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An IoT based industry 4.0 architecture for integration of design and manufacturing systems.

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An IoT based Industry 4.0 Architecture for Integration of Design and Manufacturing Systems

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Abstract

This paper proposes an Internet of Things (IoT) based 5-stage Industry 4.0 architecture to integrate the design and manufacturing systems in a Cyber Physical Environment (CPE). It considers the transfer of design and manufacturing systems data through the Cloud/Web-based (CW) services and discusses an effective way to integrate them. In the 1st stage, a Radio-Frequency IDentification (RFID) technology containing Computer Aided Design (CAD) data/models of the product with the ability to design / redesign is scanned and sent to a secure Internet/Cloud Server (CS). Here the CAD models are auto identified and displayed in the Graphical User Interface (GUI) developed for the purpose. From the scanned RFID CAD data/models, the 2nd stage adopts unique machine learning technique(s) and identifies the design & manufacturing features information required for product manufacture. Once identified, the 3rd stage handles the necessary modelling changes as required to manufacture the part by verifying the suitability of process-based product design through user input from the GUI. Then, it performs a Computer Aided Process Planning (CAPP) sequence in a secure design cloud server designed using web-based scripting language. After this, the 4th stage generates Computer Aided Manufacturing (CAM) toolpaths by continuous data retrieval of design and tooling database in the web server by updating the RFID technology with all the information. The various processes involved the 3rd and 4th stages are completed by using 'Agents' (a smart program) which uses various search and find algorithms with the ability to handle the changes to the process plan as required. Finally, the 5th stage, approves the product manufacture instructions by completing the production plan with the approved sheets sent to the Computer Numerical Control (CNC) machine. In this article, the proposed architecture is explained through the concept of IoT data transfer to help industries driving towards Industry 4.0 by improving productivity, reducing lead time, protecting security and by maintaining internationals standards / regulations applied in their workplace.

Keywords: Industry 4.0; Design and Manufacturing Systems (DMS); Internet of Things (IoT); Cyber Physical Environment (CPE).

1. Introduction and Literature Review

Research from the past three decades on Information and Communications Technology (ICT) based manufacturing systems has helped to increase the productivity & efficiency in many industries by changing the traditional way of designing, manufacturing, and delivering their products [1-2]. In the present scenario, there is a desire that these technologies embrace the concept of Manufacturing the future (Mtf) or 4th industrial revolution (i.e. Industry 4.0) by interconnecting them in a Cyber Physical Environment (CPE). The Industry 4.0 concept uses Industry / Internet of Things (IIoT/IoT) facilitated by data interoperability, AGent based Systems (AGS), machine learning techniques, Digital Twins (DT's) concepts, mobile robots, and 3D printing. Integrating these whole gamut of technologies remain an open challenge and industries face real time problems at various stages of design and manufacturing such as (i) immediate digital design / redesign of products (ii) digitally replicate the process/products (iii) manufacturing process planning and decision making (iv) feature based automatic generation of toolpaths (v) intelligent setup / fixture planning and (vi) supply chains / delivery to the market as appropriate to the products. Generally, Industry 4.0 adopts the use of robots and 3D printing for a fully automated / interconnected system, whereas in case of manufacturing systems, this will be different but comprising CAD/CAM, CAPP, Computer Aided Engineering (CAE) and Computer Numerical Control (CNC) systems [1]. Robots are part of CAD/CAM/CAPP/CAE or Computer Integrated Manufacturing (CIM) environment and are present as a material handling system. Integrating all the above-mentioned systems involves enormous amount of various 'search and find' intelligent algorithms with the ability to handle the changes and the requirements faced time to time. Complex and high-quality data in the form of big data [3,4] will be handled when we try to integrate these technologies, especially CAD/CAM/CAPP/CNC and supply chain technologies. In this case, a consistent method of data gathering and storing for assessing the demands and the way it being used in a cyber physical internet-based environment is required. Intelligent encoding and smart thinking programs are needed as the data collection requires a strong ICT understanding in an internet-based environment where various manufacturing technologies including design, tooling, machines, and manufacturers information are handled. A robust data structure embedded in a database module is also needed to access the necessary data and to make changes based on the demand using a continuous iterative approach. One approach is based on adopting 'Agent' based technologies - the smart / intelligent programmes, which help when a lot of decision making regarding the data related to different technologies is involved [6-10]. It also has the ability retrieve information in an internet-based environment [3-6] and will be more advantageous while embracing the concept of an Industry 4.0. As the integration requires use of large data driven technologies like IIoT's and digital twins [5], it becomes inevitable that a clear and concise framework to handle the various modules of the manufacturing systems is needed.

Kuo et al. [1] developed an algorithm and predicted the work status of manufacturing machines in a spring industry. They adopted a 5-stage process for the collection and analysis of the data, where the extracted feature values from parsed data were predicted using neural networks to successfully achieve Industry 4.0 workflow. Bauza et al. [2] presented an Industry 4.0 based quality control approach of parts made of aluminium which were machined to achieve part tolerances ± 25 mm or greater. In that work, authors used a Computer Tomography (CT) 2D code of the part and verified it by defining a measurement strategy leading to a successful Industry 4.0 application. In addition, a big data system framework was presented by Santos et al. [3] implemented in Bosch to achieve Industry 4.0. This work discusses the framework of the technologies involving data collection and analysis through big data analytics approach comprising different layers in the architecture, including web services, applications, databases, security, and administration.

