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ORIGINAL ARTICLE

A next-generation IoT-based collaborative framework for electronics assembly

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Abstract

In today's dynamic manufacturing environments, the adoption of virtual reality (VR)-based simulation technologies to help in product and process design activities is becoming more widespread. With the onset of the next IT-oriented revolution involving global cyber manufacturing practices, the recent emergence of Internet of things (IoT)-related technologies holds significant promise in ushering an era of seamless information exchange which will provide a robust foundation for the next generation of smart manufacturing frameworks dependent on cyber physical system (CPS)-based principles, approaches, and technologies. In this paper, we present a broad framework for IoT-based collaborations involving the adoption of VR-based analysis environments networked with other cyber physical components. The process context for this VR-centered approach is electronics assembly, which involves the assembly of printed circuit boards. In such manufacturing contexts, it is essential to have a seamless flow of data/information among the various cyber physical components to ensure an agile collaborative strategy which can accommodate changing customer needs. VR-based simulation environments play a key role in this framework which supports multiple users collaborating using haptic interfaces and next-generation network technologies. The simulation outcomes and production data from physical shop floors can be compared and analyzed using this IoT framework and approach.

Keywords Internet of things (IoT) · Cyber physical systems (CPS) · Collaborative manufacturing · Cyber manufacturing · Virtual prototypes · Next-generation Internet · Electronics assembly

1 Introduction

Over the past decades, global manufacturing organizations have faced a shift towards a dynamic customer demand with the emphasis on adoption of agile manufacturing practices. The electronics assembly industry (or PCB assembly domain) is one of the more dynamic manufacturing domains where organizations have to quickly respond (with shorter life cycles in products) for changing customer requirements. To remain competitive and agile, there is a constant need to reduce the cost as well as the time to market new products or meet customer deadlines [1]. The time to market a new product in such a dynamic environment includes the time to engineer as well as manufacture a product. This need for engineering as well as manufacturing components in organizations to collaborate by sharing information and data to accomplish target tasks has been well recognized [2–4].

In this context, the potential of emerging next-generation collaborative technologies holds significant promise in supporting seamless data and information exchange which can link cyber and physical components, resources, and partners through advanced Internet technologies; these emerging technologies (and domains) include cyber physical systems (CPS) and Internet of things (IoT) [5] which are poised to usher in the next era in cyber manufacturing which will revolutionize collaborations between geographically distributed cyber and physical resources. A brief note on CPS- and IoT-related principles and technologies is relevant.

A CPS can be described as a complex system comprising of both cyber and physical components which interact and collaborate to achieve an overarching functional objective;

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these can range from CPS for manufacturing, telemedicine, transportation, and energy management. IoT can be described as a network of interacting components capable of sharing data and information among distributed cyber and physical components which have embedded computational capabilities as well as sensors (such as cameras, RFIDs) which in turn can be used for decision-making activities (from engineering to smart home management) [6]. In an IoT, cyber components interact, interface, and integrate seamlessly with the physical world of sensors and "things" [2, 7, 39–50]. Research discussions centered on possible IoT-based applications have gained momentum in areas such as energy [8, 9], healthcare [10–13], traffic safety [14, 15], big data analysis [16, 17], and information systems [18–20].

Design principles related to a recent manufacturing initiative termed Industry 4.0 deal with integration and automation in the manufacturing world [21]. It highlights key principles including interconnection through communication using IoT concepts and promoting autonomy in decision-making [21–27].

As the current Internet was not designed for the large number of applications it supports today, several nations have embarked on designing future Internet architectures and experimental test beds to address the current shortcomings which include attempting to overcome latency, and improve throughput, among others. One of them is the Global Environment for Network Innovations (GENI) initiative in the USA, which provides a virtualized environment where multiple experimental networks could be simultaneously deployed, tested, and validated at significant scale, within a shared platform [28].

The domain of interest addressed in this research deals with an electronics assembly process (which is the assembly of printed circuit boards (PCBs)). Typical assembly components in a PCB include a variety of electronic components (resistors, capacitors, integrated chips, etc.) which can be assembled by through-hole technology or surface-mount technology. In operations using surface-mount technology (SMT), a new product is typically introduced through "trials" and testing in order to determine the shortest process cycle times and setup times along with getting a better understanding of other issues such as collisions. The major drawback from this approach is the lead time and the costs involved in physically completing these process changes for various alternatives apart from disrupting ongoing production activities along with the cost incurred from scrap materials (from the testing of boards) [29].

