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Cyber-Physical Manufacturing Metrology Model (CPM^3) for Sculptured Surfaces – Turbine Blade Application

Vidosav Majstorovic[a,]*, Slavenko Stojadinovic[a], Srdjan Zivkovic[b], Dragan Djurdjanovic[c], Zivana Jakovljevic[a], Nemanja Gligorijevic[a]

[a]*University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia*
[b]*Military Technical Institute, Coordinate Metrology Lab, Belgrade, Serbia*
[c]*Department of Mechanical Engineering, University of Texas, Austin, TX, USA*

* *Corresponding author. Tel.: + 381 11 33 02 47 ; fax:+381 11 33 02 346.E-mail address: vidosav.majstorovic@sbb.rs*

Abstract

Cyber-Physical Manufacturing (CPM) and digital manufacturing represent the key elements for implementation of Industry 4.0 framework. Worldwide, Industry 4.0 becomes national research strategy in the field of engineering for the following ten years. The International Conference USA-EU-Far East-Serbia Manufacturing Summit was held from 31st May to 2nd June 2016 in Belgrade, Serbia. The result of the conference was the development of Industry 4.0 Model for Serbia as a framework for New Industrial Policy – Horizon 2020/2030.

Implementation of CPM in manufacturing systems generates "smart factory". Products, resources, and processes within smart factory are realized and controlled through CPM model. This leads to significant advantages with respect to high product/process quality, real-time applications, savings in resources consumption, as well as, lower costs in comparison with classical manufacturing systems. Smart factory is designed in accordance with sustainable and service-oriented best business practices/models. It is based on optimization, flexibility, self-adaptability and learning, fault tolerance, and risk management. Complete manufacturing digitalization and digital factory are the key elements of Industry 4.0 Program.

In collaborative research, which we carry out in the field of quality control and manufacturing metrology at University of Belgrade, Faculty of Mechanical Engineering in Serbia and at Department of Mechanical Engineering, University of Texas, Austin in USA, three research areas are defined: (a) Digital manufacturing – towards Cloud Manufacturing Systems (as a basis for CPS), in which quality and metrology represent integral parts of process optimization based on Taguchi model, and (б) Cyber-Physical Quality Model (CPQM) – our approach, in which we have developed and tested intelligent model for prismatic parts inspection planning on CMM (Coordinate Measuring Machine). The third research area directs our efforts to the development of framework for Cyber-Physical Manufacturing Metrology Model (CPM^3). CPM^3 framework will be based on integration of digital product metrology information through metrology features recognition, and generation of global/local inspection plan for free-form surfaces; we will illustrate our approach using turbine blade example. This paper will present recent results of our research on CPM^3.

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Keywords: CPM, Modeling, Simulation, Metrology

1. Introduction

Nowadays, one of the most significant achievements in the development and application of information and communication technologies (ICT) in industrial practice, are cyber-physical systems (CPS) [1,9]. The integration of real and virtual world using Internet environment, for the industrial area are implemented as cyber-physical manufacturing (CPM). The combined development of ICT and manufacturing technology leads to the industrial revolution, simply called Industry 4.0.

Cloud computing and Internet of Things, although different concepts [2], constitute the basic structure of ICT for CPM, thus giving a new paradigm; they are a platform for the implementation and development of the CPM in practice. However, today we face the IoT [6], as well as partial solutions for different areas of service. Research related to IoT in CPM is at the beginning, and our experiment in this paper is a contribution to this area. 3D modeling, PLM systems and

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technical documentation in the CPM model are important elements [8]. This segment should be considered also within the concept of product life cycle, a special approach to traceability of the manufacturing process and quality control, which is important for the development of our CPM^3 concept.

IoT are changing the world, and therefore the application of ICT in manufacturing, through CPM model [3]. Multilevel operability of data transfer and management of these processes, from one entity to the complex systems in a chain, make IoT the key element for the success of the CPM implementation. These models use / generate huge databases, so that Cloud computing becomes indispensable tool to support the CPM.