A big data through Simulated Annealing (SA) based meta-heuristic and principal component analysis (PCA) to solve the facility layout problem was presented by Kumar et al. [4]. Authors compiled a three V's dataset, namely Volume, Variety and Velocity, with 14 criteria to efficiently plan a sustainable layout by achieving their intended outputs. A blockchain-based secure mutual authentication with fine-grained access control system for Industry 4.0 was presented by Lin et al. [6]. This work proposes a conceptual framework called BSeIn which efficiently implements a flexible and reconfigurable smart factory. Authors developed algorithms for validating the security of data among terminals, blockchain network, cloud, industrial network, and physical resources. Finally, they concluded that the secure mutual authentication with fine-grained access control system can proceed to achieve Industry 4.0.

Dinardo et al. [7] presented a smart and initiative condition monitoring system based on the continuous monitoring of the energetic features of the vibration signals acquired from the equipment under analysis. The work focussed on Industry 4.0 by predicting earlier indications of degradation in a component, to make accurate and consistent predictions. Tuptuk and Hailes [8] discussed the security of existing industrial and manufacturing systems, existing vulnerabilities with the details of the attack from the present decade. The article presents the details of potential future cyber-attacks, the weaknesses of existing measures, the levels of awareness and preparedness for future security challenges. Arkadeep Kumar [9] reviewed and discussed the methods and material technologies, along with challenges to overcome, which will be critical for enabling smart manufacturing in the form of the Internet of Things (IoT), cyber- physical systems (CPS), human-robot interaction, augmented and virtual realities.

In the context of machine learning / deep learning, Agent-based Artificial Intelligence (AI), decision making on CAD /CAM/CAE based problems, reported works discusses many advantages making it as the potential technology to achieve Industry 4.0. Peddireddy et al [11] discussed the deep learning-based approach for identifying conventional machining process using CAD data. In their work, they used simple milling and turning features from Standard Triangle Language (STL) models and trained their neural network for feature recognition. The work concluded approach provides a transferrable framework that could be used as a relearned task for a wide variety of problems such as cutting tool selection, defect detection, etc. Kim et.al [12] presented a deep-learning-based retrieval approach for piping component catalogues used for plant 3D CAD model reconstruction. In the work, they highlighted the reverse engineering concept of reconstruction from 3D point cloud data / segmented point clouds, and they used the deep-learning methods and successfully reconstructed the models required.

Rugaber et.al [13] adopted an interactive CAD game playing agent to verify the complexity and explained how the agents can be interactively adopted using TMKL2 agent modelling language. This is to control a CAD-based gaming environment named 'Freeciv', using an Application Programming Interface (API) available within the software. An approach for human-to-human interactive collaborative CAD through an agent-based approach was proposed by Fazhi He and Soonhung Han [14]. In their research, the human interaction of CAD software was corroborated through a client server-based link for a commercial software named 'AutoCAD', and tested for its consistency through multiple users.

Supporting a cognitive need-based CAD system, using an agent-based paradigm, was developed by Bento and Feijó [15]. Their work considered various cognitive needs of the designers and implementation through agent-based programming language called Xlog+ with the belief and commitment as a basic component to fulfil the CAD hybrid architecture. Moreover, Modi et al. [16] developed a human centred agent-based CAD system to achieve the task sharing, communication, transparency, cognition, and the design rationale. They developed an Atomic Control of Thought-Rational (ACT-R) cognitive architecture through which they developed a rule-based Petrinet architecture and embedded multi agent fuzzy logic-based approach.

After analysing the above literatures, the following points are observed:

[1] Design and Manufacturing systems can be integrated over a Cyber Physical Environment (CPE).
[2] Cyber physical systems and the AI-based architecture can be implemented for design and manufacturing systems integration.
[3] Big data for various design and manufacturing problems can be handled over the internet-based environment.
[4] Machine Learning (ML) and Agent-based methods can be utilised for the CAD/CAM/CAE automation.
[5] Status of machines can be predicted over the internet by using sensors.
[6] Webservices can be utilised for CAD/CAM process integration
[7] There is a scope of involving different technologies, such as RFID, machine learning for manufacturing and systems research.
[8] It is possible to have a central system for the purpose of controlling automation and control.

Based on these points, it has been decided to develop an AI based architecture with intelligent automated smart decision-making programs. This is by considering a smart cyber physical mechanism, IoT's embedded with machine learning and Agents to handle any complexity and to provide solutions for achieving industry 4.0. The next section explains the five-stage architecture proposed in this work.

