A Human-In-The-Loop Self-Adaptive Digital Twin Framework for Smart Manufacturing Using Arduino-Based IOT System

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***Abstract*—This article explains how to use Arduino product-based systems to build self-adaptive digital twins (simulations) in order to make smart manufacturing decisions by having the human operator (me) be the ultimate decision maker based on real-time data collected from equipment (like motors). The motor equipment will get created from real-time data collected from them through various collecting devices including thermistors, potentiometers and push button switches (which also allows me to make a change or modification to the control system without having to leave my desk). The control system (which consists of controlling physical processes) is done through using a motor driver that creates fault tolerance and redundancy with the automation process (like using automation only to control a process). To assist me in determining when a piece of equipment is malfunctions (like a motor is not operating as expected) an LED (lights up when there is a problem with motor) will be mounted on the motor equipment to show its current state of operation. This proposed model will be effective for both small manufacturers and educational institutions because of its low cost and ease of implementation. Future enhancements to this model will include adding remote monitoring and control capabilities via wireless communication using Bluetooth through an ESP32 board (which will allow me to communicate between my Arduino devices as well as with an Internet of Things device).**

I. INTRODUCTION

Modern industries are changing quickly due to advancements in Smart Manufacturing and Industrial Internet of Things technologies. The conventional way that manufacturers run their operations includes using a fixed-control logic-based system with a scheduled maintenance plan. This setup can create inefficiency, failures, and ultimately lead to excessive operational costs. New technologies like the Digital Twin have developed as a solution to address these issues. Digital twins utilize sensor-based real-time information to provide virtual replicas of an existing physical system that continuously updates itself and allows for monitoring, analysis and optimization of a physical system's performance. system multiple times unsuccessfully over a short amount of time or during non-standard for that individual time periods, could be considered to be engaged in a potential attack. Unfortunately, various solutions that exist today either require additional hardware, require a large degree of infrastructure complexity, or create an excessive number of alerts that in-turn limit the practical application of the solution.

In smart manufacturing, using digital twins gives manufacturers access to real-time insights into their machines, enables predictive maintenance, and provides a solution for adaptive control of machines. However, today's digital twin systems are still too complicated and expensive for small manufacturers, educators, and beginners and require advanced computational resources, which are often difficult to access. Additionally, changes made to systems often do not consider the human aspect of decision-making in the event of an abnormal condition or failure of the system. To address these issues, this project will develop a human-in-the-loop self-adaptive digital twin framework using an affordable embedded system based on Arduino Uno. The human-in-the-loop methodology employs both manual control and automated functions, allowing users to modify the operation of the digital twin in real-time. Therefore, the digital twin should be more reliable, flexible and safe than a fully automated system.

The following system provides a simplified, low-cost digital twin of a motor-driven machine. Sensors (thermistor and potentiometer, for example) capture real-time system parameter data (load and temperature) from the motor-driven process. The push-button allows the user to provide manual input to control or override the system. The microcontroller processes the data from the sensors, and controls the DC motor through the motor driver module. There is also an LED indicator that provides input into whether there are system faults or abnormalities so that the user is alerted to problems.

This example shows that a true digital twin implementation can be achieved through a simple, low-cost approach without requiring expensive infrastructure. The system combines data from sensors, user interaction and control logic to consistently self-adjust as if it were operating as a true digital twin system. In addition to these characteristics, this system is scalable and provides for integration of IoT using modules such as the ESP32, allowing the user to remotely monitor and control their system using cloud or mobile applications.

The example of a low-cost research project described here is intended to show an example of how to create and utilize digital twins in relation to making decisions by humans. An important product of this research will be a prototype of a low-cost digital twin. This project will also demonstrate how to create automated processes that utilize embedded systems and work in conjunction with human decision making to produce adaptive and intelligent adaptive manufacturing solutions.

II. PROBLEM STATEMENT

Automation and data-driven decision-making are also becoming more popular in new industrial engineering / manufacturing set-ups. Most of the current industrial/manufacturing operations (especially those in small industries) and educational settings, utilize some type of very simple control systems (with no real-time monitoring, adaptability or intelligent feedback). As a result, there is often no way of continuously checking (analyzing) the actual condition of machines and equipment since almost all of the basic control systems are designed based on predetermined logic. This causes many issues when machines operate in an abnormal or over-capacity state and cause significant failures of a machine or an entire manufacturing/production system, or to damage equipment such as engines and process systems.