IoT as a paradigm based on the Internet, utilizes the benefits of interrelated technologies such as RFID (Radio Frequency Identification) and WSAN (Wireless Sensor and Actor Networks) for the exchange of information [5] in the CPM hardware structure. CPM has an extremely expressed requirement for better control, monitoring and data management. Limitations still exist in storages, networks and computers, as well as the requirements for complex analysis, scalability and data availability. In addition, intensive communication between CPM elements usually using wireless technologies raises the issues of data privacy and security. Cloud platform for CPM is a new area of research, and this paper is a contribution to manufacturing metrology area.

IoT for CPM can be defined as a future in which machines work 24 hours, and the people and systems are connected through the Internet, managing services and processes related to the production. The current reality is digital factory and digital production; a near future is the smart factory-of-things. Starting points are integration between IoT and PLM platforms using semantic web technologies and Open Services for Lifecycle Collaboration (OSLC) standard on tool interoperability [11].

Service-oriented manufacturing (SOM) [4], represents the new paradigm of world production, and CPM are an ideal solution for the further development of this concept. As previously stated, one of the key problems is the quality of data: their origin, generation, transmission and usage. For solving these problems, it will be used formal semantics of workflow nets (WF-nets) based on process-oriented ontology, with the necessary optimization of these processes.

In the context of CPM, it is extremely important to create consistent data exchange, mainly through open and global information networks, with two-way flow of information [10]. Special Research Area is the knowledge bases within the CPM concept. Our model explores this area through intelligent inspections planning for CMM as a framework for the CPM^3 knowledge base, based on the ontology concept.

Program Industry 4.0 makes the IoT and CPM integration, creating a new framework for increased productivity, flexibility and quality of industrial production [7]. It also contributes to the improvement of all supply chains for industrial production. All these approaches allow further improvement of eco-system at all levels, creating the concept of sustainable competent production, as well as intelligent, connected and decentralized factory [12].

Our research in this study supports this concept through the integration of CMM with CPM.

2. Cyber-Physical Manufacturing Metrology Model

The framework of our CPM^3 model is presented in Fig. 1. It consists of the following sub-modules: (a) Module for recognition of geometrical features (GF) from CAD/GD&T model of the measurement part, (b) Intelligent inspection process planning (IIPP) module, that contains methods for prismatic parts presented in [15], and method for freeform surfaces from this paper, (c) Coordinate measuring machine (CMM) – generation of control data list for CMM that is transferred to CMM using cloud technology, and (d) Module for analysis of results and generation of the reports. Cloud services within the company provide the necessary information for integration of knowledge and data from various phases in product design and manufacturing into inspection planning, and make available information about inspection results to all interested parties in product lifecycle.

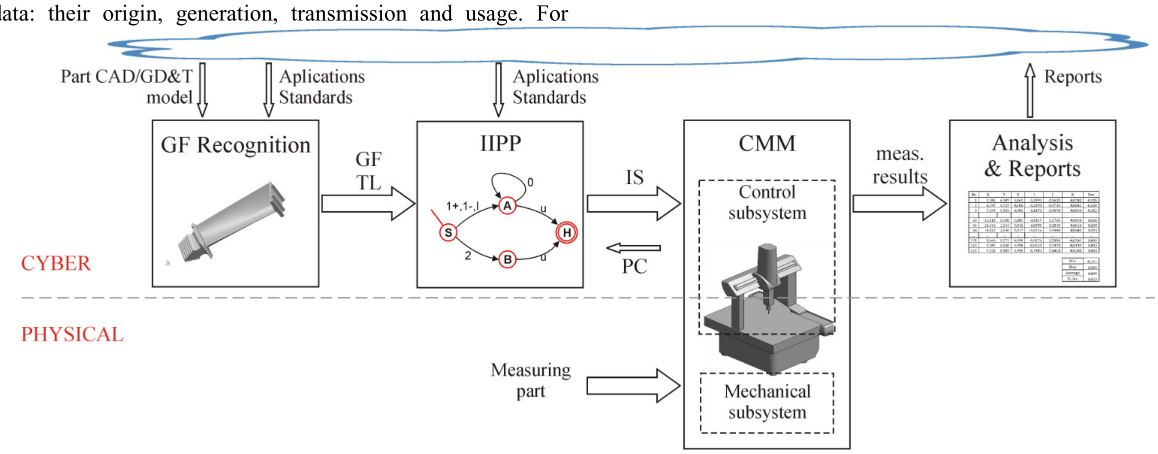

Fig. 1. Cyber-Physical Manufacturing Metrology Model

GF recognition module recognizes geometrical features from 3D model of measurement part in a neutral CAD format, such as STEP or IGES. GFs of interest depend on the type of measurement part and the applied standards. If GF recognition module does not have the application for recognition of the geometrical features for the considered measuring part in its database, the application for GF recognition needs to be provided along with the part model.