In this paper, our focus of interest is the design of an IoT-based cyber physical system framework which integrates planning/simulation tools (cyber resources) with physical PCB assembly resources. The simulation environments developed are 3D virtual reality (VR)-based environments that seek to perform assembly and factory level simulation-based analysis; they can support distributed teams to propose, analyze, and compare process flow alternatives at various levels of abstraction. While IoT-based frameworks have been proposed for other manufacturing domains including micro assembly [2], the IoT-based collaborative framework discussed in this paper is the first reported framework for the field of PCB assembly. Through this innovative framework proposed for PCB assembly, our research seeks to develop a more agile approach taking advantage of IoT principles and harnessing both cyber and physical components. Such an approach will also enable PCB manufacturers to develop detailed process level designs using digital mock-ups (or virtual prototypes) for new product designs as well. There are several commercial tools available for creating VPs and VR-based simulation environments (such as Delmia); however, tools such as Delmia focus only on the creation of VR-based simulation environments such as for process simulation involving CNC machines/operations and other assembly environments. Our approach focuses on a collaborative framework that involves interfacing and integration of multi-functional tasks involving both virtual (cyber) and physical components; the VR-based simulation is a key component within this framework. With tools such as Delmia, such cyber physical interfaces and seamless information integration and exchange using cloud-based next-generation Internet technologies is also not possible. Our emphasis on adoption of next-generation GENI-based networking technologies to support the distributed collaboration involving distributed resources and users is also unique in the general manufacturing context.

2 An IoT-based CPS framework for electronics assembly

We propose an IoT-based framework using next-generation networking technologies to support interactions between cyber and physical resources for electronics manufacturing specifically PCB assembly. As shown in Fig. 1, the role of IoT-based data exchange assumes significance as it straddles a complex collection of cyber and physical modules. The cloud-based cyber resources include VR-based simulation environments, an IoT manager, and a task monitoring module. The simulation environments can be accessed from different locations by engineers who can propose assembly and factory level plans; using next-generation Internet technologies, they can work as a team using haptic and non-haptic interfaces to propose and compare process design alternatives for a given PCB design. An IoT manager (software module) is responsible for the overall accomplishment of the cyber physical-based activities; a task monitoring module keeps track of the progress of various tasks in this cyber physical cycle. An overview of the IoT-based cyber physical interactions is shown in Fig. 3.

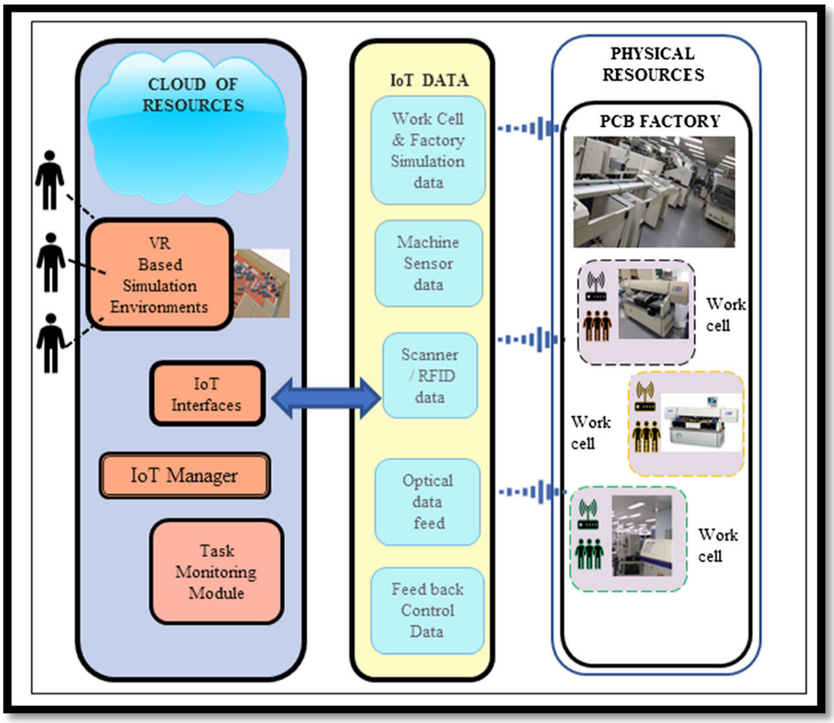


Fig. 1 The modules and functions of the CPS IoT framework for PCB assembly

For overall cyber physical interactions, our approach proposed involves a modular approach (Fig. 1) where each cyber and physical component focuses on a specific activity and work together to complete the IoT-based cyber physical cycle; for this high level of complexity, the individual modules can employ an assortment of algorithms to achieve specific function or set of functions. We have focused more on modular approach; the functioning of each component has been described in the subsequent section of this paper.