One of the primary disadvantages is the lack of access to a suitable Digital Twin model due to an overall absence of cost-effective Digital Twins & Industry 4.0 solutions for lower-cost environments. Large-scale industries have created advanced Digital Twin technology that is used for predictive maintenance and other forms of optimization. Large-scale digital twins require significant computational power, highly-sophisticated sensors, and significant cloud-based technology, all of which are not affordable for small-scale industries, student projects, and other low-cost applications. This creates a significant disparity between the solutions created by larger-scale industrial players and the 'real-world' examples of demonstrating the foundational concept of Digital Twin technology.

Moreover, many automated systems do not have a human-in-the-loop (HITL) component. This component is essential for safe and flexible operation of automated systems. In fully automated systems, the system does not work properly in response to an unexpected event because the system is programmed to react to the logic contained in the programming. In actual, operational manufacturing facilities, operators play a critical role in making decisions, especially with regard to the occurrence of faults and/or uncertainties. Without having a means in which to allow for HITL inputs, the system will become inflexible and/or unreliable.

A further challenge is that sensing, monitoring, and actuation function independently from each other. Even in the simplest systems where sensors have collected data, no systematic approach typically exists to use that collected data for adaptive control. For example, a simple motor may continue to run at temperatures above acceptable limits or when a significant change in the load may occur. As a result, potential damage risks increase and operation becomes less-efficient.

Additionally, there is also a need for a system to be designed with simplicity of design, ease of use, and cost efficiency while providing key aspects of real-time monitoring, feedback control, and system adaptability. In most cases, current solutions employ complicated hardware configurations and require an advanced level of scripting complexity, which are often difficult to understand or implement for beginners.

The solution requires a pragmatic and affordable framework that provides for:

- Continuous monitoring of various system parameters (e.g., temperature, loading etc.)
- Continuous adaption of control based on real-time data
- Allowance for human interaction to make better decisions
- A basic implementation of the digital twin concept
- Easy deployment of common components (e.g., Arduino Uno)

The objective of this project is to develop a HTL (High Temperature Low Volume Flow) self-adaptive digital twin system on an embedded platform which will address the aforementioned issues. The HTL self-adaptive digital twin would respond in an adaptive manner to changing environmental conditions using typical input/output devices and control techniques (e.g., logic functions) providing the user the ability to create a basis for understanding smart manufacturing technologies.

III. SYSTEM ARCHITECTURE

The proposed architecture for a digital twin's simple implementation of a motor involvement (including any process) allows for real-time monitoring of that motor's actions; this utilizes an embedded platform hardware configuration that encompasses sensing, processing, control and humans interacting with the processing system.

3.1 Overview

The entire digital twin architecture can be broken down into two major components as described below.

Real System (Physical Layer) -

- DC Motor (represents machine/process)
- Sensors (e.g. Thermistor, Potentiometer)
- Displaying the User Inputs (e.g. Push Button)
- Displaying the User Outputs (E.g. LED output to indicate status/fault, etc)

Digital Twin Core (Control Layer) -

- Arduino Uno
- L293D Motor Driver Shield (to control assistive devices)
- Continuously collecting and processing information from the Physical Layer (Real System) and sending back control signals to cause actions on the Real System (this emulates what digital twins do).

System Components and their Functions:

3.2 System Components and Their Functions:

Microcontroller:

The microcontroller for this project is an Arduino Uno. It will be the central processing unit for the entire system. It will receive information from the other programmed sensors, and then retranslate all the information it receives and send the information back out from the system in an output signal. The Arduino Uno will also run control algorithms/programs to confirm outputs to the motor and LED (function).

Input Devices:

Thermistor - The thermistor is the input sensor that measures the temperature inside the system. It produces an analogue signal that is sent back to the microcontroller, with which the microcontroller compares to an internal reference point to identify when over temperature conditions are present.

Potentiometer - The potentiometer is the input device that is used to measure the amount of load placed on the system (i.e. the speed setting). By using a variable voltage signal from a potentiometer, the speed of the motor can be changed in real-time.Components of a System and Their Function:

The system consists of four basic components, each performing one of four basic functions.

The Microcontroller (Arduino Uno).

The microcontroller is the central processing unit of this system. The microcontroller will receive information from other programmed sensors for processing and retranslate that information back out of the system through an output signal. The Arduino Uno will also run any control algorithms/programs that will be used to confirm that the motor and the LED have been activated.

Input Devices

Thermistor - The thermistor is the input device that measures the temperature inside the enclosure. The thermistor provides an analogue signal back to the microcontroller, which the microcontroller uses to compare to an internal reference point in order to determine if there are any over-temperature conditions present.