The role of IIPP module is to generate inspection sequence (IS) for probe configurations (PC) that CMM supports. It has geometrical features and tolerances (TL) at input. During inspection sequence generation, it is necessary to extract metrological features (MFs) from geometrical features.

The metrological, as well as the geometrical features, depend on the type of measuring part and the applied standards. If necessary, the application for metrological features extraction should be provided to IIPP module.

3. Inspection planning based on CPM^3 for free form surfaces

Currently available commercial software for inspection planning do not have open interface for modifications and upgrades made by user. This in particular refers to the impossibility of the inspection time reduction by measuring path optimisation and generating the collision-free path. On the other hand, the relationship between geometry (feature) and tolerances that is necessary for inspection planning process does not exist in a form of CAD output record. The only alternative is STEP-NC standard but software developers still have not managed to implement all forms of tolerance. Our approach implies the open interface for developing CPM^3.

This section presents a feature-based model for probe path planning for sculptured surfaces using an example of turbine blades. The probe path planning model represents a part of CPM^3 for free form surfaces. In this model the geometrical information for feature description is taken from CAD model of the part in IGES format. Fig. 2 presents the complete inspection plan. The plan consists of input CAD data, recognition of metrological and geometrical primitives, definition of inspection sequences, distribution of measuring points, collision avoidance principle, and measurement and analysis of the results.

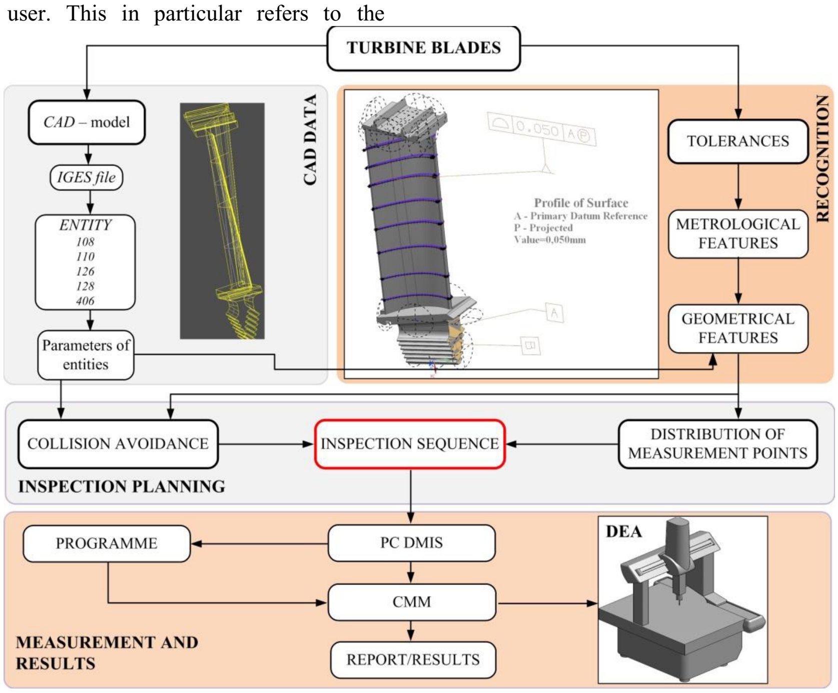

Fig. 2. Inspection planning of turbine blades

The extraction of geometrical feature parameters from IGES file is based on the recognition of its structure. An IGES file is composed of the following five sections: start section, global section, directory entry section, parameter data section, and terminate section. All geometric entities are given in the directory entry section and parameter data section. The extraction of parameters is carried out using IGES type numbers that correspond to specific geometric entities (geometrical features).

Metrological features are recognized using the tolerance of turbine blades (profile of surface) and the geometrical features parameters. They (MF) define the link between tolerance and geometrical features.

