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WIRELESS MONITORING OF POWER CONSUMPTION FOR INDUSTRIAL ROBOT DURING A PICK AND PLACE TASK FOR PREDICTIVE MAINTENANCE

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ABSTRACT

Industrial companies follow different maintenance strategies to increase operational reliability and reduce costs. One way to reduce maintenance costs is by real-time inspection of power consumptions to predict the potential failure of industrial machines. Wireless monitoring is essential as it provides safe and remote measuring for such applications. Related studies utilized efficient devices and strategies for monitoring the energy consumption of industrial machines, but didn't present a cost-effective and simple design accurately monitoring the power for multi-degree of freedom (MDOF) robots. The objective of this work is to develop a cost-effective wireless power consumption monitoring system enhancing predictive maintenance purposes for MDOF industrial robots. Unlike the traditional Zigbee-based WSN mentioned in the literature, the presented scheme includes only two RF modules, a single remote-sensing node called router XBee and another module at the monitoring station connected to a PC. The key feature of this cost-effective design is the ability to measure, process, and transfer data required to perform energy monitoring by only using two modules. ABB-IRB-1200 robot manipulator is used as a practical platform to test the effectiveness of the developed design. The measurement of power consumption is conducted via performing a task called pick-and-place by the robot. The produced consumption profile of the robot input power can be used further for energy modeling and estimation.

Keywords: *Five Power consumption, Monitoring, ZigBee, Wireless sensor network, industrial robot.*

1 INTRODUCTION

1.1 Background

Every day we rely on a wide range of machines. But the truth is that every machine eventually breaks down unless it's being maintained. Companies follow different maintenance programs to increase operational reliability and reduce costs. One way is to do monitoring for power consumption, where the machine is used to its limits, and repairs are performed only after machine failure. Complex systems such as industrial robots are composed of some very expensive parts that can't risk running it to failure, as it will be extremely costly to repair highly damaged parts. Many industrial organizations try to prevent failure before it occurs by performing monitoring as regular checks on their equipment. One big challenge with preventive maintenance is determining when to do maintenance. By scheduling maintenance very early, industrial companies are wasting machine life that is still usable, and this adds costs [1]. However, if these companies can monitor to predict machine failure, they can schedule maintenance right before it [2]–[4]. One of the key components to solving this issue is by enhancing the operating system by a monitoring property that lets users estimate the time to failure. Remote or wireless monitoring helps to detect the levels on which the maintenance needs by comparing with pre-specified thresholds. This will avoid operating safety-critical equipment of industrial companies' failure occurrence. It also pinpoints problems in complex machinery like robots and helps to identify what parts need to be fixed. Monitoring circuits can minimize downtime and maximize equipment lifetime.

In order to early detect faults and performing related maintenance strategies, this study discusses the importance of monitoring the power consumption rate of an industrial robot. A cost-effective wireless monitoring design and prototype helps to early detect faults and maintenance.

After the background in this paper, the introduction section also includes a literature review, discussing Zigbee-based wireless sensor networks and compare with WIFI and power consumption analysis. Section 2 describes the adopted approach methodology including an overview, design features, and experimental setup. The results, in section 3, are composed of three subsections; calibration, Real measurements with joints' positions, and real measurements within different ranges. The concluded remarks are highlighted in section 4.

2.1 Literature review

Industrial robots play a significant role in the industry section and companies follow different maintenance programs to increase operational reliability and reduce costs. One way to reduce the maintenance cost is health monitoring to predict the potential failure and one technique for failure prediction is by monitoring the power consumption rate of industrial machines [2]. The complex power pattern of multi-degree of freedom (MDOF) robots can be modeled by fitting these measurements with a method called Bode-Equation Vector-Fitting (BEVF), which is presented in [5]. Several studies analyze and model the power consumption of industrial robots [6]–[12]. Remote monitoring for the industrial machine is considered to ensure human safety and reduces communication wires [13]–[16]. In general, there are various components that significantly consume energy in the industrial robot, for example, motors, motors control drivers, controllers, and fans as well as mechanical loads represented by joint gears and friction. Although those efforts targeted to develop algorithms and techniques for diagnosing faults in industrial machines, their schemes either complex or required extra added sensors to the system to perform the faults detection tasks.