2. Five Stage IoT based Industry 4.0 Architecture for Integration of Design and Manufacturing Systems

As discussed, a completely interconnected ICT based design and manufacturing system in a cyber physical environment requires a strong AI. Furthermore, the interconnection requires intelligent automated AI based smart programmes which can learn, think, and make decisions on its own, to execute and implement the various manufacturing requirements. To achieve this, an AI based 5-stage architecture as shown in Figure 1 is proposed by representing the integration of various technologies mentioned above to achieve Industry 4.0. In the first stage, a CAD model information with the ability to design / redesign is scanned from a RFID technology and sent to a secure Internet / Cloud Server using a GUI. The 2nd stage uses the scanned RFID CAD data and analyses the manufacturing shapes / features in the part by machine learning technique(s). This is achieved through a continuous searching of surfaces in the CAD model based on tagged or feature based information's. The 3rd stage adopts agents for the identified manufacturing features / product data information and generates a list of tooling, machine tool information and the supply chain detail by using internet / web calls from a database. Once completed, the 4th stage generates a process planning information and generate toolpaths, which is stored for a standard set of surfaces by retrieving design/manufacturing features information. In the 5th stage, the CAM section handles production plan and is verified through agents and transfers it to the identified CNC machine for manufacturing. Until this stage all the information will be updated in the RFID technology developed and will be verified prior to the final manufacturing for data security and verification. In this research, simple CAD model(s) and various 'search-find' machine learning algorithms with agent-based smart programs are adopted to make decision irrespective of human intervention. CNC machines will be tested for product manufacture at various stages in a fully cyber physical environment. It is planned that human intervention is only at the start stage scanning the RFID data and rest being executed in a fully cyber physical environment. This architecture is a central system which will help the industries trying to drive towards Industry 4.0 by achieving a reduced manufacturing lead time, improving their productivity, human less / automated decision making by improving efficiency and reliability in the workplace.

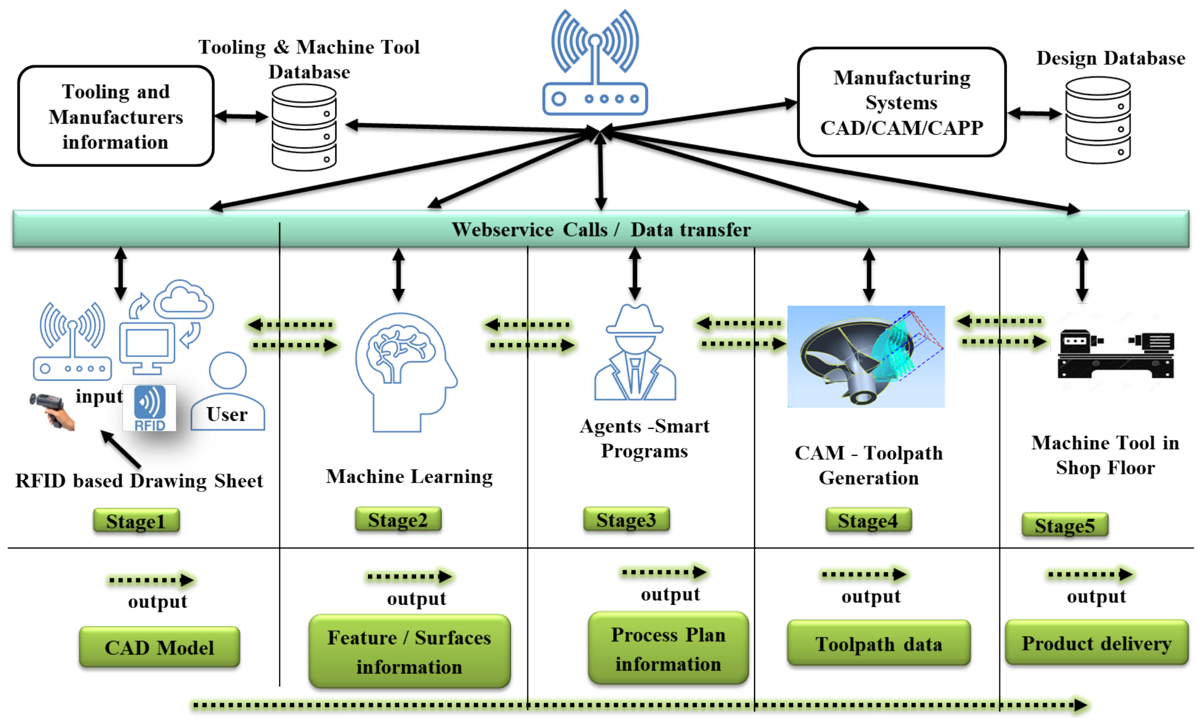


Fig. 1. Five Stage IoT based Industry 4.0 Architecture for Integration of Design and Manufacturing Systems

3. Stage 1: Radio-Frequency Identification (RFID) CAD Data

The proposed RFID based concept in the 5-stage architecture addresses the issue of immediate design / redesign by embedding design and manufacturing data. The challenge is, it is the input to create a large set of data in the whole process i.e. with product features / shapes & material (combinations) details it can identify the process plan, machine status, toolpaths, availability etc. This will be handled over the internet-based environment and requires a RFID input by international digital CAD standards such as STEP AP203/214/224. The concept will help to achieve a Digital-Twin' like simulation where we can achieve a IoT based information access and retrieval methods for achieving Industry 4.0.