3.1 Inspection sequence generation

The inspection sequence of measuring sensor is defined as a set of points that contains two subsets. The first subset represents the measurement points obtained from geometrical features. In the case of free form surfaces, the geometrical features of interest are non-uniform B-spline (NURBS) curves. Starting from NURBS control points, knots and weights extracted from IGES file, we calculate the points on NURBS, and select the appropriate number of measurement points. The distribution of these measurement points defines the scan path for CMM. The second subset provides a collision free inspection sequence and it is obtained using a principle of collision avoidance.

Input information for inspection sequence generation is taken from IGES file, while input data regarding tolerances are obtained from already created drawing. Output is point-to-point collision free measuring inspection sequence that defines the path between measurement probe and part.

Our inspection sequence generation model transforms the complex geometry of the turbine blades to the set of points whose sequence defines the collision free measuring path of sensors taking into account the form tolerance.

3.2 Distribution of measurement points

To define the distribution of measuring points for a feature, the Cartesian coordinate system (*OXYZ*) is needed. The coordinates are denoted by $P_i(x_i, y_i, z_i)$. The distribution of measuring points is based on sampling strategy for IGES features such as line entity (type 110), rationale B-spline curve entity (type 126), rationale B-spline surface entity (type 128), and closure property entity (type 406) [16]. Fig. 3 represents ten closed NURBS curves calculated from data extracted from turbine blade IGES file.

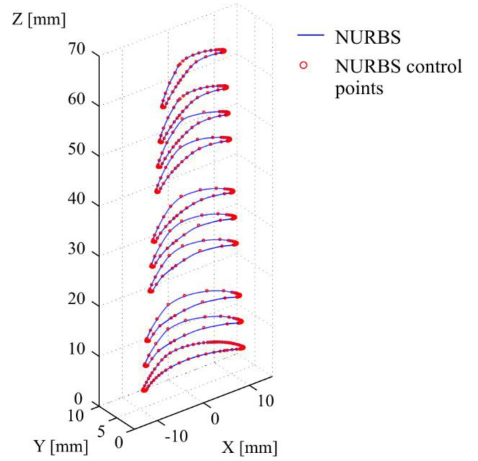

Fig. 3. Extracted NURBS curves along turbine blade

3.3 Collision avoidance

Collision avoidance principle is based on turbine blade geometry and tolerances. Using this principle, three characteristic points on each blade cross section α_i are selected, Fig. 4. These are the following points, Fig. 4: (1) starting point $P_S(\alpha_i)$, (2) medium point $P\alpha_i$, and (3) ending point $P_E(\alpha_i)$, where α_i denotes the i^{th} cross section. For the $i+1^{st}$ cross section these are the points: $P_S(\alpha_{i+1})$, $P\alpha_{i+1}$, and $P_E(\alpha_{i+1})$. The path to avoid collisions is marked red in Fig. 4, and it consists of two parts. The first part is a 2D collision avoidance path for inspection in the cross section plane. The second part of the path is necessary for crossing of the sensor from the previous cross section plane (α_i) to the next one (α_{i+1}). It is the path from $P_E(\alpha_i)$ to $P_S(\alpha_{i+1})$. The scanning path is marked green in Fig.4 and it contains the points from the first subset (subsection 3.2).

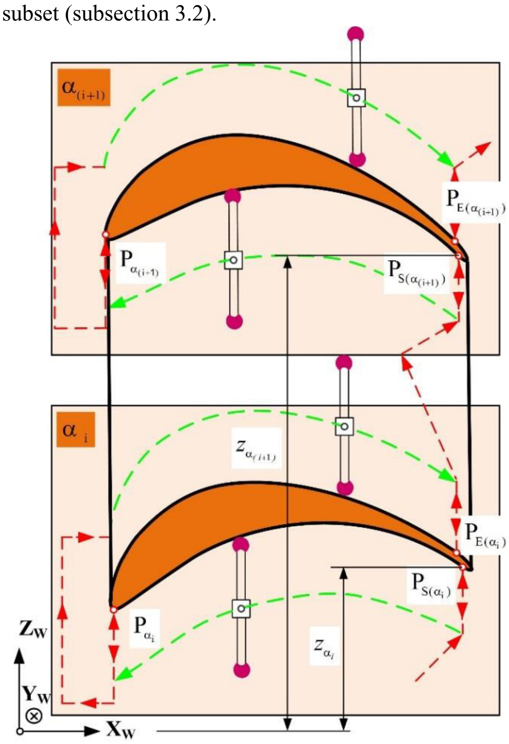

Fig. 4. The principle of collision avoidance

4. Application of CPM³ to free form surfaces

In this section we apply the presented CPM³ approach to the inspection of the free form surface of an aircraft engine turbine blade presented in Fig. 5. Considered turbine blade is manufactured using additive manufacturing technology - Selective Laser Sintering.

