Intelligent Monitoring of Robotic Systems with PIC microcontrollers and a Petri-Net based Approach

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Abstract –**This paper investigates the development of an intelligent and low-cost monitoring system for simple robotic systems, considering the need of modern industries for fault diagnosis and identification for early detection of failures for maintenance and managerial activities. Grippers are investigated as part of a pick-and-place system and a PIC microcontroller-based monitoring system is developed. The use of Petri-nets becomes a vital part of this work and allows the modeling of the process. A distributed monitoring system employing industrial networks and internet technology, developed by the Intelligent Process Monitoring and Management (IPMM) Centre group, is used to monitor the operation of an industrial pneumatic gripper. Overall, the project reveals the efficacy of a low-cost, microcontroller-based monitoring system, using a Petri-net approach, for robotic operations and by doing so it demonstrates its important advantages in intelligence and flexibility.**

Index terms – **Fault diagnosis. Intelligent monitoring, Robotic grippers, PIC microcontrollers, Petri-nets.**

I. Introduction

In the modern industrial world, new technologies and innovations provide the ability to get more intelligence out of a process. Process and condition monitoring are essential tools for every efficiency improvement attempt because of their capability to provide key information that is necessary to plan production in a strategic and efficient way. Cost and time reduction, leaner and more competitive processes as well as improvement of Overall Equipment Effectiveness are results of effective and intelligent monitoring [1].

The monitoring of automated robotic systems, such as pick-and-place devices, was considered in this work. Such systems can be found almost everywhere in industry; simple robots in a production line for handling products or assembling and performing pick-and-place operations, or even part of bigger and more complicated processes and machines, like a tool-changing process in a CNC cutting machine. The most common and more critical elements used in such systems are actuators, used to provide the axis movement and the end-effectors (grippers in most cases) which interact with the system's environment. The monitoring of those two elements was thus investigated separately, in order to identify the important aspects and key parameters to be considered for monitoring. In this paper, the gripper monitoring part of the process is considered, as representative of the work and was investigated on a microcontroller based distributed system, comprising low-cost positioning sensors. The Petri-net monitoring approach gave further functionality in this part, while the implementation of Petri-nets inside the program memory of the microcontroller, which is also described, upgrades this system into a distributed monitoring system.

II. IPMM Centre Distributed Monitoring

The development of monitoring systems led the research group in IPMM Centre to propose a monitoring system based on an architecture that enables flexibility, data integration and provides resource sharing capability.

In this architecture (Fig. 1), following the basic hierarchy, the Monitoring Module is a data acquisition and processing module based on Microchip® PIC microcontrollers. The increasing processing power capabilities, reduced size ,affordable prices, instruction set simplicity, power consumption and the flexibility provided by these microcontrollers, has encouraged their use in many application areas where computer based systems were previously the best choice. They are equipped with bi-directional digital ports and ADC capabilities, on board timers and interrupt controllers which can be used to build an intelligent data acquisition system. This approach is being used to collect both digital data (like the status of different switches) and analogue data (like fluid flow, pressure and voltage measurement for different processes) [2].

The Connectivity Module is a hardware specific development, based also on microcontroller technology, which provides internet connectivity, therefore enabling the monitored events to be recorded in a remote database. The Management Application, a software implementation based on PCs, provides a common interface to databases. A common communication bus (CAN) connects together the Monitoring and Connectivity Modules, thus providing a way to address some of the critical aspects of microcontroller-based implementations [3].

The Controller Area Network (CAN) protocol was a result of application area requirements for a robust and fast serial communication technique. It specifies the implementation of the two lowest layers of the OSI model (physical and data link), for a serial bus application [4]. It provides the basic network infrastructure to support the implementation of a distributed system. In this system, the Microchip MCP2510 CAN bus controller was used, fully compatible with the PIC18C452 microcontroller.