Potentiometer - The potentiometer is the input device used to measure load on the system (i.e. speed setting). By using a potentiometer to provide a variable voltage signal to the microcontroller, the microcontroller can adjust the speed of the motor in real-time.

3.3 Data Flow

• Sensors (i.e., thermistor, potentiometer) collect data in real time.
• Data is sent to the Arduino for processing.
• System evaluates whether conditions are normal or faulty.
• Control signals are sent to the motor driver.
• The motor is run according to these control signals.
• The LED shows the status of the system.
• Push button input can allow for human intervention at any point.

3.4 Working Principle

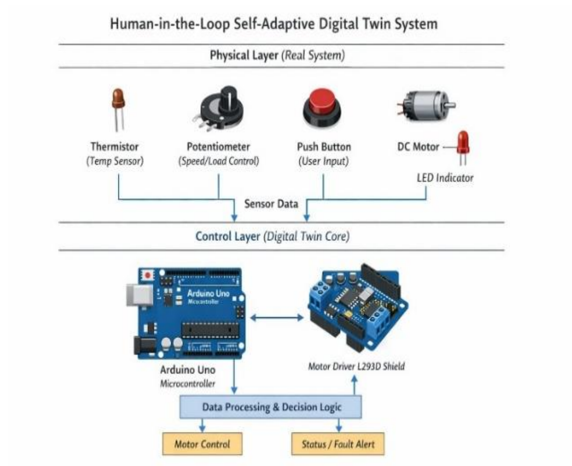
The system will constantly monitor both environmental and operational parameters of the system. Using the data from the sensors mentioned above, the system can modify the operation of the motor, which may include turning the motor ON or OFF, as well as adjusting the speed of the motor. When abnormal conditions are detected (for example, a high environmental temperature), a fault will be identified and the system will change the way it operates. Because it can use an HMI (human-machine interface), the user has the ability to intervene manually (this is often necessary).

3.5 System Characteristics

- Real-time observation and assessment.
- Adaptable control from the responding to sensors.
- Merging human decision-making into the process.
- Affordable and simple to implement.
- Expandable for applications based on IoT.

Conclusion To Architecture

This architecture illustrates clearly how a basic embedded system can represent a digital twin. By bringing together sensing, processing, controlling, and interacting with people, this system forms the basis of a practical approach for smart manufacturing.



IV. METHODOLOGY

The methodology includes implementing a digital twin system using a human-in-the-loop approach in the digital twin system using an embedded platform. The methodology includes: sensing and processing data through controlled logic and interactions with users that simulate ongoing adaptive capabilities.

4.1. System Configuration

The configuration of hardware is based on use of an Arduino Uno together with an L293D motor driver, with a motor (DC) (M1) connecting to the motor connections through to the motor terminals which is connected using both analog terminals for input to sensors, a thermo and pot); a connection to both buttons (push button) and LEDs (are connected to) through two additional digital connections. External battery power to supply the motor through the driver will also be used to provide an additional source for the driver motor.

4.2 Gathering of Data

- The automatic data gathering system continuously gathers real-time data from the input devices:
- Thermistor: Temperature changes are detected and the output from the thermistor is produced in an analog format
- Potentiometer: Motor speed or load conditions are identified by the output produced from the potentiometer
- Push Button: Input supplied from the user to operate any function on a manual basis

- The Arduino will take input data from each input device via its digital and analog pins at specified time intervals.

4.3 Data Being Processed

- The data that is processed from the data that was received will be processed according to the logic of the embedded programming.
- The thermistor temperature value will be converted to a temperature reading
- The potentiometer value will be converted to a value for use determining how much output speed the motor should have
- A manual override operation will be identified by checking for an active button press

A system state will be determined based upon the set thresholds (normal or fault).

4.4 Problem Solving (Adaptive Logic)

- The system makes decisions based on sensor readings:
- When the temperature is too hot, the system recognizes there is a problem.
- The motor will have different speeds through the potentiometer as the potentiometer reading changes.
- Pressing the push button will make the motor stop/restart and/or the motor turn at a higher/lower speed than automatic operation.
- Adaptive logic allows the system to work in real-time similar to a digital twin by reacting to external influences on a regular basis.

4.5 Disruption

- Using both decision and processed data to control the operation of the motor driver board, the system communicates the result of the decision-making process through:
- turning either ON/OFF the DC motor or through speed variations to control the DC motor
- visually indicating if there is a problem or what is happening with the system by illuminating the LEDs

The disruptive process will continue to adjust the physical system based on input conditions as they change.