Fig. 5. Photos of considered turbine blade: on the left: pressure side; on the right: suction side

3D model of the part in IGES format (Fig. 6) is obtained from design department. For GF recognition module, we have developed an application for extraction of free form GFs in the form of NURBS curves. Measuring part IGES file is at the input of the application, while the points on NURBS curves are at output (Fig. 3). These are the points on closed curves

(IGES type 406) along turbine blade body. Starting from GFs, the inspection sequence is generated within IIPP module.

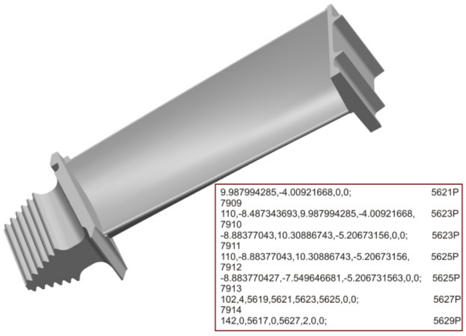

Fig.6. CAD model of the turbine blade

Following the generated inspection sequence, the measurement is performed on CMM DEA Epsilon 2304. Datum coordinate system and datum planes (3-2-1) are selected as presented in Fig. 7.

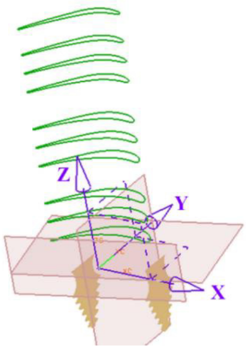

Fig. 7. Datum coordinate system (PC-DMIS coordinate metrology software).

We have carried out the measurement along all 10 curves from Fig. 3. The results of measurement along curve close to Z =5mm are presented in Fig. 8 and Table 1. Table 1 shows the measured coordinates of the first control section (*X, Y, Z*), the contact probe approach vectors (*I, J, K*) and measured coordinates deviation (*Dev*) relative to the nominal value. Positive deviations are outside, and negative deviations are below the nominal contours. At the end of the table the

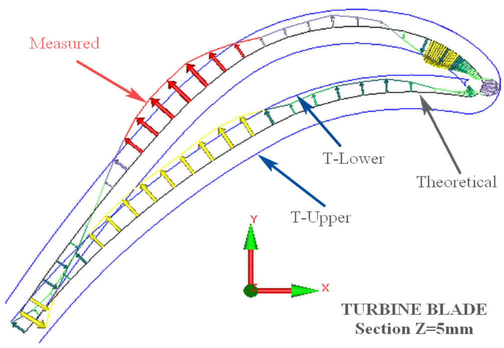

Fig.8. Measurement results for curve at Z = 5 mm

analysis is shown (*Min, Max, Average and Standard Deviation*).

Table 1. Measurement results for curve at Z = 5 mm

No	X	Y	Z	I	J	K	Dev
1	9,185	6,487	4,869	-0,2594	-0,9632	0,0702	-0,025
2	8,197	6,727	4,886	-0,2093	-0,9755	0,0681	-0,028
3	7,199	6,933	4,902	-0,1470	-0,9870	0,0654	-0,052
...	...	...	...	...	...	...	...
63	-11,018	0,430	5,001	-0,8147	0,5765	0,0630	0,166
64	-10,440	1,244	5,010	-0,8092	0,5843	0,0616	0,169
65	-9,837	2,038	5,017	-0,8016	0,5949	0,0602	0,153
...	...	...	...	...	...	...	...
121	9,646	8,271	4,998	0,8076	0,5894	-0,0201	0,006
122	9,585	8,350	4,998	0,8020	0,5970	-0,0199	0,003
123	9,554	8,387	4,998	0,7984	0,6018	-0,0200	0,001
						Min	-0,197
						Max	0,189
						Average	0,009
						StDev	0,123

5. CPM^3 application case model

Realization of the CPM^3 model in practice is being investigated for the DEA CMM, which is based on the IoT Cloud technology, Fig. 9. Connection of the physical and the virtual world is provided using an IoT device - Raspberry Pi3, which, via industrial router, has access to the Internet and realizes direct communication with the CMM control unit, using Ethernet or Wi-Fi connection.