3.1. Rationale behind Immediate Design/ Redesign and RFID integration

Many times, it is hard to manage immediate designing or redesign of CAD models especially if there is a new or change in existing requirement. i.e. it will be time consuming if the change of shape has to be incorporated in the design of product or manufacturing setup and require a 'fast making' capability by verifying them in a real-time simulation like a 'Digital-Twin'. For example, two primitive design features are shown in Fig. 2. The shapes of features in Fig. 2 (a) and (b) being simple slots and Fig. 2 (c) and (d) being w-slots. The 'nature of the feature' of the features being 'Through' and 'Blind' [17]. By considering the dimensional parameters mentioned in these features, a smart IF-THEN rule-based system as given below can make the possibility of these primitive features to be immediately designed / redesigned. i.e. to vary the 'nature of the feature' [17] from 'Though' to (or) from 'Blind', the following IF-THEN rules can be used. Here (i) $L_{(i)}$ is the Length of the feature (highlighted in brown colour in Fig.2) and (ii) $OL_{(i)}$ is the Outer Length of the part, where i = 1,2…n; (highlighted in blue colour in Fig.2).

- IF (L1 & L2 = OL1 & OL2) THEN (Feature Nature = 'Through'); Similarly,
- IF (L1 & L2 < OL1 & OL2) THEN (Feature Nature = 'Blind').

We can use this simple IF-THEN rules by adjusting the dimensional parameters to change its shapes i.e. for a 'Through' 'nature of the feature'[17], if the L_1 and L_2 values are reduced from its existing value which initially is equal to OL_1 & OL_2, then automatically the feature type will be 'Blind'. Similarly, to vary the 'shape of feature' [17] and to make a design / redesign from a normal slot to a w-slot the following IF-THEN rule set can be used. Here (i) $W_{(i)}$ is the Width of the feature (ii) UW(i) is the Upper Width of the feature

- IF (W1 < UW1, W2 < UW2, and L1 & L2 = OL1 & OL2) THEN (Feature Shape = Through W-Slot – TWSL)
- IF (W1 < UW1, W1 < UW2, and L1 & L2 < OL1 & OL2) THEN (Feature Shape = Blind W-Slot – BWSL

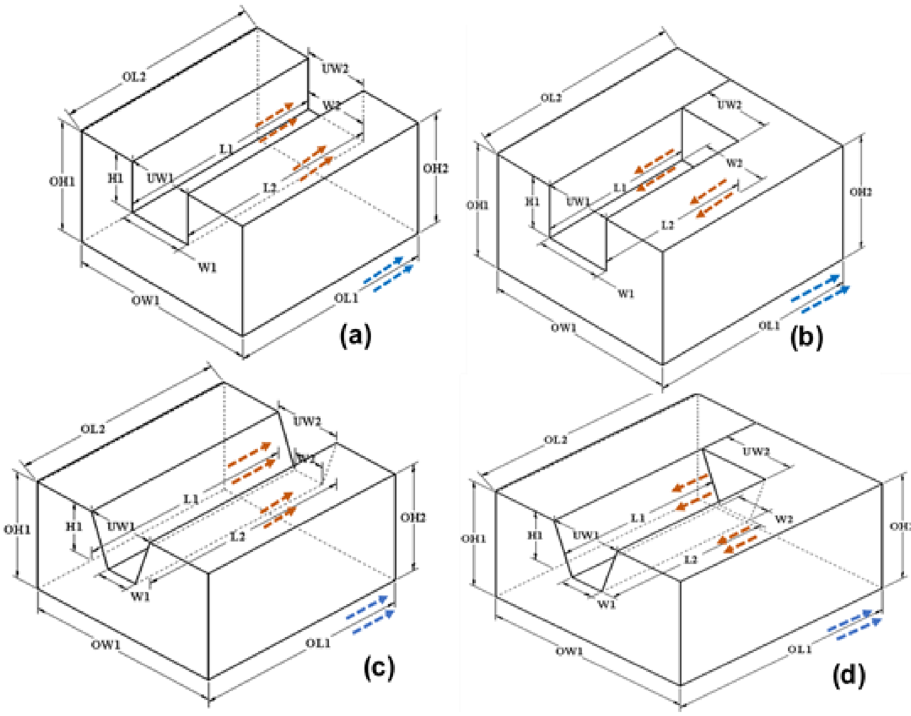


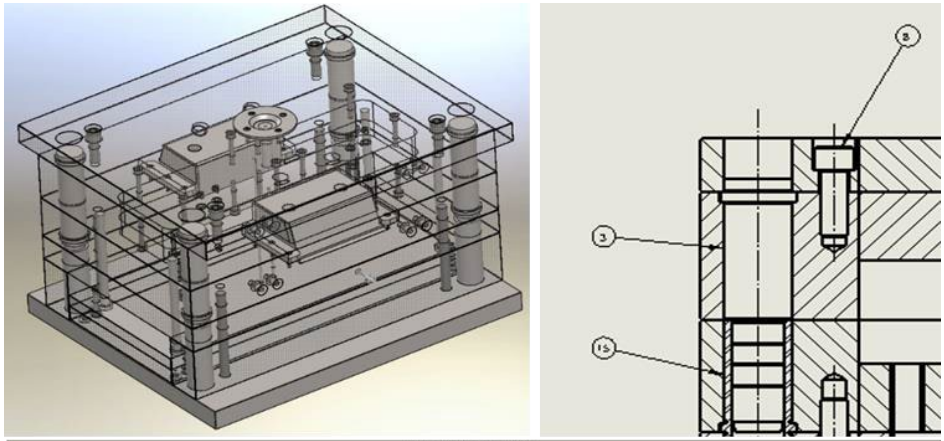
Fig. 2. Series of primitive shapes and their Dimensions – What if these needs to be automated?