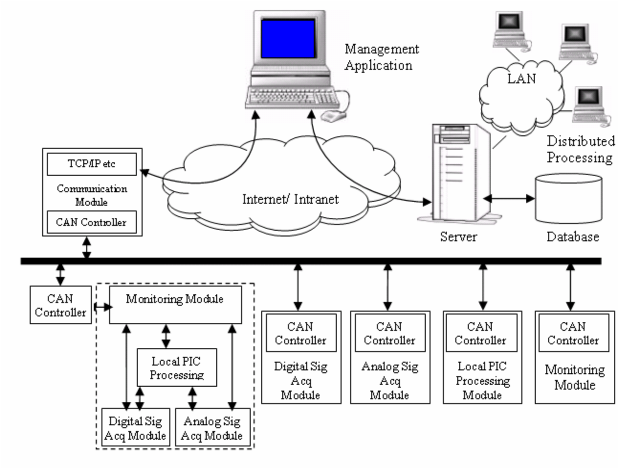

Fig.1 Distributed monitoring system architecture

Another technology area considered was the Internet connectivity, as well as the exchange and integration of information based on database systems, with provided Ethernet capabilities on board. SQL based database systems were considered the natural choice for the storage of the monitoring system records, easing data and presentation approaches and enabling the integration of monitoring information in other applications. The Management application is able to select a system's database, set-up the communication parameters and assign a name to the monitoring task, which will used to create a set of tables where monitoring records will be stored. The monitored events are sent to the Management application over the Internet and the records received will be displayed on the application window while forwarded to the database [1].

III. Gripper Operation Monitoring

A. *Monitoring of the Gripping Process*

In a simple robotic system, the main mechanical actuated parts are the actuators and the gripper, the end-effector of the system. The gripper, which runs independently of the rest of the system, is the most critical link in any robotic system since it ultimately defines the level of interaction that the robotic system may have with its environment [5]. The control of the robot is done with respect of the position and the status of the gripper, acting like an interrupt in the system. The power source is typically pneumatic or hydraulic, with a simple on/off valve control switching between fully-open and fully-closed states, but can also be motor driven.

Grippers often have built-in sensors to monitor the operation, since it is critical for the robot controller to acknowledge that the action has been successfully completed and proceed in further action. Usually, sensors are placed in the tips of the jaws or even on the end of the robot wrist holding the gripper. Proximity sensors, force/torque, pressure sensors, tactile switches, CCD systems and more complicated sensing systems have been used. However, the key aspect of the gripper operation monitoring is that it should be low-cost, comprising low cost electronics and industrial sensors.

The majority of the applications have no need of sophisticated and expensive grippers. The essence most often is ultimately a reliable gripper being able to detect and identify "hard" faults and reset the operation if needed. Thus, a low-cost gripper with an intelligent and flexible monitoring system is more suitable. Furthermore, the development of "soft" faults and trends that can lead to failure of the systems should be diagnosed for effective predictive maintenance.

A common hard fault in this case would be an object not been gripped or slipped while moving. However, faults like a lower air pressure in the pneumatic cylinder which drives the gripper (perhaps caused by a leaky seal), would not result in an immediate failure, but will reside in the system, reducing the system's efficiency, developing a fault trend and eventually causing a bigger failure ("soft" fault). Such faults were considered in this work and were actually detected in the gripper set-up in the lab.

B. *Gripper Experiment Set-up*

In this work, low-cost mechanical limit switches were used. Various configurations were proposed, with two or three limit switches placed in different areas in the fingers and the base of the gripper. In this basis, a primary monitoring system could monitor the status of the limit switches and thus, the status of the gripper operation, identifying successful gripping, failure to grip or even detecting the slipping of a gripped object. Thus, a degree of intelligence was given to the gripper with simple and low-cost sensors.

Fig. 2 shows a simple and ergonomic configuration of limit switches on the gripper. It consists of three limit switches; one placed at the base of the gripper (G1) and the other two on the finger (G2 and G3). Switch G1 detects the home position of the fingers, thus the fully open position of the gripper, while the fully closed position is indicated when both G2 and G3 switches are pressed. Finally, when an object is gripped, it will be detected by switch G3, without G2 being pressed.

Clearly, there is no optimal configuration, but depending on the application, the objects to be gripped and the design of the gripper itself those can fit best. This

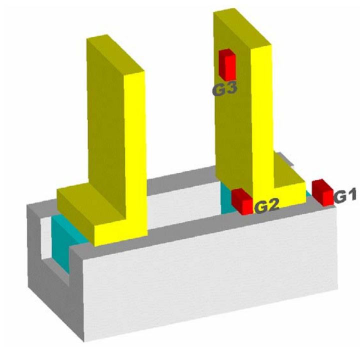

Fig. 2 Gripper configuration with three limit switches

setup is the one used in the tests for the pneumatic gripper in the lab.