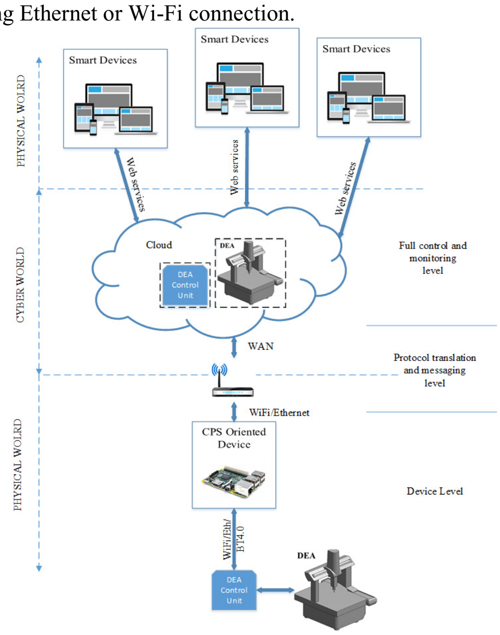

Fig. 9. Configuration of the CPM^3 model for DEA CMM

In our concept, CMM DEA is accessed remotely, from anywhere in the world via an Internet connection. Besides the division of physical and virtual part, the solution contains the following parts: (a) unit which provides management and monitoring of the entire system, (b) unit which defines protocols for communication Cloud - CMM and vice versa, and (c) unit which represents a physical implementation of the model, in other words, IoT device and CMM and their communication.

The starting point for the implementation of the CPM^3 model is approaching the CU (Control Unit) architecture and source code for which the drivers generate CMM execution codes, using the high level programming skills and knowledge of the IoT Cloud technology. In the next step, system creates virtual clones of CU and CMM DEA in the Cloud [17]. Virtual twins behave as physical devices and CMM programming can be done in the cloud, without using the physical CMM.

Using the smart devices (cell phones, tablets, notebook) user accesses the Cloud by web-browser, with a unique username and password. In this research we have opted to employ Raspberry Pi3 since it is open to easy programming of communication protocols. Using our CPM^3 method new control codes are generated and directly loaded on the CMM. For GD&T definition PMI (Product Manufacturing Information) can be utilized since it contains additional information about free-form surfaces. Cloud keeps the previously used control codes (GD&T for the previously measured parts, reports) in databases, and user can access and download it, at any time, to own device. Also, it is possible to monitor the work of CMM in real time. This is an important option, in the case of an error, since the user can stop the CMM remotely. After each measurement, report is generated and automatically sent to the Cloud where it is stored. The system sends the report to a user or a predefined group of users, via email or SMS service: start/end of measurement, various alarms, environment sensor readings and other important information.

The protocols used for communication in this concept, are very important. For example, due to poor communication of IoT devices (CMM or IoT devices) Cloud may cause packet or data loss which may result in the breakdown of the machine. For these reasons, it is necessary to provide a good and reliable Internet connection. Also, it is necessary to establish parallel protocols to check all packages and compare them with the expected / required conditions. This mode eliminates the errors, and thus avoids potential accidents due to CMM collision. Nowadays, there exists wide range of security protocols for IoT. Besides TCP/IP security protocols which are most significant and designed to fit IP network, there is a wide range of general purpose key exchange and security solutions that exists for the Internet domain. Protocols such as IKEv2/IPsec [18], DTLS [19]. EAP[20], and TLS/SSL [21] are candidates for security measures of IoT for future development of CPM^3 model.

6. Conclusions and future researches

Our research presented in this paper was concentrated on the: (a) defining CPM^3 model and its structure, (b) development of a model knowledge base for this model, for chosen example, and (c) the establishment of total hardware and software configurations. The next steps of this research are: (a) developing software structure of the virtual part of the model, and (b) testing the IoT elements for this model.

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