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IoT Enabled Vibration Monitoring Toward Smart Maintenance

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Abstract— **Maintenance costs are a significant part of the total operating cost of all manufacturing plants. Condition monitoring is a key element of the maintenance program. Most comprehensive predictive maintenance programs use vibration as the primary parameter to monitor. However, the typical process of vibration monitoring relies too much on the human factor and has limitations. To overcome these shortcomings, a method is proposed in this paper. Moreover, the potential IoT using for smart maintenance is demonstrated. Additionally, it is explained how it can shape the maintenance toward the Industry 4.0. and how industrial IoT can help the condition monitoring of rotating machinery using vibration analysis. In this way, a method is proposed to make rotating machinery to IoT enabled devices by adding hardware to them. This hardware was designed and developed based on the requirements. Moreover, a new generation of accelerometer sensors has been introduced to measure the vibrations. For this purpose, a data acquisition web application is developed to evaluate the hardware. The evaluations show the quite precise of the results.**

Keywords: Internet of Things, Predictive Maintenance, Online Condition Monitoring, IoT Sensor, Smart Factory

I. INTRODUCTION

Maintenance of equipment means using a method to prevent equipment failure and keep them operational. Maintenance costs are a significant part of the total costs of operation for all factories and manufacturing plants. Maintenance costs can be from 15% to 60% [1] even 70% [2] depending on the industry of total costs.

Maintenance management techniques can be classified into three key categories [3] that are as follows in order of efficiency [4]: a. Run-to-Failure (R2F) or Corrective Maintenance - Maintenance procedures are carried out only after failures have occurred. b. Preventive or Planned Maintenance (PvM) - Maintenance is performed on the basis of time or process iterations according to a planned schedule. c. Predictive Maintenance (PdM) - Maintenance is conducted based on an assessment of the health status of the equipment that comes from monitoring.

Monitoring is the key element of PdM, in other words, PdM can be considered as condition-based PvM [1]. The maintenance program, particularly the PdM approach, that requires constant monitoring of the equipment, is often applied for an important equipment category called rotating machinery [1], which includes motors, pumps, fans, turbines, gearboxes, etc. A comprehensive predictive maintenance program employs several technologies concurrently, such as vibration analysis, ultrasonic, oil analysis, thermography, process parameters, tribology, and etc. [1]. Almost all predictive maintenance programs use vibration analysis as the main technique [1]. Vibration analysis is one of the most efficient and successful techniques for fault diagnosis of rotating machinery [5].

The typical process of vibration analysis in factories is that condition monitoring technician goes into the factory and measures the vibration of machines using a data logger; then, he/she investigates the gathered data and according to the known patterns of various possible defects that may occur detects the faults. Regarding the diagnosis of severity and type of faults, he/she announces the need for repair or replacement of the equipment. This method has some shortcomings such as:

- Human error in sampling.
- Missing data between different data sampling sessions which may include important information about faults.
- Lack of access to some equipment for human.
- Limited number of equipment under monitoring due to the high cost of sampling devices as well as the limitation of the human resources.

To overcome the first problem, which is the missing data between sampling sessions, there should be a solution that can convert sectional sampling to continuous sampling or data streaming. The second problem is human error during sampling. The technician may place the sampling device at different points at different sampling sessions and obtain different results. The sampling should be done automatically to prevent human errors, such as mistakes in reading or inserting numbers. The next problem is sampling at different conditions of the equipment in terms of load, which means that sampling may be performed at a time of extreme load and subsequently be performed at a lower load, which may make the results incomparable. This problem will be resolved by solving the first problem, because if the sectional sampling converts to a data stream, the equipment data will be sampled at all times and it will be possible to examine the data at a specified time. Another problem is the inaccessibility of some equipment for human. To solve the problem, we need to look for a solution that does not require the technician to be at the location of the equipment for sampling.

The solution that can address these problems is to make the equipment smart. Equipment must be able to announce its status at any time and this capability leads us to the concept of the Internet of Things (IoT). Internet of Things was first employed in 1999. The IoT is the network that connects things together. These things can be computers, smartphones, people,

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data, processes, and physical objects such as machines, devices, and appliances [6]. IoT can integrate various manufacturing devices in order to sense, identify, process, communicate, operate and network. This deeply integrated intelligent cyber-physical environment brings so many opportunities and values for manufacturing businesses [7]. Using IoT inside the industry is called industrial Internet of things (IIoT). This term refers to the industrial subset of the IoT. IIoT in manufacturing could make so much value that it will finally head to the Fourth Industrial Revolution or Industry 4.0 [8].