3.2. Real time case of a Design/ Redesign and RFID integration

Let us consider a scenario of pharmaceutical manufacturing of products such as ventilators, plastic bottles, medicine coverings, syringes, pacemakers, etc. The process requires CAD models along with simulation connected to an appropriate feedback system. The products are critical as it involves lives of human beings and must be verified to high precision before it is being manufactured and released. Many times, this is hard, and requires a quick design / redesign of the system, as the shapes in the manufacturing process changes based on the requirements. This can be noticed where new manufacturing setups as shown in Fig. 3 are required when a new product demand arises, e.g. an immediate requirement of manufacture of ventilators to save the lives of COVID-19 affected patients require quick manufacturing setup along a process simulation. In the present scenario, digital twining can solve the issue if a continuous feedback system can be utilized using RFID based CAD integration and IoT technologies in an Internet based environment giving the flexibility of process simulation.

3.3. RFID and CAD model integration

The structure of the RFID technology considered for this framework is shown in Fig. 4. It consists of five integrated information's (i) CAD model information in the form of drawing sheet with the unique identification number, (ii) Geometric Dimensioning and Tolerancing (GD&T) information, (iii) features that are linked with the suitable machines available for the giving drawing sheet, (iv) appropriate toolpaths and (v) setup and the fixture plan. At this stage of the architecture, the CAD model data / drawing sheet data is taken up and the other information's will be automatically uploaded when each module completes the necessary workflow as appropriate to the stage. As illustrated in Fig. 2, the RFID CAD data will be passed to the cloud server where it appropriately integrates all the necessary tooling information to the connected RFID data owner in the whole process. This will automatically connect the GUI based sever where the CAD model is requested for the generation of toolpaths / process plan and until the final manufacturing. By this way, the RFID technology will help industries to achieve Industry 4.0 focusing an immediate design / redesign for digital twining process giving the flexibility to maintain copyright and patent information.



Bill of Materials			
ITEM	PART NUMBER	DESCRIPTION	QTY.
3	K 10-396 596-36	HASCO Metric Clamping Plate	1
15	K 40-396 596-96	HASCO Metric Spacer Block	2

Fig. 3. Digital-Twin required for a complex manufacturing setup applicable to a new process [18]

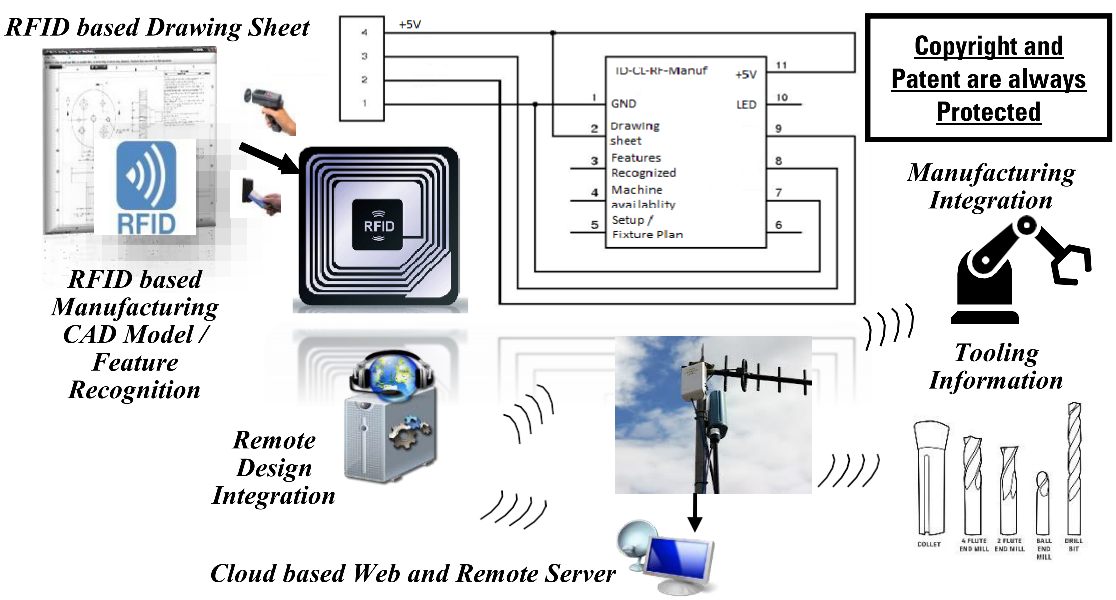


Fig. 4. RFID based CAD data model for uploading into cloud-based web server.

4. Stage 2: Web Services Based CAD Model Retrieval & Machine Learning

Once the RFID technology with the CAD model is scanned (in stage 1), the next process is to retrieve and display in the GUI from the web server. The process architecture of this stage is illustrated in Fig. 5. Here the GUI is linked with a web service Simple Object Access Protocol (SOAP), which is the messaging protocol specification for exchanging structured information for CAD model retrieval. In the process, the user accesses the GUI and creates a link between the local computer and to the remote business / web server that is available in a specified location. This location contains the RFID CAD data information in their relevant databases. As highlighted earlier, the connection is established through SOAP calls handled inside the GUI and the data bridging is performed to retrieve the appropriate data. The connection is made by using an internet-based client server architecture, which can be applied locally and globally. Once the connection is established, the CAD model data is retrieved and stored in the local database where the GUI is being executed. As the GUI is a Java-based platform, it completely interlinks and retrieves the data from the remote business server. Then the data retrieved and stored in the local database is added with the user input from the GUI and created as an Extensible Mark-up Language (XML) file. The XML file which will act as a data for machine learning and CAD/CAM software is checked internally for its continuity and the data loss. Once it is conformed, it is then imported to the machine learning tool and CAD/CAM software to carry out further processing.