Zigbee-based networking plays a significant role in various domains of energy monitoring, such as industrial applications [17]–[19], building energy metering, and smart home applications [20]–[23], in temperature and structural monitoring [19], [24]. The wireless energy networking becomes complex as nodes and sensors number involved increases. The use of wireless sensor networking (WSN) with robot joints enables the system to acquire data of voltage, current, and temperature sensors automatically. Also, it provides efficient control for different consumed elements in the robot.

Although the above-related studies utilized efficient devices and strategies for monitoring the energy consumption of industrial machines, they didn't present a wireless, cost-effective, and simple design for accurately monitoring power consumption for MDOF robots. The proposed technique can provide all the required information for energy estimation, modeling, and energy predictive maintenance not only for MDOF robot but also some complex industrial machines, but due to the lack of power sensors and their accessibility, this article presents a strategy of adopting a measurement-driven method to model the power consumption of a robot manipulator. Unlike the traditional Zigbee-based WSN mentioned in the literature, the presented scheme includes only two RF modules, a single remote-sensing node called router XBee and another module at the monitoring station connected to a PC. The key feature of this cost-effective design is the ability to measure, process, and transfer data required to perform energy monitoring by only using two modules. For more clearly, there is no traditional microcontroller involved in the design that adds cost and complexity to the system. The objective of this work is to develop a cost-effective wireless power consumption monitoring system enhancing predictive maintenance purposes for MDOF industrial robots. ABB-IRB-1200 robot manipulator is used as a practical platform to test the effectiveness of the developed design. The feed-back readings of the joints' angular positions are used as a reference and used to calibrate the circuit measurements. The measurement of power consumption is conducted via performing a task called pick-and-place by the robot. The produced consumption profile of the robot input power can be used further for energy modeling and estimation.

2.2 Zigbee based wireless sensor network and compare with WIFI

Two of the most common wireless technologies that exist today are Wi-Fi 802.11 and

ZigBee 802.15.4. Choosing which wireless technology is best for a particular application can be decided by examining three main characteristics, the power, the bit-rate, and the range are the characteristic to consider when choosing which wireless technology is best for the considered application.

The battery life is typically one to two days for 802 11 Wi-Fi devices, while for Zigbee 802 15.4 wireless technology, which is commonly used in smart grids and wireless measurement systems can have a battery life as high as three to five years. The next characteristic to consider is the max bit-rate. For Wi-Fi, the max bit-rate is 54 megabits per second. In contrast, ZigBee only allows 250 kilobits per second, which is a big difference in the bandwidth between the two. The third characteristic to consider is the range, typically the line-of-sight; Wi-Fi can be accessed up to 100 meters while ZigBee can reach 1,000 meters. It is important also to know about network topologies when considering an application range. With Wi-Fi, there are access points and clients, wherewith an Ethernet network, several access points can be used to extend the range, and then the wireless is used to connect to the client such as laptops or smartphones. To increase the range more access points can be installed on the Ethernet. By contrast, looking at Zigbee, Ethernet is also can be used, but instead of access points, a gateway is used, which provides connectivity from distributed nodes back to the Ethernet backbone the nodes have a wireless antenna and they communicate wirelessly using ZigBee back to the initial gateway unlike Wi-Fi. The system needs to you can install to add more nodes to install without having to extend the gateway. This is known as mesh routing, the maximum range can be 1,000 meters. Additional nodes can be added connecting to the network which can communicate wirelessly as well, but rather than the device serve as a node. It becomes a router what it's doing is routing info from the end node back to the gateway. This also allows redundancy by providing a second node available if the first one loses connectivity. Therefore, if one were offline data could be provided back to the Gateway. As can see there are a lot of characteristics to consider when choosing a wireless technology.

Based on the above Zigbee characteristics represented by the self-power consumption and transmission range as well as its cost-effective prosperity in networking, it is considered in this work as it is more appropriate for wireless energy monitoring systems.