The interactions and process flow of this IoT-based framework are illustrated in Fig. 2. As seen in Fig. 2, the input for generating assembly sequence and path plan are input data such as layout, part, and feeder positions. The output from the assembly and path plan generation modules are assembly sequence and path plan, respectively (Fig. 2), which serve as an input to the assembly level simulation. The assembly level simulation outcomes are fed into the factory level simulator module which is also linked to a discrete event simulation (DES) engine. Using this DES engine, factory level analysis can be accomplished for various periods of time (from months to a year, if necessary). Using the physical data stored in the enterprise resource planner (ERP) systems of a PCB factory, the simulation outcomes can be compared with the physical outcomes of a given PCB factory. Sensory data through IoT-based interfaces provide this information to the ERP system and the IoT manager, which enables the integration of both cyber and physical data and activities (Fig. 3).

2.1 VR-based cyber environments within IoT framework

Two environments (modules) have been created to support the planning and simulation activities for this IoT framework. Both these environments can be viewed as virtual prototypes (VP) created using VR technologies to support distributed interactions in a concurrent engineering context. In general, a VP refers to a 3D computer graphics-based model that

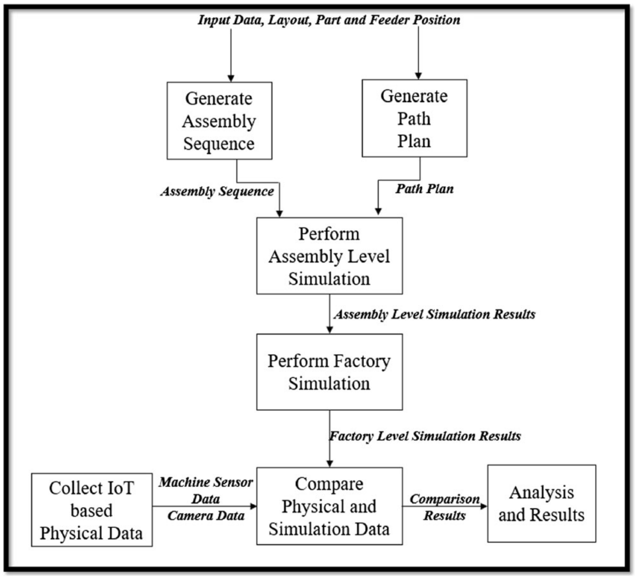


Fig. 2 Flowchart showing the cyber physical interactions

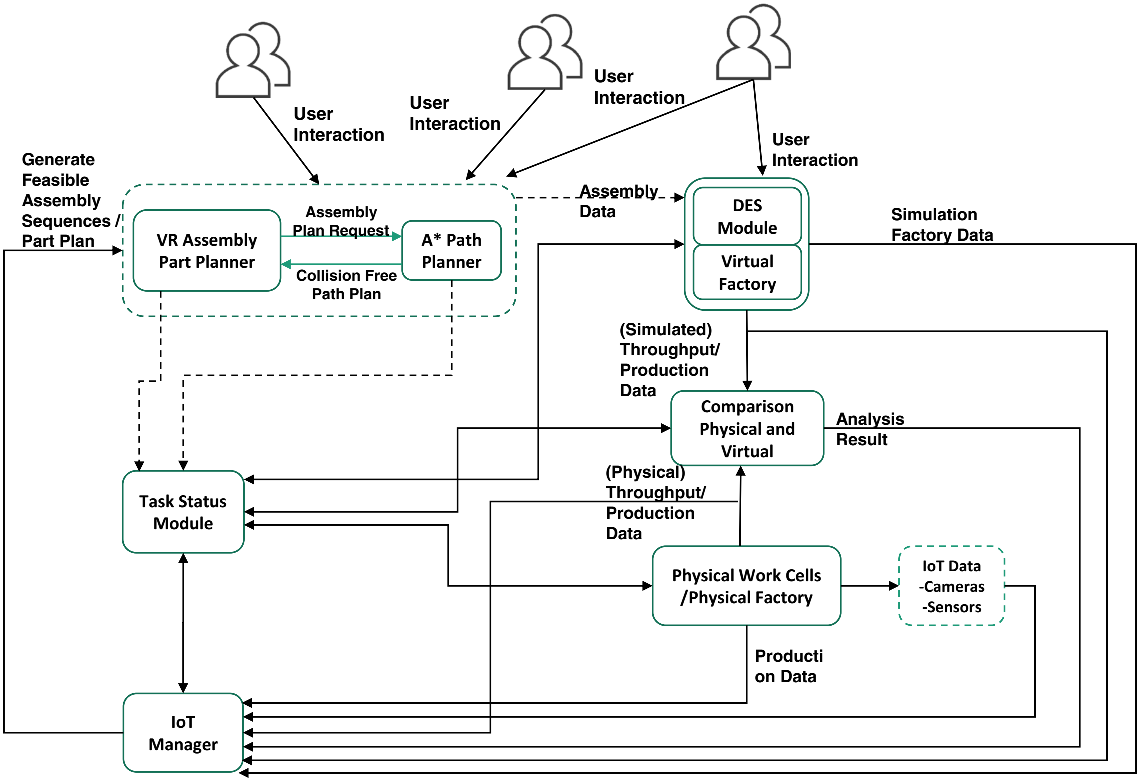


Fig. 3 Overview of the cyber physical interactions within the IoT framework

contains accurate geometry and topology of a target object, system, or environment along with a set of process characteristics that mimics its real-world counterpart [29]. There are two core VP-based simulation components in this IoT-based CPS framework. The first component is termed the virtual assembly environment (VAE) while the second is the virtual factory environment (VFE).

The *VAE* focuses on the work cell level simulation relating to the placement activities of PCB components; this enables assembly design comparison, layout modification, and process analysis at the workstation level of the SMT-based placement activities; in this environment, SMT-related placement/assembly process design issues can be studied, potential solutions proposed and validated (VP) [29, 30]; various SMT-based environments can also be studied prior to purchase of a specific assembly work cell; distributed engineers from different locations can work as part of concurrent engineering teams to study a work cell layout (modifying feeder designs, positions of feeders, robot placement heads, etc.) in an interactive manner using next-generation Internet techniques.