4.6 Perceptual System

- The button gives the operator a way to interact with the system (the actions of the operator include):
- Manually starting/stopping the motors.
- Overriding automatic control when there are faults.
- Simulating actual human operator's decisions.
- This capability of the perceptual system enhances the reliability and flexibility of the system by integrating automatic and human control.

4.7 Looping (Embedded) Process

- The entire process runs in a continuous loop:
- Read (Sensor) Inputs
- Process Input
- Use Decision Logic
- Control Output
- Update System Status
- The continuous loop provides real-time monitoring and synchronization between the "actual" and "imagined" systems.

4.8 Summary of Method

The method integrates sensing, processing, control, and human interaction to produce a simple digital twin system. In addition, this shows a method of controlling a physical process using real-time data to adjust the process mechanics. As a result, this system is applicable to the industry 4.0 and internet of things (IoT) applications.

V. RESULT ANAYSIS

5.1. Result Analusis

- The implementation of the proposed system was completed using an Arduino Uno and an L293D motor driver shield and basic sensor devices. The objective of this task was to demonstrate a simplified Digital Twin with a human-in-the-loop control for a motor driven process.

5.2. Results of Experiments

- After assembling the hardware and uploading the program, the results obtained were:
- The DC motor was able to turn ON/OFF in response to a press of the push button input.
- The potentiometer was able to control the speed of the motor resulting in a smooth change in rotation.

- The thermistor was able to detect temperature changes and provided adequate response to the exceeding of a predetermined threshold.
- The LED indicator turned ON during abnormal conditions (excess temperature) allowing for the identification of the situation visually.
- The system was able to continuously monitor all 3 inputs and update all outputs in real-time.

These results show that the system has the abilityto effectively perform the basic functions of sensing, decision making and actuation.

5.3 Digital Twin Representation

- The system mimics the fundamentals of a Digital Twin and what Digital Twins do through a simplified model, consisting of:
- Collecting sensor data on an ongoing basis (real time) to obtain system operational data
- Processing the data in order to establish current conditions of the system
- Making an adjustment to the physical system based on the data from sensors
- Providing output back to the input source via visual indicators

The relationship of the input data to the response of the system demonstrates the basic principles of a digital twin.

5.4 Benefits Realized

- Low cost, easy to implement
- Real time monitoring and response
- Simple hardware implementation for beginners
- Human In the Loop Capability
- Expandability for IoT (Internet of Things) applications

5.5 Limitations

- Basic sensors limit accuracy.
- No Cloud Based Digital Twin Visualization
- Small scale operation of the system

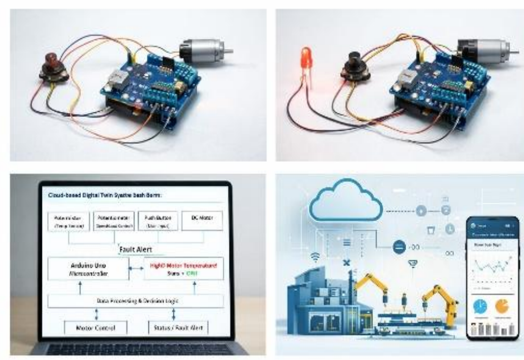
Manual threshold settings versus intelligent prediction of values.

5.6 Discussion

- The findings illustrate that it is feasible, even with essential components, to create a basic structure of a digital twin. Adding human-in-the-loop capabilities increases flexibility and enhances reliability in comparison to fully automated configurations.
- Although the developed system does not currently leverage sophisticated applications such as machine learning or cloud composition, it provides a fundamental base from which to explore smart manufacturing principles. The addition of IoT devices such as the ESP32 module would enhance the current implementation by providing options to monitor remotely, as well as engage remotely in real-time.

Conclusion of Results

The proposed system meets its goal of providing a low-cost, flexible, interactive digital twin design and demonstrates the potential of using minimum resources to implement smart manufacturing principles from the ground up. Furthermore, it stresses the value of integrating automation with some level of human involvement.



VI. APPLICATION

- The proposed human-in-the-loop self-adaptive digital twin system can be used in many different ways; for example, there is an opportunity to develop real-time monitoring, control, and user interaction via the digital twin platform.

1. Small-Scale Manufacturing Monitoring & Control. For example, the use of instruments and devices such as Arduino Unos would allow for accurate monitoring and/or controlling of any number of industrial machines/parameters (e.g., temperature and load) and thus provide better safety and operational effectiveness.