In fact, the equipment is needed to move from a static entity to a network entity that can share its status and condition to the network at any time and become one of the things of the IoT. Such equipment that is able to share its status in the network is called IoT Enabled Device. Sharing the status is not the only desirable characteristics of an IoT enabled device. Things in IoT are expected to have various characteristics which include: sensing, connectivity, processing, energy efficiency, cost-effectiveness, quality and reliability and security [9].

In order to make a rotating machine intelligent for performing vibration analysis, a hardware must be added to it. A kind of hardware that can measure the vibrations of the machine and send it to the network. The purpose of this paper is to design and manufacture this hardware to measure the vibration of rotating machines with the ability to share it on the internet in order to prove the concept of the proposed solution.

The rest of this paper is structured as follows. Section II provides discussions on related work. In section III we introduce the enabling technologies for vibration sensing. Section IV provides the implementation details of the manufactured hardware. Results are discussed and evaluated in section V. Section VI concludes the paper and lists the possible future works.

II. Related Work

In this section, related works have been reviewed. The previous research of the authors [10], investigated the applications and capabilities of the IoT for condition monitoring and fault diagnosis of rotating machinery. The paper provides a solution and investigates the feasibility of it.

In [11], for the health monitoring of semiconductor equipment, an online predictive maintenance method is introduced. The first stage involves an online prediction of the health indicator; the second stage classifies the indicator into one of the health categories. The classified indicator is further considered as a piece of knowledge for decision making of the maintenance. To this end, a computational efficient algorithm called as kernel recursive least square (KRLS) is employed for online prediction stage. This paper has used the data from currently installed sensors and does not develop new hardware. The paper investigated the semiconductor equipment which doesn't involve the rotating machinery and so vibration analysis.

The future of smart vibration monitoring belongs to MEMS accelerometers. In this way, they gradually become an alternative approach for vibration monitoring in maintenance. However, MEMS technology has not been fully investigated for much broader applications. One example is [5] that examine the feasibility of utilizing MEMS accelerometer in vibration sensing. It integrates the sensor with the intelligence of vibration analysis. This paper did a similar job to the current paper and has been a primary resource for us. One major difference is that the sensor designed in [5] does not have the ability to send data to the network and it processes the data locally. In other words, it is not IoT enabled.

In [6] the main objective is to investigate the prediction and fault detection based on the IoT data collected in the process industry. It utilizes IoT enabling technology related to SAP. The introduced method in [6] is composed of two phases. The first step identifies the fundamental relationship of the physical machines. For this purpose, it investigates the device sensor data without involving the information of the physical manufacturing system. This is because, if faults of particular machine are discovered by monitoring the healthy index of this machine, it calculates the potential faults of other machines. Therefore, the faults can be predicted based on the underlying relationship identified in the earlier phase. This technique is employed in a real application of IoT with the cooperation of an industry partner.

The purpose of [12] is to predict the motor's bearing failure using the vibration and temperature of the induction motors. Moreover, the technique in [12] employed IoT in order to present a real-time condition monitoring solution for the maintenance of industrial induction motors. Furthermore, the collected vibration and temperature data is processed in an application. This application has the facility to show sensor data for a period of time and save this data in a local or cloud-based database. Additionally, the solution in [12] monitors system data for undesired conditions that happens and informs the maintenance unit of the factory. For vibration measurement, a piezoelectric sensor is used in [12] which are investigated further in the current paper that is not well suited for IoT enabled devices due to their power inefficiency.

In [13], a condition-based preventive maintenance solution and condition monitoring framework are integrated together. This framework collects data from device tools in order to inspect them using an information fusion method. This is because the aim of [13] is to utilize this information for condition-based preventive maintenance. The introduced method is implemented as a software service and deployed on the cloud. By collecting machine actual processing time and machining time per tools, this service estimates the expected remaining useful life of components. This paper puts its main focus on demonstrating the capabilities of cloud computing for condition monitoring, in addition, it does not step into rotating machinery, instead, it works with data related to machining time of equipment which can come from the operational center of the factory or the equipment directly with no need to add extra sensors to them.