2.3 Power Consumption analysis

Usually, the main input power of industrial machines is the alternative current (AC), while this power is internally converted into DC in a power conversion stage inside the machine to be controlled according to a set speed, torque, and/or operation requirements. Therefore, the developed data acquiring circuit is placed on the DC line. The consumed power of industrial robots can be demonstrated in Figure 1.

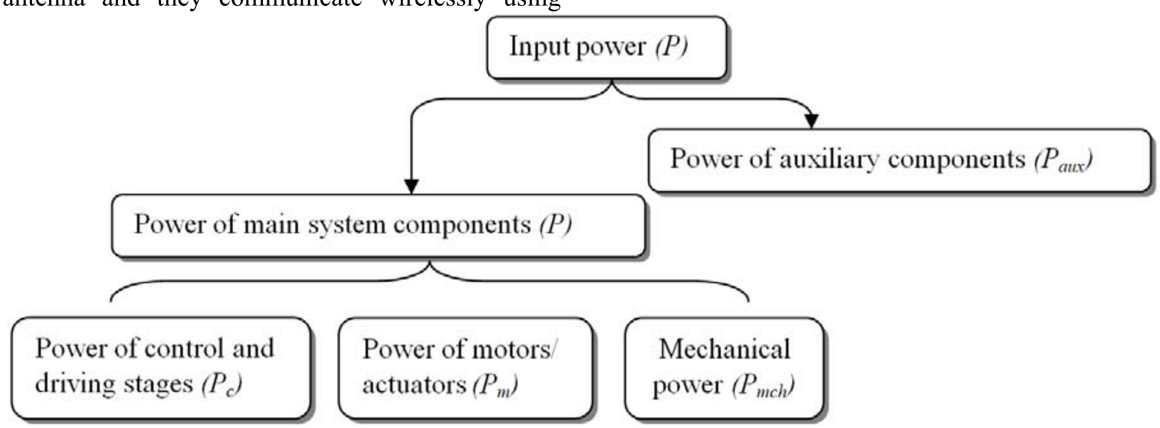

Figure 1. The consumed power distribution of industrial robots.

The input power (P) of an industrial robot can be divided into two main parts according to the loads; a constant power consumption due to auxiliary components (Paux) (such as monitoring PC, compressor, cameras, and other sensors), and variable power consumptions of main system components, which reflects the power of performing a particular task. The main components include motors' drivers and controllers (Pc), motors/actuators (Pm), and mechanical power losses (Pmch). Accordingly, the power rate or energy consumption can be written as [2]:

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$$E \text{ or } P = f(\text{task}, \text{speed}, \text{torque}, T, t, ..)$$

This formula interprets the influence of the power consumption by performed task, speed, load (torque), Temperature (T), and time respectively. Furthermore, motors are the most variable consumer of industrial robots, which is permanent magnet synchronous DC motor with efficiency range between 83% to 92% [9], [25]. The power consumption of these motors has been given by:

$$P_m = P_{Fe} + P_F + P_{copper} + P_{stray}$$

where P_{Fe}, P_F, P_{copper}, and P_{stray} represents the consumed power due to iron, mechanical, copper, and stray losses respectively. Mechanical and iron power losses can be considered as constant losses. They are specified by manufacturers and do not affect by the motor load variation.

2 METHODOLOGY

2.1 Overview

This section discusses the role of the monitoring part in the predictive maintenance chain, where the monitoring is the main and first stage. A large set of sensor data representing healthy and faulty operation is collected making sure that the collection of this data under different operating conditions. For example, the same robot machines running in different places and performing the same task, one in Iraq and the other one in Malaysia. One may be performing under highly humidity conditions whereas the other one operates with low or dry weather, as in Iraq. The system flow can be represented as shown in Figure 2.