A gripper model was initially built in the lab (Fig. 3) for the simulation of the system to be investigated, using replaceable parts, giving the flexibility to test different set-ups. Various configurations with limit switches were built in the end part of the gripper. The status of the limit switches and, thus, of the gripper operation was indicated using a series of LEDs. This simple system could be placed near a pick-and-place system for an operator to watch or use the digital signals from the switches to send feedback to a main control system of a robotic application, indicating a failure. However, an intelligent monitoring system would have to predict soft faults and would require logging the event and sending the data for further analysis.

In the next stage, a pneumatic gripper, similar to the ones used in various applications in industry was used (Fig. 4). This was a two-finger, parallel moving pneumatic gripper, connected to a pneumatic servovalve providing a pressured air supply for opening and closing the jaws of the gripper. Three limit switches were mounted on it, using the configuration in Fig. 2 and, thus, three digital signals, the combination of which gave the ability to identify the status of the operation with respect to the object to be gripped.

The way to achieve stand-alone, low-cost and efficient method of acquiring the signals from the process, trusted to operate full time proposed within this project was using one or more microcontrollers to acquire the signals and monitor the sequence of events. A PIC16F877 was programmed initially to test four digital inputs acquired from the system; the valve signal indicating that it is open, sending pressured air to the pneumatic cylinder moving the gripper fingers and the signal from the three limit switches. Microchip MPLAB®v6.40 was used with an ICD development board kit for programming and PICStart Plus for downloading the program into the microcontroller's memory. The functionality of the microcontroller program and the sequence of events were established. This system could be the intermediate stage to an intelligent monitoring system.

Considered that the timing information is a critical factor for the monitoring of such systems, an enhancement of this primary system was investigated. The measurement

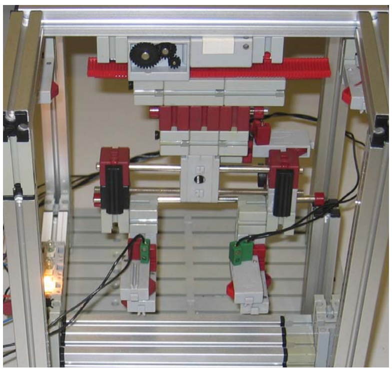

Fig. 3 Gripper model

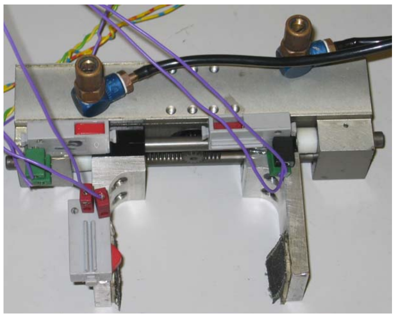

Fig. 4 Pneumatic gripper used in the lab

of time interval is a common task for microcontrollers and PICs provide superb capabilities for carrying out such measurements. A more interactive, intelligent and open monitoring was made possible by using a Petri-net based approach for the monitoring system.

IV. Gripper Petri-Net Monitoring Approach

A. Petri-Nets –Gripper implementation

Petri-nets were proposed in the early 1960s by Carl Adam Petri, as a result of his investigation into a method to model and analyse the relationship between components of a system [6]. Since then, several investigations have been conducted to make further use of the concept. Characteristics such as concurrency, sequencing and synchronization make Petri-nets a powerful tool for the representation and modelling of a variety of different and real discrete event systems [1]. Earlier uses of the method were reported in relation to process and condition monitoring [7]. A Petri-nets' power is related with the graphical representation the method enables, stimulating its use for many engineering applications [8]. Further investigation was carried also by researchers at the IPPM Centre, resulting in a monitoring system running in a PC/Windows® environment [9], also used in this work. The original Petri-net modelling concept is based on the definition of "places" (circles) to represent system states, "transitions" (bars) to identify the progress of events and "arcs" (arrows) to provide the relationship between places and transitions. The status of the system is represented by "tokens" (dots) occupying places and the movement, number and distribution of these tokens within the places describes the system's operation. The Petri-net based monitoring system developed tracks the operation of a process and it can record the changes to the process in a database.