III. Vibration Sensing

For vibration analysis it is required to properly measure the vibration. Vibration measurement can be accomplished measuring various parameters such as displacement, velocity, and acceleration. There are different types of sensing devices to measure the mentioned parameters. Each type of measuring is based on a distinct principle [5]. Vibration is most commonly measured through acceleration using an accelerometer. An accelerometer calculates the dynamic acceleration and demonstrates it as a voltage in output [14]. Measuring acceleration brings the ability to measure tilt, and vibration or shock. Therefore, accelerometers are employed in a wide range of purposes and applications such as crash detection, hard disk drive protection, impact detection, gaming, pointing devices, and wearable devices [15].

Accelerometers have diversity in design, size, and range. Accelerometers have various types that are based on different principles. Vibration is mostly measured by a piezoelectric sensor in industry case. This type of sensor works based on the piezoelectric effect that happens when a voltage is produced across particular types of crystals as they are stressed. Fig. 1 shows an industrial piezoelectric accelerometer [14].

Energy efficiency and cost-effectiveness mentioned as the desirable characteristics of an IoT enabled device in the introduction. Looking at piezoelectric sensors which are expensive and energy-consuming devices show that they are not the best choice for being used for an IoT enabled device. Furthermore, piezoelectric sensors work based on a mechanical concept which is less compatible with smart electronic solutions like IoT than electronic based accelerometers.

Among various technologies, microelectromechanical system (MEMS) accelerometers are proposed to be very promising for the smart maintenance [5]. This is because, MEMS has insignificant size and low power and they can be employed with ease of integration. The performance of MEMS sensors gives the opportunity to play a meaningful role in the massive expansion of today's personal electronic devices. In addition, these characteristics bring innovation in gadgets such as smartphones, activity trackers, and gaming controllers [16]. Fig. 2 shows a MEMS accelerometer beside a coin to emphasize the small size of it.

MEMS technology is broadly employed in various applications including automotive, biomedical and consumer sectors like wearable gadgets. However there is not enough study on MEMS accelerometers for vibration measurements of industrial maintenance of rotating machinery [5]. MEMS accelerometers have several superior characteristics over legacy mechanical piezoelectric sensors like small-size, low-power and energy-efficiency.

Figure 1. A piezoelectric based accelerometer from Hansford Sensors

Figure 2. Comparing a MEMS accelerometer's dimension with a coin.

Nevertheless, the usage of MEMS for vibration sensing has been limited to applications that can work with low bandwidth. [17]. The key criteria for industrial condition monitoring accelerometers are low noise and wide bandwidth. A few MEMS manufacturers provide MEMS accelerometers with bandwidths above 3.3 kHz while some particular producers provide accelerometers with bandwidth up to 7.7 kHz) [15]. There is no industry standard to define what category an accelerometer fit into but the categories accelerometers are generally classified into and the corresponding applications are shown in Table I [15].

Another limitation of MEMS accelerometers is noise. This is because; noise performance in MEMS is not low enough to detect faults in industrial machines. Although there are some low noise MEMS accelerometers available, they are limited to very-low bandwidth [17].

On the other hand, piezoelectric accelerometers have bandwidth from 3 Hz to several hundred kHz. In addition, they can also work fine in high-temperature environments. But, piezoelectric accelerometers have low efficiency around dc whereas there are several faults that can happen at lower frequencies as shown in Fig. 3. Moreover, since piezoelectric accelerometers are mechanical in nature, they do not scale up to large volume of manufacturing unlike MEMS sensors. Finally, piezoelectric accelerometers are costly in price and consuming in power in comparison with MEMS [15].

IoT technology aims to reduce cabling in such a way to utilize wireless and low power technologies which works with onboard power supply. These are the desirable characteristics that have been mentioned for IoT enabled devices. Thus, the superiority for MEMS accelerometers over legacy piezoelectric sensors in terms of size, weight, power consumption, and potential for integrated intelligent solutions is shown [15].

