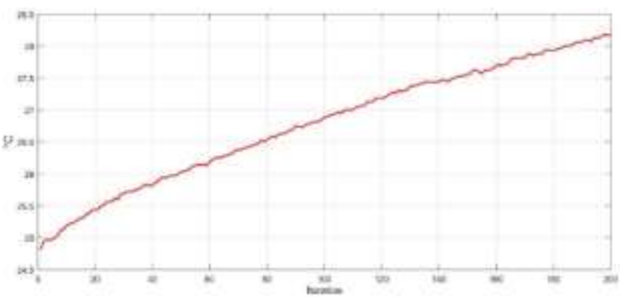


**Figure 6** Results obtained from the measurement of oil temperature during 200 continuous iterations
*Source: Own Elaboration*

The advance time of the hydraulic cylinder in each iteration was calculated as follows. The RPi processor time is taken when the activation of the start-of-stroke sensor is detected and stored in a variable. When the activation of the end-of-stroke sensor is detected, the RPi time is taken again and stored in another variable. A difference of the end-of-stroke time minus the start-of-stroke time is made to know the advance time. The results are shown in Figure 7.

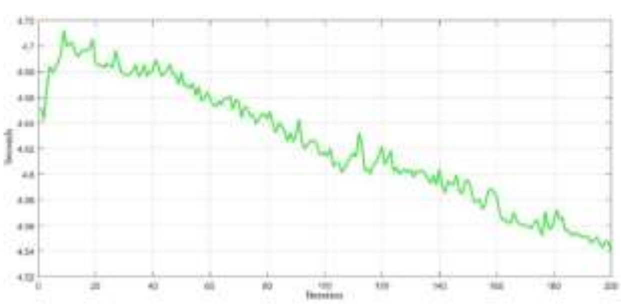


**Figure 7** Hydraulic cylinder advance time for 200 continuous iterations
*Source: Own Elaboration*

The distance between the limit switches is a constant quantity with a value of 15.6 cm, as shown in Figure 8.

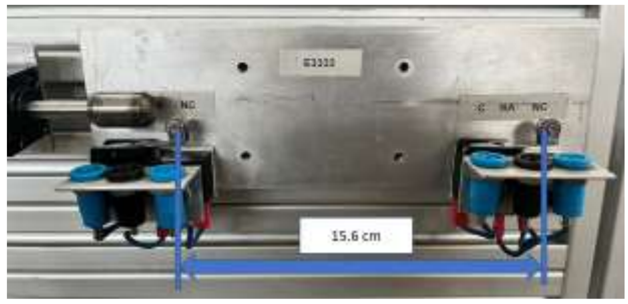



**Figure 8** Fixed distance between the stroke limit sensors

It is possible to calculate the forward speed, using the equation:

$$\text{forward speed} = \frac{scrolling}{time\ of\ advance} \qquad (3)$$

The results of the 200 continuous iterations are given in Figure 9.

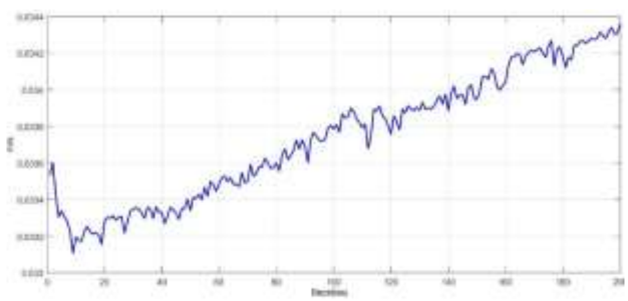


**Figure 9** Results of the feed rate of the hydraulic cylinder during 200 continuous iterations
*Source: Own Elaboration*

## 3. Analysis of the data obtained

The oil temperature increased during the 200 continuous forward and reverse iterations of the double-acting cylinder, probably due to the effects of friction and fluid recirculation. It is important to note that no heating devices were used during the experimental tests. Also, no components were used to cool the oil during its flow through the hydraulic circuit.

The oil used in the hydraulic circuit is synthetic oil for automatic transmission, which has the physical properties given in Table 2.

| Property | Value |
|---|---|
| Viscosity @ 100°C, cSt | 7.5 |
| Viscosity @ 40°C, cSt | 34.0 |
| Pour point, °C | -60 |
| Flash point, °C | 249 |

**Table 2** Properties of synthetic oil used in the hydraulic circuit
*Source: Own Elaboration*

It is understood that increasing temperature affects the viscosity of the oil. Moreover, according to Wang (2014), the increase in temperature causes the fluid to flow faster. Therefore, the velocity is increased, as proven by the results of the forward speed of the hydraulic cylinder.

The analysis carried out shows that it is important to consider the effects of temperature on the oil in a hydraulic circuit when it is necessary to maintain the advance speed or, directly related, the advance time of the final actuator. Since, in sequential industrial automation processes, the times in each of the stages of the process are important to keep fixed. Therefore, the relevance of heat exchangers in the oil recirculation path in a hydraulic circuit and the continuous monitoring of the temperature as a variable of great interest for the correct operation of the industrial process.

## Conclusions

It has been possible to build a low-cost data acquisition system using an RPi minicomputer, in addition to obtaining a characterisation of the DS18B20 temperature sensor with a percentage error between the regression model and the readings obtained by the temperature sensor of ±1.8%. The advance time of the double-acting cylinder in a real hydraulic circuit is also monitored.

The experimental tests yield relevant data to understand the behaviour of the fluid in a continuous process of several iterations. The analysis of the data demonstrates the importance of oil cooling for sequential automation applications where constant cylinder advance times are guaranteed.

Future work will consider including a larger number of sensors to measure other variables of interest that are related to the change in fluid properties such as flow rate.

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