For the pneumatic gripper experiment set-up, a Petri-net was developed in this project to describe the sequence of events and monitor the status of the operation by monitoring the status of the digital signals from the valve and the limit switches (Fig. 5). Following the sequence of events in this Petri-net, transition T01 will fire, provided that the gripper is at its fully-open position (indicated by G1).Transition T02 fires when the gripper is fully open and the valve is energized (indicated by the digital signal Valve_On). The gripper fingers are moving from the fully open position (NOT G1) and transition T03 fires resulting in a token passed to place P03, when the gripper is closing. The two branches are now conditions for transitions T04 and T05 to fire. Transition T04 will fire only if switch G3 is ON and NOT G2, indicating that the object is gripped. This also fires branches from place P04 to T06, continuing the normal operation with the gripped object and to T07 which will fire, indicating that the object is no longer gripped. Transition T05 will fire when both G2 and G3 are ON, i.e. the gripper is at its fully-closed position and has thus failed to grip. This will trigger the output transition T11 and issue an alarm. A token is also passed on to place P05, as well as from T06 and T07, and transition T08 will fire when the state of the valve changes to open the gripper. The token is passed to T09, where the jaws of the gripper are moving towards the fully-open position, in which state T10 is fired and which finally passes a token to the start of the process, in place P01.

The current state of any part of the process or system can be judged by viewing the Petri-net, while any abnormal system event or disturbance will be reflected in the processing of the Petri-net. The Petri-net monitoring system can eventually be implemented inside the memory of a microcontroller, where the transitions are in effect static data structures defined in a microcontroller program memory [3].

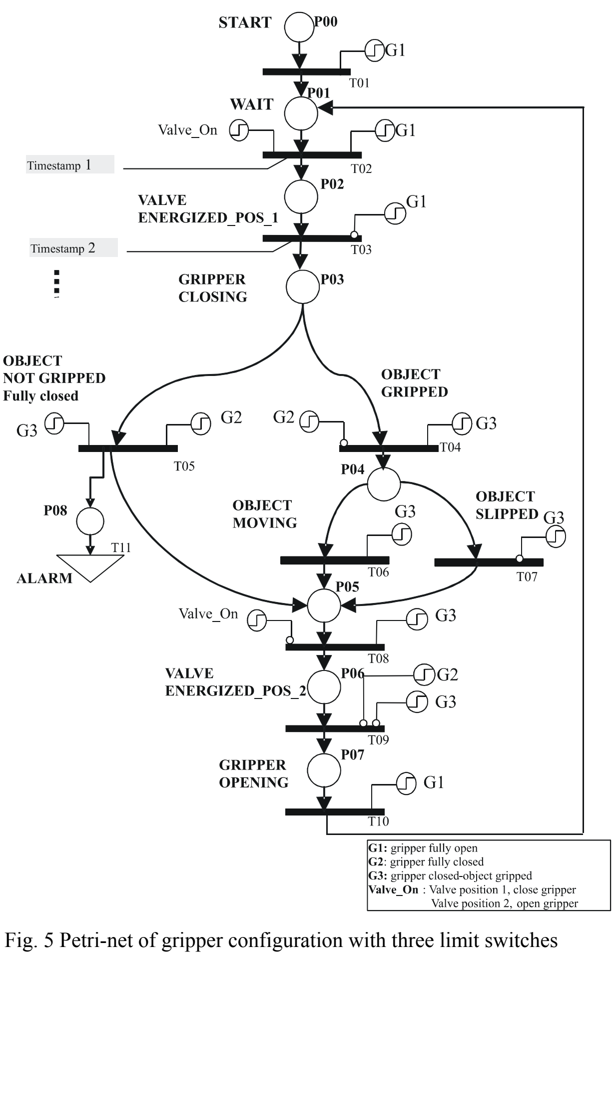

Fig. 5 Petri-net of gripper configuration with three limit switches

B. On-PIC Petri-Net Implementation

Installing and running a Petri-net based monitoring system into a PIC can represent a cheap and easy to install solution. It is important that the monitoring hardware and software implementation should not be dependent upon the process. This avoids the necessity of providing a new software/hardware set-up for each different process. For this reason, the Petri-net describing the process was placed into a separate data table. A new Petri-net can be created to monitor any new or changed process, input into the data table and integrated into the PIC based monitoring system.