TABLE I. ACCELEROMETER GRADE AND TYPICAL APPLICATION AREA [15, TAB. 1]

Accelerometer Grade	Main Applications	Bandwidth	G-Range
Consumer	Motion, static acceleration	0 Hz	1 g
Automotive	Crash/stability	100 Hz	<200 g/2 g
Industrial	Platform stability/tilt	5 Hz to 500 Hz	25 g
Tactical	Weapons/craft navigation	<1 kHz	8 g
Navigation	Submarine/craft navigation	>300 Hz	15 g

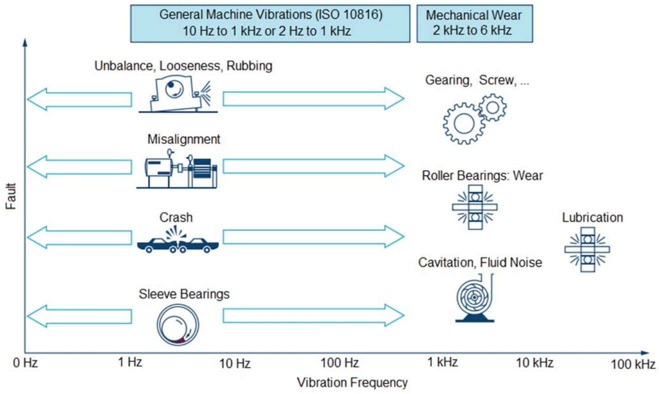

Figure 3. Rotation equipment fault vibration artifacts [15, Fig. 3].

In early 2017 Analog Devices, a major MEMS accelerometer manufacturer, introduced the next-generation of MEMS with new capabilities. This MEMS generation is augmented for industrial vibration monitoring. They provide wide bandwidths up to 50 kHz and ultralow noise efficiency. MEMS accelerometers have taken an extensive leap forward in performance. That is why this new generation overtakes the domains previously ruled by piezoelectric accelerometers [15]. Introducing this new family of accelerometers and their application for smart maintenance is one of the major contributions of the current work.

IV. IMPLEMENTATION OF PROPOSED METHOD

The required hardware should be able to perform three main tasks which are: A) Sensing B) Processing C) Transmitting Data. In the following, the details of implementing the hardware for performing these tasks are provided. The final section brings the manufactured hardware with technical specifications.

A. *Sensing*

Based on the discussed reasons and explanations in the previous section, MEMS accelerometer is used in this paper to develop the required hardware. An essential factor for selecting the proper MEMS sensors is bandwidth [5].

The maximum frequency that the accelerometer is able to capture is the bandwidth of the sensor. The occurrence of prominent frequency components in the frequency analysis of the captured signal represents the machine state. These frequencies are associated with the rotational speed of the equipment. For instance, if the rotational speed of the machine is considered as (f_r), the coupling misalignment will cause a prominent component at (f_r), while, misaligned will appear at $2\times f_r$ [5].

Therefore, the rotational speed of the equipment, as well as the type of faults to be detected, are factors that are important in determining the required bandwidth. In this paper, the plan is to use a hardware on low-speed motors around 1500 RPM (25Hz). Hence, the ADXL335 accelerometer sensor from Analog Devices was selected. The ADXL335 is a small, lightweight, and low power accelerometer. This sensor is able to measure acceleration in the range of ±3 g within a bandwidth from 0.5 Hz to 1600 Hz, which is within the scope of this paper and beyond.

B. *Processing*

In order to receive, process and send data to the sender module, the LPC1768 microcontroller with ARM Cortex M3 processor is selected. The processor receives data from the sensor and samples the signal by using the microcontroller's internal A2D unit to convert it from analog to digital signal.

The Nyquist–Shannon sampling theorem [18] states that "If a function $x_{(t)}$ contains no frequencies higher than B hertz, it is completely determined by giving its ordinates at a series of points spaced 1/(2B) seconds apart". Therefore, for a particular sample rate f_s, a bandlimit of $B<f_s/2$ is needed to ensure accurate reconstruction. Therefore, if it is intended to detect shaft misalignment on a machine with a 25Hz rotating speed, it will generate a prominent component at 2f or 50Hz. Based on the explained Nyquist–Shannon sampling theorem, the sampling rate should be 100Hz at least. Here, a sampling rate of 2500Hz is chosen for more precise results plus to cover more complicated faults as well as higher rotating speeds.