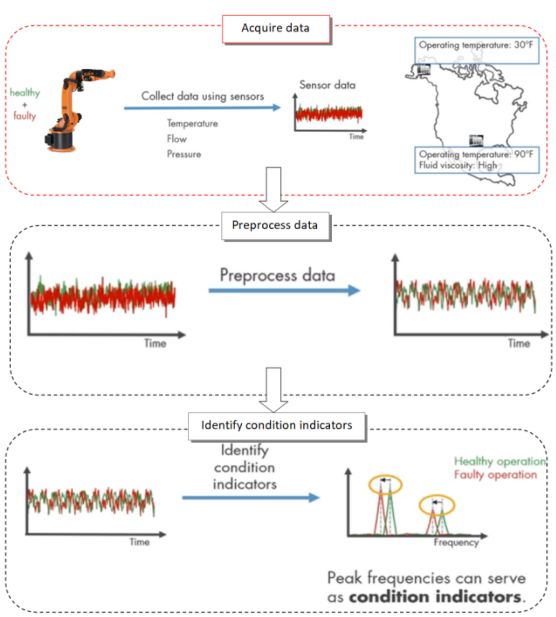

Figure 2. Monitoring system for predictive maintenance purposes.

Although the same type of machines, one may fail sooner than the other due to these different operating conditions. Capturing all this data will help the owner develop a robust algorithm that can better detect faults. In some cases, it may not have enough data representing the healthy and faulty operation. In such cases, it is essential to build a mathematical model of the machine and estimate its parameters from the data collection of sensors. We can then simulate this model with different fault states under different operating conditions to generate failure data. Once the data are collected, the next step is to remove the outliers and clean them up by filtering out the noise. Sometimes further preprocessing is necessary to reveal additional information that may not be apparent in the original form of the data. For example, converting time-domain data to a frequency domain may help to extract some useful features also referred to as condition indicators. These are used to distinguish healthy from the faulty condition.

In the plot, it is clear that the peaks in the frequency data shift left as the robot degrades, and therefore the peak frequencies can serve as condition indicators. This example shows how to extract some features from an acquired data wirelessly that help to understand the healthy and faulty operation of the robot. This research focuses on the part of acquiring the power consumption data of industrial robots when performing remotely by using cost-effective WSN.

2.2 Design features

The objective of this work is to develop a cost-effective wireless power consumption monitoring system enhancing predictive maintenance purposes for MDOF industrial robots. The developed circuit for monitoring the power consumption of industrial robots is unlike the traditional Zigbee-based WSN by exploiting the embedded microcontroller of the Zigbee module, which has a 10 bit analog to digital (ADC) converter. The main system component in the developed method is shown in Figure 3.

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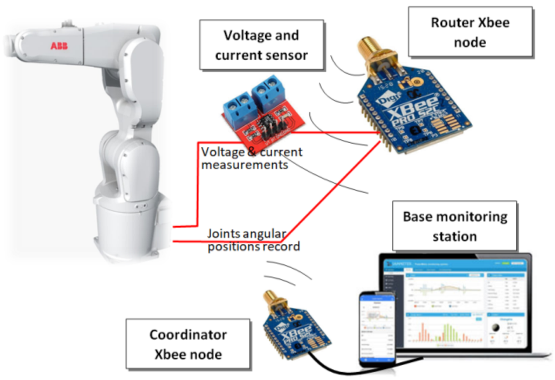

Figure 3. Main system component in the developed method.

Only two RF modules have been used to perform energy monitoring of industrial robot, a single remote-sensing node with five analog input channels called router XBee, and another module at the monitoring station connected to a PC called the coordinator. The key feature of this cost-effective design is the ability to measure, process, and transfer data required to perform the monitoring without an additional microcontroller kit. ABB-IRB-1200 robot manipulator is used as a practical platform to test the effectiveness of the developed design. The feed-back readings of the joints' angular positions are used as a reference and used to calibrate the circuit measurements. The measurement of power consumption is conducted via performing a task called pick-and-place by the robot.

2.3 Experimental setup

Two main parameters that affect the precision of measurements are sensor circuitry and software code. Since the internally produced DC voltage of the robot is constant, the measured power is expressed by recording the current values from the remote Xbee channels. The other five channels are employed to send the readings of the joints' angular positions from the robot external terminal to the coordinator Xbee at the base station.

Serial interface protocol as a communication technique is used to transfer the measured data. The coordinator XBees was configured by Application Programming Interface (API), which provides structured packets through the serial interface. A frame-based API is created to satisfy a host interaction. The serial data received is queued up to be transmitted via radio transmission process. The proposed control algorithm for the adopted software can be expressed as a flowchart shown in Figure 4.