Petri-nets transitions are considered as static structures because, within this approach, they describe the process sequence of events and therefore do not change. A collection of static structures can thus be used to describe the process Petri-net in terms of such events. A PIC microcontroller program was developed based on previous work, to describe the gripper Petri-net of Fig. 5. The structure defines a data table in which the identification, along with the inputs and outputs of the transition are defined. Various flags provide more detailed information like whether the firing of a transition should become public event, or sending a message with a timestamp. In the rest of the code block of every transition, digital and analogue signals are assigned and also subnet inputs and outputs. At the start and the end of each code block a places are defined to receive tokens going in and out.

Using this capability, the Petri-net describing the sequence of events for the gripper operation was implemented into the PIC memory and later into the distributed monitoring system. In this approach, the signals from the inputs were compared with the levels defined in the transition data structure and the latter was fired if all the input conditions are present. As a result, output places are updated and, when enabled, a message containing the event identification and timestamp was sent out. The timestamp was obtained from a timing function based on one of the microcontroller internal timers. In the Petri-net described in Fig. 5, timestamps were obtained from every transition fired for monitoring purposes of the gripper positioning timings. Fault detection and predictive diagnosis was intended to be based on these timings, measuring the time that the fingers of the gripper need to move between fully-open, fully-closed or gripped positions and compare those with predefined time levels. Changes in these levels and thus, either slower or faster movement, indicate a potential malfunction of the valve, air pressure fluctuation due a leakage or other possible faults. In some cases, a timeout feature can also be presented in a transition. When a place receives a token, a timer is triggered. The timeout value is based on previous cycles or programmed. Whenever a timeout will occur, a data record will be transmitted and an alarm can be triggered to indicate an anomaly in the process [3].

C. Petri-net Advances

Since the gripper operation acts as an interrupt to the system, this was also described as a sub-net in a main operation Petri-net. An integrated Petri-net was presented, combining the actuator and gripper operation, as in a simple industrial pick-and-place system. The token in this case passes from the main net to the gripper subnet waiting for its successful completion. In case of a failure to grip or slipping while gripped, other transitions are fired inside the gripper sub-net who in turn results in a reset in the gripper operation.

Enhanced features developed by the IPMM research group could be implemented into this work, like the "place timeout" function, as well as triggering the acquisition of analogue signals [2]. Analogue signals can also be handled by another modelling structure defined for this approach, the "analogue transition". In this case, the analogue signal is compared against a threshold defined in the transition's data structure, in the form of a "higher than" or "lower than" logic in order to determine the firing condition. In terms of this work, a timeout feature was also considered in several transitions as well as a counter to be increased every time the timeout occurs in series and a count limit for pressure acquisition to be triggered, measuring the pressure in the cylinder and sending information for further analysis.

V. Integrated Monitoring System Results

A. Distributed System Set-up

The gripper set-up was connected to the existing distributed monitoring system using a CAN bus and Internet Connectivity module, sending data over the Internet to a remote database. Running the Management Application from a local PC, we were able to monitor the status of the sequence of events in real time, following the transitions firing in the Petri-net developed (Fig. 5). The application was connected to a database, sending data that was retrieved and viewed later on.

Various tests were made on gripping different sized objects, failure to grip and different air pressures, resulting in slower and faster movement of the fingers of the gripper. The timestamps sent to the database indicated the time intervals between the states of the gripper. This monitoring task has need of small time resolution, since the times between various states can be very small and in this work some were not easily detected. This can be solved with smallest time intervals acquired according to the needs of each application.

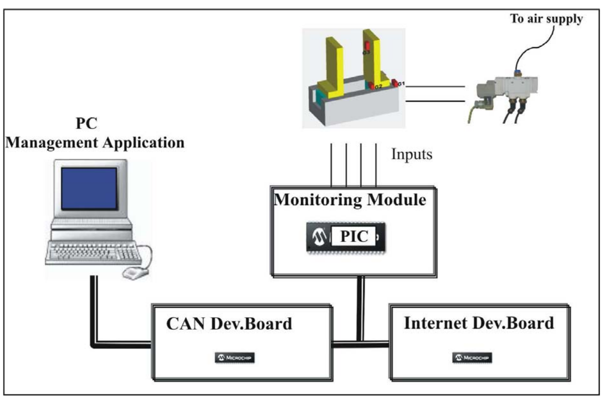

Fig. 6 Distributed monitoring system gripper Set-up

B. Results – Discussion

The results taken from the gripper experiments meet the expectations of an intelligent low-cost monitoring system. The timing information taken from the states of the operations showed that the sequence of events can be monitored efficiently using timestamps from the various events taking place in the process.