Each sent sample from the sensor is a 4-digit number from 0 to 4096. 0 shows -3g and 4096 represents the maximum range which is +3g in this sensor. The sensor sends each sample in 12 bits which fits in 2 bytes. In order to reduce the overhead, a simple buffering is performed by putting every 500 bytes into a frame and the frame is sent to the sender module (Wi-Fi module).

Two LED indicators are implemented on the circuit to notify the status of the board's main operations. One blinks on the receiving of each frame of data from the sensor and the other blinks on sending data to Wi-Fi module.

C. *Transmitting Data*

In order to send data from the board to the internet, a Wi-Fi module is needed. The ESP8266 module has been selected to do this job. This module connects to the microcontroller using a serial connection via the UART interface. ESP8266 requires to recognize the server address which is going to send the data, as well as the credential of an access point, to get connected.

Afterward, by turning the board on, this module tries to be connected to the access point and after a successful connection, it will establish a TCP connection to the socket running on the server. Later, the data frames are transmitted over this socket to the cloud.

D. *Manufactured Hardware*

Fig. 4 shows the complete assembly of the sensor, designed and developed for this research. Part (A) is the ADXL335 accelerometer sensor, connected to the board via four 20cm long wires. The sensor is not on-board to make it possible attaching the sensor on the machines. Part (B) is the LPC1768 microcontroller which the processing unit. Part (C) is the ESP8266 module which sends the data to the server. Part (D) represents the LED indicator for receiving data from the sensor and the LED indicator for sending data to server. Part (E) shows the button for restarting the board and finally part (F)

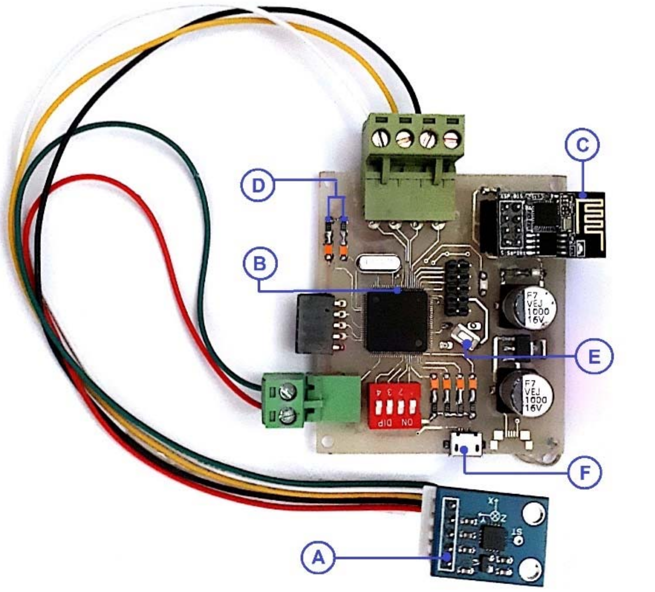

Figure 4. The developed hardware for IoT enabled vibration measurement

shows the mini-USB port used for connecting to a 5-volt power supply. The block diagram of the circuit is shown in Fig. 5.

This hardware is able to measure dynamic and static vibrations with a sampling rate of 2500Hz and send it to the user specified server on the cloud in real-time.

V. EVALUATION

To evaluate the designed hardware, a data acquisition web application has been developed. This application consists of three main components.

The first component is responsible for receiving data from the sensor. This component is written in python and consists of two threads working simultaneously. The first thread task is to receive data. It opens a TCP socket and listens to it, waiting for a connection from the sensor. When the connection is established, it receives the data frames from the sensor and puts them in a queue. The second thread is responsible for storing data. It reads data from the queue, processes and saves them into the database. The process includes:

- Converting the received bytes to 4-digit numbers by merging each pair of bytes.
- Confirming the integrity of received data.
- Filling the missing data in case of a buffer overflow in the sensor.
- Removing irrelevant data in case of existence.
- Store the processed data into a queue to perform a bulk create in the database to reduce the overhead of inserting data into the database.

The second component of this web application is a Django application providing a RESTful API for accessing to stored data in the database over HTTP protocol for clients.