2. Predictive Maintenance - The predictive maintenance model allows the identification of several different early warning signs of a potential failure of your system while providing real-time monitoring to prevent catastrophic failures and assisting in planning for preventative maintenance.

3. Teaching Industrial Automation Concepts - The purpose of the project is to deliver training and educational materials covering many of the critical concepts associated with automated manufacturing, as well as integration of sensor technology and automation in a manufacturing environment, while providing students with hands-on experience through the use of embedded systems and digital twins.

4. Human They need to know how to use pub buttons within the human part of the system so the database can work on systems that need to have a human in the process. An example of such systems would be safety critical applications and those systems that would require an emergency override.

5. Future Expansion of IOT Monitoring - As we begin to develop further designs (i.e., just like the modules currently being developed are modular, but also support wireless technologies like the ESP32), it is possible that new designs will allow remote monitoring/controlling of embedded devices using either a mobile platform or via the Cloud.

6. Researching and Simulating This web site is a portal for users to start building more sophisticated research projects around smart manufacturing, digital twins and adaptive control systems.

7. Small Scale Industrial Applications The web site can be used by small-scale industries or shops that require low-cost monitoring and control systems is provided without requiring sophisticated infrastructures.

Conclusion of Applications

The web site has numerous potential applications and is only the beginning for developing more advanced smart manufacturing, IoT-enabled industrial applications, and human interaction with the system.

VII. ADVANTAGES AND DISADVANTAGES

7.1 Advantages

- Quick Construction, Low Investment

It is possible to fabricate a prototype quickly and inexpensively from basic materials such as an Arduino Uno. This makes this type of prototype very suitable for students or a small group of people who can prototype quickly in a tentative manner.

- Constant Monitoring

This particular prototype can continuously read temperature and load from a potentiometer, and will respond to a user input that requests a change (e.g. an increase in temperature) in almost real time.

- Adaptive Control

Adaptive control makes it possible for data from the sensor to be used to change how the motor operates (for example slowing or stopping a motor once it reaches a maximum operating temperature), allowing for a safe, effective and efficient way to operate.

- Manual Push Button Control

By adding a simple manual push-button control, you provide an extra level of reliability and safety in case of failure elsewhere in the controls system.

- Modular Design, Future Proof Technology

This prototype is modular and can be easily designed to incorporate of the Internet of Things (IoT) devices for remote monitoring and control.

- Motor Driver Shield Protects Motor

The motor driver shields protect your microcontroller if it drives a motor, because it provides electrical isolation from the power supply for the motor.

- Educational Value

This prototype demonstrates many of the educational concepts like sensors, digital twins and automated electronic control using very basic electronics as a demonstration of the principles of these educational concepts.

7.2 Limitations

- Limited Accuracy

Basic sensors (thermistor, potentiometer) provide approximate readings; they are not suitable for industrial applications requiring precise measurement information.

- No Cloud/Visualization Layer

The system does not provide a complete digital dashboard; there is no cloud counterpart that allows visualization of the Digital Twin.

- Manual Thresholds

The system utilizes fixed values or limits (such as a temperature threshold) to make decisions rather than relying on intelligent, predictive technology.

- Single Motor Prototype

The prototype demonstrates the concept of using the system for one motor; a complete manufacturer system utilizing the hardware presented is not demonstrated.

- Hard-Wired Technologies

The base system cannot communicate wirelessly with the cloud and must use wired connections; an additional component (an ESP32) must be used for wireless connectivity.

- Basic Control Logic

The system does not include any advanced processing capabilities, such as predictive algorithms, using machine learning or artificial intelligence.

- Power Consumption Issues

Power for the motor must be supplied separately (from a battery) and be grounded properly; the device is not built to support high load applications.
To sum it up, the System has an easy-to-use and inexpensive way to inform users about smart manufacturing, as well as digital twin technologies while providing areas of missing functionality or capabilities that are not likely to be improved upon by any upcoming updates or enhancements (that will be third-party installations or integrators and/or from the ability of other IoT/GPS application(s) or the ability to have real time/fulcrum of information via the Cloud and Look and Calculate Tools have more robust functionality).