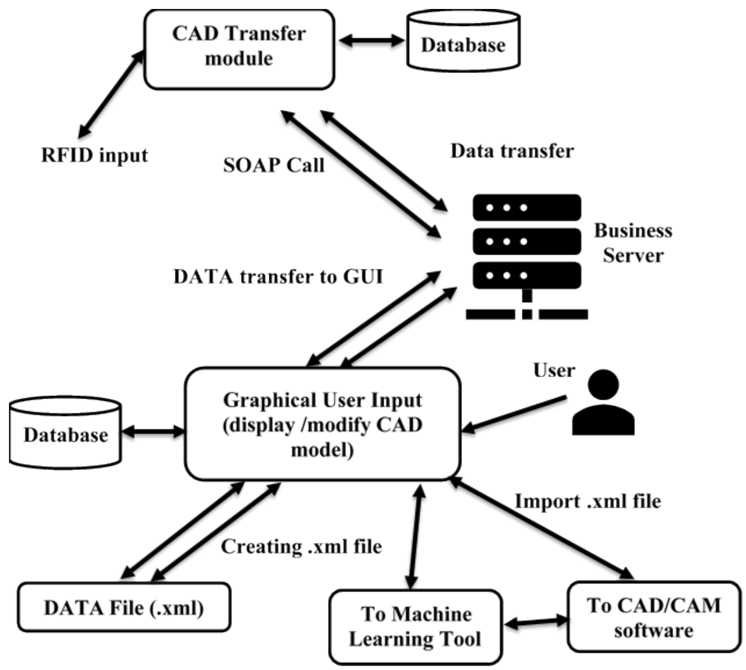


Fig. 5. Business model of GUI prototype with SOAP based protocol for CAD model retrieval.

4.1. Development of Machine Learning Based Features / Surfaces Recognition

From the RFID based CAD data sent from stage-1 as XML format, machine learning method is used to observe different variations of the CAD models and to recognize manufacturing shapes/features (stage-2). machine / deep learning is a term given to computer based artificial intelligence rule-based approach which predominantly adoptsthe concept of Artificial Neural Networks (ANNs). The approach is from the biological concept how the neurons in human brains work based on a continuous / deep training through observing different variations to make a correct decision [10-11]. A ML tool is used in the work (tested earlier) to develop, unique methods, training and visualizing deep neural networks [10] to recognize manufacturing shapes / features. Two approaches of CAD data, both separate and in combination will be tested here (i) static images (JPEG, PNG's etc.) and (ii) CAD neutral formats. To explain, Figure 6, is presented with two scenarios to show how training the machine learning tool can help resolve the present problem. In the left-hand side i.e. scenario 1, a set of images containing 'whale face' and 'no face' is trained in machine learning tool. Then one image with whale face is tested for an exact match. Similarly, in scenario 2, a CAD model image with individual features/surfaces will be trained separately and in combination with (i) a static image of simple features/surfaces (1-8) and (ii) CAD neutral format (e.g. STEP). Then a CAD model ('M') with all these features are tested to extract the information of individual features from the developed method. It is possible to identify the individual dimensions, orientation of the features with this approach.

5. Step 3 & 4: Agent based Computer Aided Process Planning (A-CAPP)

Agents are adopted in this work to solve various complex problems requiring intelligent thinking and conscious decision-making especially in stage 3, 4 & 5 where creation of process plans, toolpaths and production plan verifications are needed. Basically, these Agents are 'small or ant colony sized' codes which are used to solve various complex problems requiring intelligent thinking and decision making. Basically, each Agent has 4 constructs [19]: (i) A Beliefset: representing agent beliefs using a generic relational model. (ii) An Event: describing an occurrence in response to which the agent must act. (iii) A Plan: An agent's plans are analogous to functions. They are the instructions the agent follows to try to achieve its goals and handle its designated events, and (iv) A Capability: Allows the functional components that make up an agent to be aggregated and reused. A capability can be made up of plans, events, Beliefset's and other capabilities that together serve to give an agent certain ability. The Design Palette shown in Fig.7(a) explains the associated symbols with each of the above described characteristics of the Agent. This concept is adopted in the present work for creation, modification, and deletion of agents to handle intelligent thinking and conscious decision making. To explain, Figure 7(b) is provided where an agent named 'Feature based Manufacturing' creates a process plan for a simple identified feature / shape 'slot'. It has the Capability to 'Create Feature Based Manufacturing information' with the Event 'identify manufacturing features and cutting tool and machine information' associated with it. When such an event or goal arises, it determines what course of action it will take and completes the process. It will then execute the 'Plan' by accessing the belief set just as a rational person would from a database of tools and process parameters. If a new shape other than 'slot' is identified, then it will access the 'belief set data' and will either modify the existing agent or create a new one by modifying its characteristics. i.e by 'spawning' and 'mutation' to make conscious decisions. In this way, the stage- 3, 4 & 5 are handled for product manufacturing in a CPE where the full process plan and toolpaths are generated.