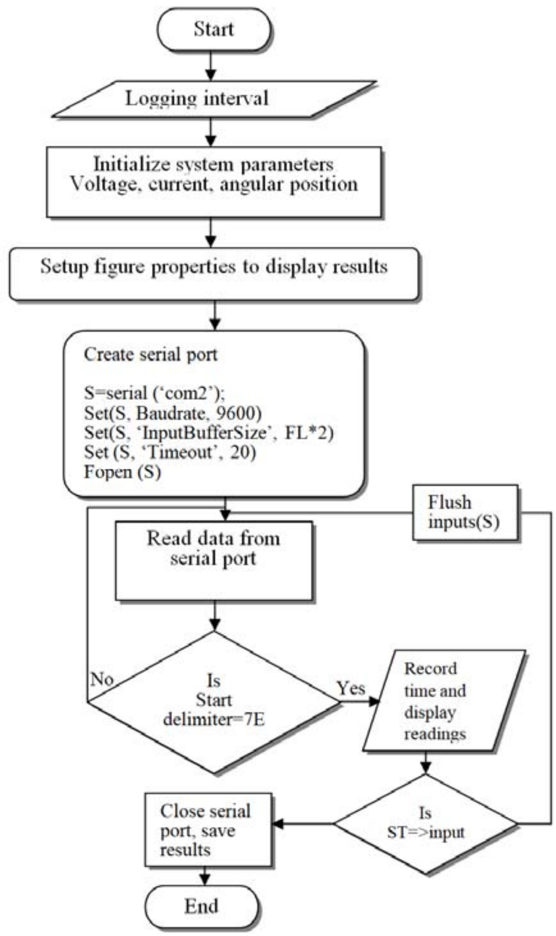

Figure 4. Flowchart of the proposed control algorithm.

Initially, the remote/ router and base/ coordinator RF nodes were configured with appropriate parameters to ensure fast network communication. Both Xbees functioned as a data transceiver and these parameters were set using XCTU. The coordinator at the base station was operating as an access point to receive the measurements in a form of data packets from the remote (end device) node. As mentioned earlier, the remote/router node was configured to set the available 6 channels as ADC inputs, one for current measurements and the remaining 5 channels for transmitting joints' instantaneous positions. The sampling rate of these channels was 20ms. Accordingly, the base/coordinate station node was receiving 24-byte per sample including 12-byte of data and the rest 12-byte for framing.

3 RESULTS

3.1 Calibration

To calibrate the measurements and validate the effectiveness of the measurement for reading the

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power consumption, four sinusoidal input signals with two different amplitudes and phase shifts have been accessed and sent by the router (end device) node to be monitored on the base station display through the coordinator node. The sent signals were with 1Hz frequency, while each of them was 3Vp-p, 1.5 offsets, 0 phase-shift reference, 3Vp-p, 1.5 offsets, 90º lag, 2Vp-p, 1 offset, 0 phase-shift, and 1.2Vp-p, 0.75 offsets, 90º phase-shift respectively. The distance between the router and the coordinator nodes was around 150m. The received signals have been displayed over the monitor as shown in Figure 5.

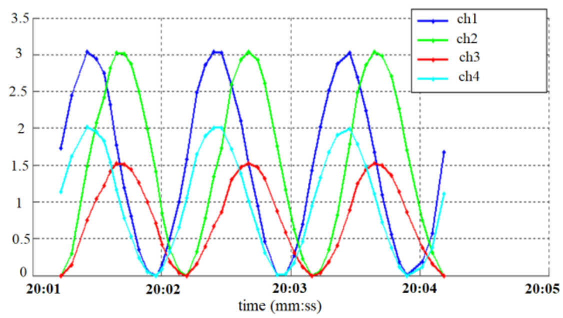

Figure 5. Received/monitored signals by the base station 150m away.

The result of the four tested channels shows an accurate representation at the base station, which motivates us to implement this simple circuit on the industrial robot domain for monitoring and analyzing its power consumption rate remotely.