XIII. FUTURE SCOPE

Suggestions for Future Applications
Although the current suggestion gives an example of a Digital Twin Framework, many other improvements can be made to the current design to meet the requirements of the Smart Manufacturing industry. Some of these future enhancements include:

1. IoT Connections
Connecting wireless communication using devices such as ESP32s to the existing Digital Twin would provide:
Remote access to mobile devices for monitoring
Remote access to the Cloud for storing collected information/data Real-time alert/notification function

2. Fully Cloud Based Digital Twin
Creating a web portal to allow the user to view the Digital Twin from their browser where they can see the Digital Twin and all its components and how they integrate with each other through graphical representation or other indicators would allow for the control/monitoring of the Digital Twin and help with the necessary analytics needed to provide value/benefit from the Digital Twin.

3.Artificial Intelligence Using Predictive Maintenance - By utilizing advanced predictive algorithms you have the ability to predict issues before they arise; monitor ambient crack lots with temperature and loading trend analysis; use machine learning to optimize system performance and reduce downtime.

4.Multi-Machine Monitoring - An additional extension of the current application would include the ability to concurrently monitor multiple machines/motors, industrial production lines, and/or distributed systems in a smart factory environment.

5.Advanced Sensors Integration - In lieu of conventional sensors, use state-of-the-art sensors such as precision thermocouples for temperature measurement, accelerometers for vibration detection; and current transducers for load measurement, etc.

6.Mobile Application Development - Develop a mobile application exclusively for the purpose of controlling your system via WiFi or cellular network; sending notifications to the user; allowing users to visualise real-time data from their controller.

7. Improved Automation
Automated systems can be enhanced in their operation by devising systems that give them the capability to be "smarter" such as: automating system failure shutdowns, implementing Adaptive Control Strategies,

and reducing reliance on human actions in the operation of equipment and other systems.

8. Optimized Hardware

- Controllers will be developed and subsequently used as replacement controllers/alternative controllers for systems presently using hardware such as: Arduino Uno plus Internet of Things (IoT) devices, and industrial-grade controllers intended for real-world manufacturing.

- Final Thoughts and Future Directions

This type of system forms the foundation for advanced smart manufacturing systems. By using IoT, cloud-based computing, and smart algorithms, businesses can translate these systems into fully functioning digital twins that may be helpful to manufacturers within industrial environments.

IX. CONCLUSION

This paper describes the development of a Human-in-the-loop Self-adaptive Digital Twin Framework for Smart Manufacturing. An embedded system developed using Arduino Uno was used as the basis for creating the Digital Twin model and demonstrating its capabilities for realtime monitoring and control of a physical system (DC motor setup) via input data from sensors (temperature and load), as well as by interacting manually with the user.

Integration of sensor inputs, data processing, and actuation provided a simple means of creating a digital representation of the system. Because manual intervention can be utilized in cases of abnormal operation, the Human-in-the-loop component of this model increases reliability and flexibility. The results indicate that it allows for real-time adjustment to both environmental and operational parameters; thus, improving safety and efficiency.

In addition to being an elementary specimen of the digital twin concept, the test system supports the original idea of developing and implementing the digital twin concept in a cost-effective manner. Also, the test project provides a solid groundwork for the future development of Internet of Things (IoT) based monitoring, predictive maintenance, and smart manufacturing systems. The potential for further development using technologies such as ESP32 could enable remote control, cloud-computing technologies and/or the ability to intelligently analyse information.

In summary, the developed system provides a means of connecting the theoretical principles of digital twins to their practical application, thus representing an excellent resource for educational purposes, research and small-scale industrial production.

X. SUMMARY

Project Overview

The goal of this project is to develop a cost-effective digital twin framework for the purpose of digitally creating an adaptive human in the loop (HITL) self-adaptive digital twin framework to be applied to smart manufacturing. The solution uses an Arduino Uno with motor driver shield for controlling a direct current (DC) motor, reading and monitoring real-time data from the DC motor and making adjustments based on the real-time data, to control the DC motor while simultaneously monitoring the DC motors' temperature, load, etc.

The sensors used to collect the input data to the microcontroller are temperature thermistor and load potentiometer type of sensors that the microcontroller then processes for motor control. In addition, the microcontroller also communicates with the user through manual control of the motor via drawings on the board. The microprocessor continually modifies the operations of the DC motor in correspondence to the input data, by means of fault indication through an LED, to simulate a Digital Twin – where the physical system and the physical systems' control logic are continuously synchronized.

This project illustrates three key aspects of real-time monitoring, adaptive control, and human-in-the-loop interaction with embedded systems. This low-cost, easy-to-build, educational or small-scale project has the ability to offer significant additional capabilities by leveraging IoT technologies for remote monitoring and control. Therefore, it provides an excellent platform for developing future smart manufacturing applications.

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