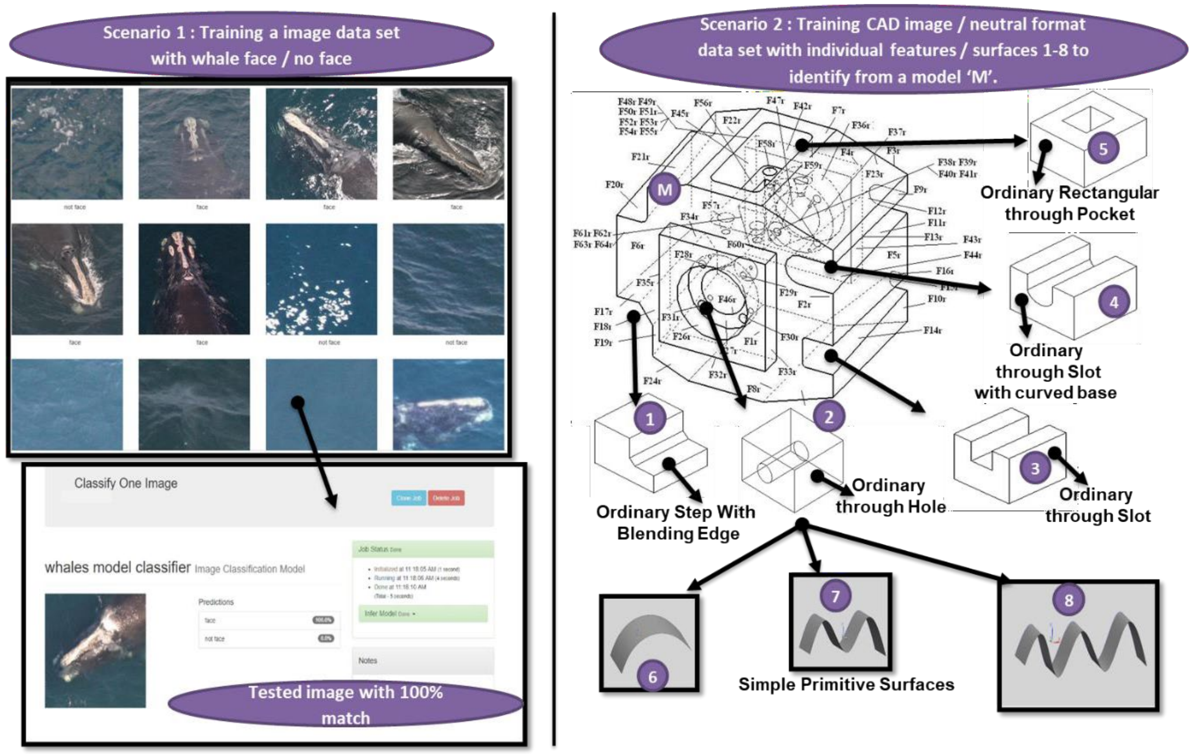


Fig. 6. Schematic representation of identified whale face from an image data set alongside image / CAD data set consisting of manufacturing features / surfaces.