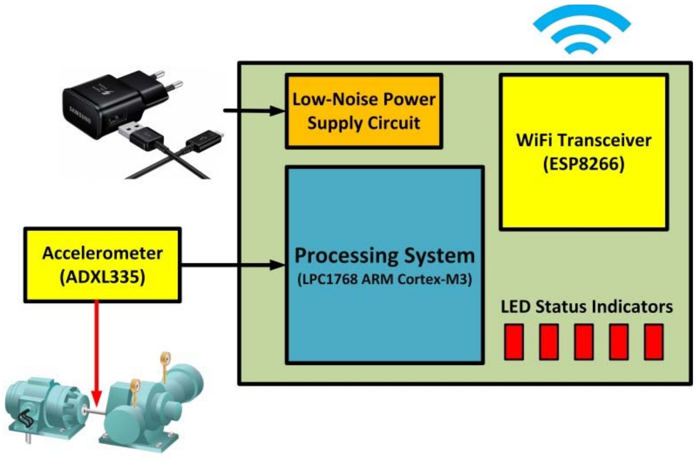

Figure 5. Block diagram of designed hardware

The third and last component is the client-side application. This application retrieves data from the server's API and plots the real-time graph of them. The graph is a line chart, represents the vibration data in order of G.

In order to evaluate the hardware, the accuracy of data received on the server is compared with data captured locally from the sensor at the same time. We attached the sensor to a motor with 1500 RMP speed and then we ran the server and client applications. The vibration data presented on the graph in real-time. Meanwhile, by connecting the sensor locally to an oscilloscope, vibration data would be captured and presented on the oscilloscope, too. Fig. 6 displays the client application and oscilloscope at the same time.

As seen, the data retrieved from the server matches the data measured locally on the oscilloscope at the same time with reasonable precision. The second round of the motor rotation is marked on both images in Fig. 6 to show the similarity.

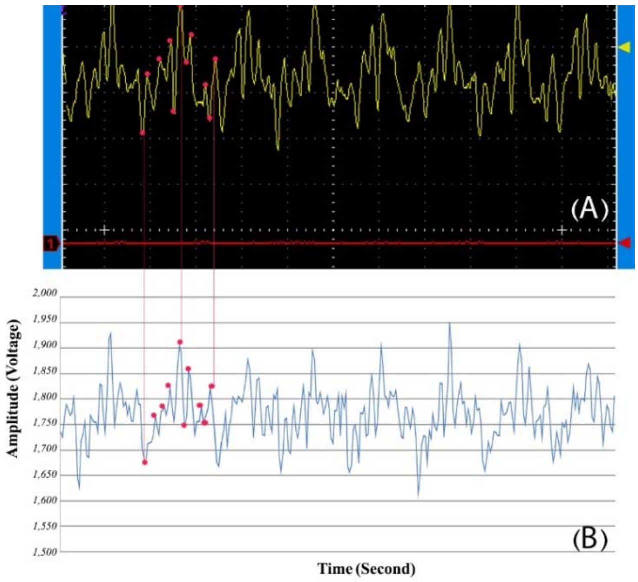

Figure 6. vibration data captured and presented locally on the oscilloscope (A) and from the server on the web application (B) represents the same values

VI. CONCLUSION

In this paper, we demonstrated the potentials of IoT for smart maintenance. We explained how IoT can help the condition monitoring and fault diagnosis of rotating machinery using vibration analysis. Further, vibration sensing has been investigated and the new generation of MEMS accelerometers has been introduced. We discussed the superiority of MEMS accelerometers on legacy piezoelectric accelerometers and their importance in the future of smart maintenance.

We proposed to make rotating equipment to IoT enabled devices by adding hardware to them. According to the requirements, the hardware was designed and developed. This hardware is able to measure vibrations with 2.5 kHz sampling rate in the range of ±3 g and send them in real-time to a specified server on the cloud. This way the machine will be able to send its vibration status to the server and the maintenance engineers will be able to monitor it anytime, anywhere. The developed hardware has been evaluated by comparing the results of online and local data measurements at the same time. The results of the evaluation have been proved to be very precise.

This paper proved the concept of using IoT enabled sensors in predictive maintenance to overcome some gaps in the commonly used methods of condition monitoring of rotating machinery. The results can be extended to a larger scope of equipment, faults, and parameters.

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