3.2 Real measurements with joints' positions

The experimental measurements of the developed circuit have been conducted on the 6DOF industrial robot ABB IRB 1200 [26]. The data of 6 channels have been acquired when performing one-cycle of pick-and-place task. The robot performed this task over about 5.3 sec. Note that the joints numbering is started from the base (joint 1) and last with the end-effecter (joint 6). Since this circuit is designed mainly to monitor power consumption, the joints with zero variation are neglected. A photo marking the robot joints is shown in Figure 6, while the monitored power and position measurements at the base station 100m away are shown in Figure 7.

Figure 6. Photo marking the robot joints

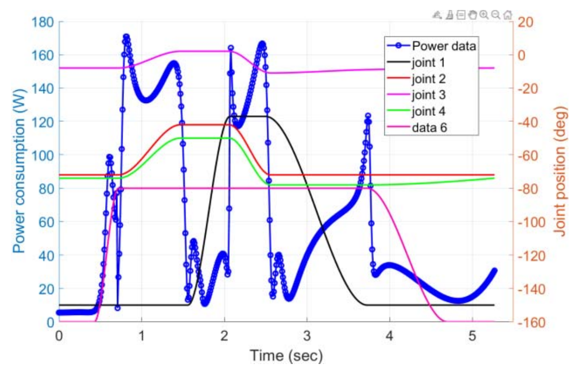

Figure 7. Received/monitored signals (Six channels of power consumption and joints positions) by the base station 100m away.

The joints measurements show the variations of the angular position of each moving joints over-performing pick-and-place task. The results of the power consumption profile show that the power consumption is highly influenced by the number of activated joints (in a move), end-effector position, and load. The measurements reflect the energy required for performing such a task and can be modeled as a reference for future energy estimation and fault detection.

3.3 Real measurements within different ranges.

Another analysis showing the developed approach effectiveness as a wireless monitoring design is the range test. Measurement has been experimentally conducted to compare three operation conditions of power consumption acquiring, measurements at the robot terminals (direct measurements), at 100 meters, and at 150 meters away distance with respect to the robot installation. The range effects test on the developed wireless monitoring circuit is shown in Figure 8.

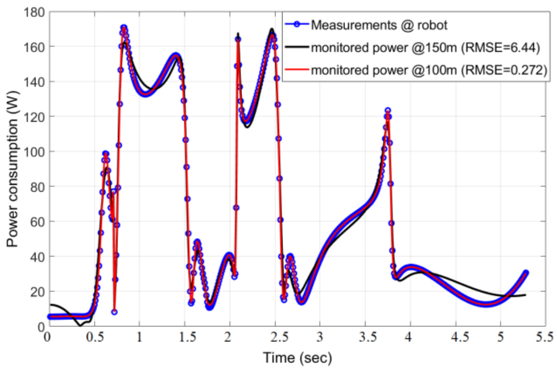

Figure 8. Distance effects test on the developed wireless monitoring circuit

This result demonstrates the difference in power consumption profile with respect to the reference that measured at the robot directly. It is found that the RMSE of the 150m profile is 6.44 as compared to directly acquired data, while it is 0.272 when the distance was 100m away from each other. This interprets the expected range effects on the accuracy of the monitored measurements.

4 CONCLUSIONS

This paper discussed the importance of monitoring the power consumption rate of an industrial robot that helps to early detect faults and maintenance. This approach provided a new circuit for monitoring the power consumption of industrial robots, which is unlike the traditional Zigbee-based WSN by exploiting the embedded microcontroller of Zigbee module.

The results of the power consumption profile show that the power consumption is highly influenced by the number of activated joints (in a move), end-effector position, and load. The measurements reflect the energy required for performing such a task and can be modeled as a reference for future energy estimation and fault detection.

As compared to direct acquiring data measured at the robot directly, it is found that the RMSE of the 150m power profile is 6.44 as, while it is 0.272 when the distance was 100m away from each other. This interprets the expected range effects on the accuracy of the monitored measurements. Therefore, the developed design is successful to process and transfer the measurements of more than 5 analog signals including the power consumption to the base station.

Future work is planned by:

- Expanding the wireless coverage by increasing the network nodes or developing an appropriate antenna as well as looking for more suitable RF modules.
- Using IoT strategy to access over the cloud.
- Increasing the applicability within the predictive maintenance chain of an industrial robot, by performing more tasks and scenarios.

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