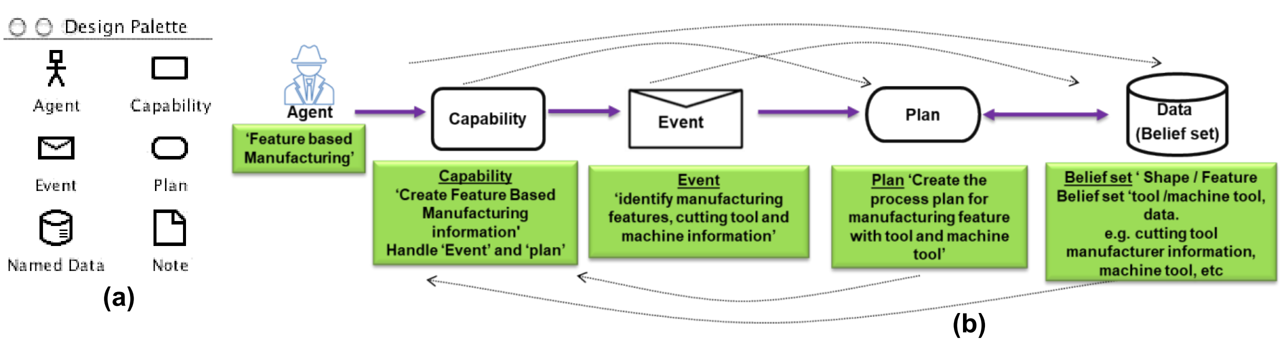


Fig.7. A simple Agent for 'Feature based Manufacturing' based on BDI concept

6. Stage 5: Interoperability Between CAD/CAM Software to CNC Machines

In stage 5, interoperability of CNC programs or G&M codes [21] for final manufacturing is handled. In manufacturing systems environment, transfer of data from a CAD/CAM software [18, 20] to CNC machine is challenging over a CPE. This is owing to various problems encountered while machining even with skilled personnel. Some of them are faced while decision making and toolpath modification in scenarios such as (i) tool breakage inthe middle of machining (ii) improper generation of toolpaths from a CAM package (iii) cutting tool shortages etc. The list will be lengthier as the machining complexity will vary and increase based on other factors such as capability of CNC machine, part complexity, material etc. In many cases, a quick and fast change with the CNC program orG&M codes is necessary, which is highly challenging and tedious to achieve. Especially, when one of these situations arises during a real time machining. There are CNC machines and CAD/CAM software's to help but the context of the problem will differ when a new part needs to be machined with non-machinable design to 'fast make' the product. The present architecture considers to make use of the IoT technologies to address these issues by using electronic interfaces similar to a Raspberry Pi, transistors for Industrial Internet of Things (IIoT) information exchange, cloud rail box, etc., for getting a real time and check if a digitalized twin of the whole process if achieved. i.e. at this stage, the final production plan in the form of G&M codes with the approved sheets are sent to the CNC machine as obtained from the previous stages. These are updated in RFID technology to maintain data security and to cross verify in the CPE before the final manufacturing. Fig.8. explains the process of CNC machining toolpaths of a product being verified by using a real time CAD/CAM model of the CNC machine and machined over an IoT environment.

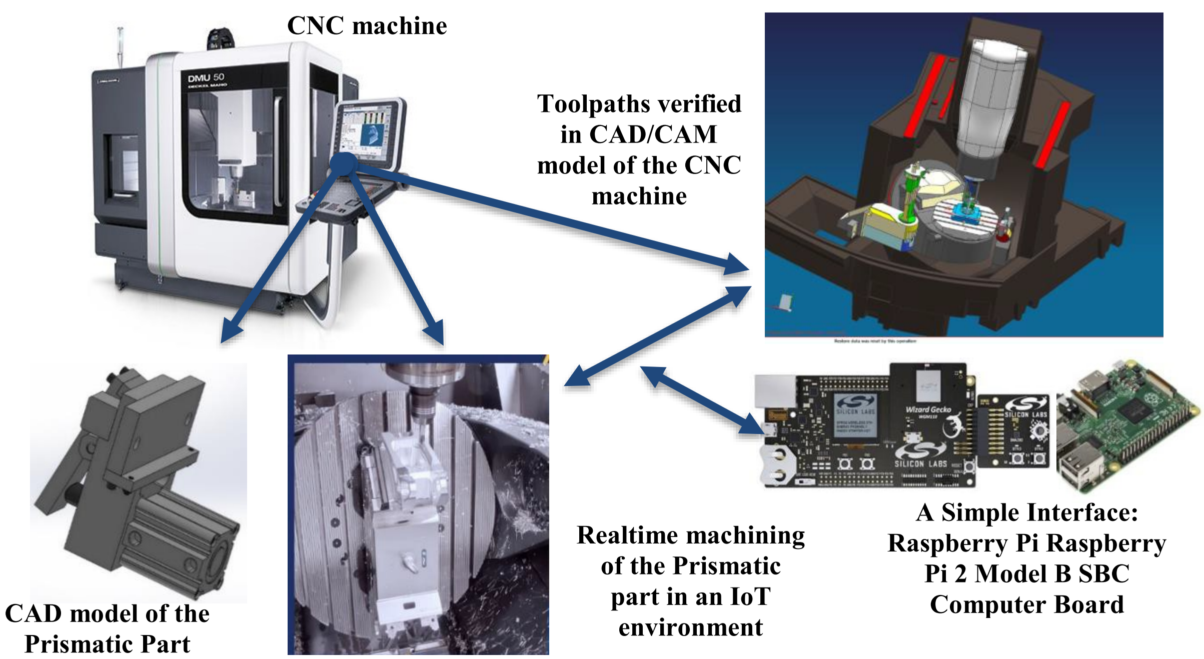


Fig.8. CAD/CAM to machine transfer for real time manufacturing

7. Conclusions & Scope for Future Work

In this paper, a 5-stage architecture is discussed with the aim of (i) integrating design and manufacturing systems in a CPE by identification and recognition from a large CAD/CAM model data sets (ii) interlinking RFID technology with CAD models and by developing ML methods / concepts (iii) decision-making agent-based smart methods / programs to decide selection of process plan data and toolpath generation for manufacturing and (iv) possibility of CNC machines (machining) operated directly from the output of CAD/CAM software leading to Industry 4.0. The proposed architecture potentially transforms the present design and manufacturing systems by successfully achieving the following (i) Interconnectivity - At present, the manufacturing systems are semi-automated, manual or have user intervention. This architecture interconnects using various systems (software / hardware) using machine learning and agent-based approach. (ii) Standardization - This approach standardizes in an intelligent or smart way by RFID link to CAD models to decide the best suited machine tools, cutting tools, etc. when rapid manufacturing is required. (iii)

Knowledge preservation and application tools - In terms of human knowledge encoding, the CAD model automation with process plan and toolpath generation provides enormous benefit by improving efficiency and productivity. (iv) Independency - At present, most of the toolpaths are generated make interoperability tedious. By using this interconnectivity method, it is possible to make independent decisions (v) Time / Cost Benefit - Cyber physical integration will drastically reduce the time and cost associated for each part to be manufactured and (vi) Achievable - Through this approach, there is high possibility of achieving Industry 4.0. Still there are many challenges in this ongoing research and the future work will address eliminating the risks associated with use of ML methods, decision making using Agents, CNC machines being used in CPE with associated data for copyrighted information and security.

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