Clearly, there is a time limit that the operation exceeds when an object is not successfully gripped. Considering this, by monitoring the times between these events, the monitoring system can detect that the operation is heading towards a failure, identify a fault and issue an alarm or log the data of an abnormal cycle. However, other faults in the system can cause different behaviour of the operation cycle and alter the timings of the cycle, like a lower pressure in the gripper which causes a delay in the opening and closing of the jaws. This anomaly doesn't result in an operation failure, but it should attract the attention of the monitoring system for further monitoring and analysis, without disrupting the process.

In Fig. 7 the two cases of a successful gripping action and a failure to grip are shown along with a case where the operation is successful but exceeds the time limit that has been set, compared with the rest normal operations. The level of intelligence, however, given to this monitoring system is such that it can recognize the success of the operation, confirmed from the sensors placed in the gripper. Thus, during and after this abnormal cycle, the operation will be continued normally but the abnormality will be recorded and compared with the following cycles for further monitoring activity.

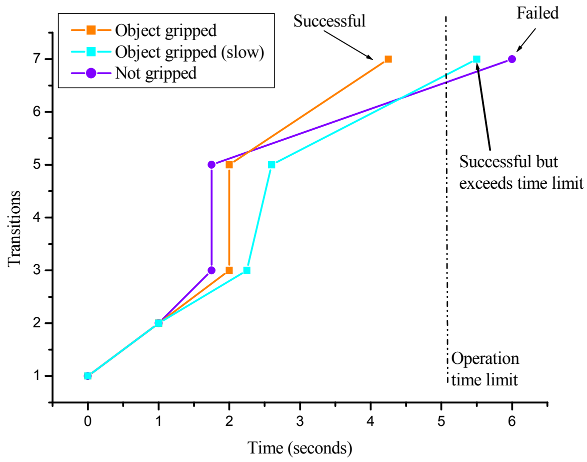

Fig. 7 Different timing results in a gripping operation

The results show the efficiency of the monitoring system proposed in this work. The intelligence proposed can identify and diagnose faults successfully and solve many problems in automated processes like unnecessary system shutdowns and guide preventive maintenance and managerial activities.

VI. Conclusions

This paper focuses on the development of an intelligent and low-cost monitoring system for simple robotic systems and moreover of the gripper part of the system. The way forward in this kind of operations monitoring is advancing the intelligence of the monitoring system itself and at the same time is keeping the cost low, mainly with the use of microcontrollers and low-cost industrial sensors

The key areas of consideration were the development of a microcontroller based primary monitoring system, the development of Petri-net models describing the sequence of events and thus giving a direction for fault detection and identification. Also, the implementation of Petri-net models into the microcontroller program memory and the successful incorporation of the pneumatic gripper system with the existing IPMM distributed monitoring system.

Summarizing the conclusions coming out of this work, the PIC microcontrollers represent a reliable and flexible alternative for intelligent and low-cost monitoring systems with low-power consumption and less installation requirements, while the Petri-net modelling approach represents a very good monitoring solution and especially for the microcontroller implementation, easing the monitoring task and reducing development time. Furthermore, Petri-nets can be used for more complicated monitoring tasks and the use of advanced features researched by the IPMM research group can give useful capabilities to the system like triggering the acquisition of analogue signals, such as a pressure measurement, and using astutely the time intervals between the events. The distributed concept allows the monitoring of more complicated operations however many they are, and enabling further off-line analysis of the data for fault trend diagnosis and management purposes.

It was shown that the use of Petri-nets implemented in the microcontroller memory was a far more intelligent and accurate solution, while fulfilling the requirements of a low-cost monitoring system. The PIC microcontrollers can corporate very well with CAN-bus protocol forming distributed monitoring nodes transmitting messages and communicating through the internet through the Internet Connectivity Module.

The functionality of this kind of monitoring solution was justified and its capabilities were shown and proved, considering the increasing call for operations in modern industries that operate either without failures or with the early detection of failures when they occur, especially for machines that require repeatability and efficiency, in order to achieve minimum downtime and higher levels of productivity.

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