The *VFE* deals with production simulation of the entire factory in a 3D VR environment along with being able to perform discrete event simulation; it allows users to view/modify the virtual layout of the facility and is also capable of analyzing the factory production rates, etc. Facility planning tools such as DES help in scenario analysis of impact of capacity planning, assembly sequence, and scheduling of products through the manufacturing system. DES is a methodology where the behavior of a complex system is modeled as a sequence of events and simulated over a course of time to understand the effects of these events on the system through performance metrics. The "events" in DES are specific change to the state of system at specific point in time. A DES model focuses on the operation of the entire factory system over a period and can be used to study various issues including identifying process bottlenecks, impact to manufacturing costs [31], and assist in analysis of process planning and scheduling [32].

In this PCB IoT framework implementation, there are several kinds of sensor data collected such as vision-based data from camera and machine state sensors; this IoT data is fed into data collection modules which are linked to an ERP module as well as to the overall IoT manager. The ERP (which records the actual operation data for the entire facility) receives the work cell-related data such as process time for each product from the IoT manager. The outcomes of the simulation at both the assembly and factory levels can be compared to the actual production data from the ERP system. Additional details of these virtual environment data collection activities are discussed in next section.

3 Design of the virtual assembly environment

The focus of the assembly process for our IoT framework is the surface-mount technology (SMT) process. In general, creation of VR-based environments have been explored by several researchers to support various manufacturing activities [33–35]; our past efforts have focused on the design of assembly environments for cross-functional analysis without network capabilities and using non-haptic interfaces [33–35]. In our current framework, our emphasis is the design of a cyber manufacturing approach based on an IoT framework which is capable of interacting with cyber and physical components. The CAD models of the various machines, robotic equipment, conveyors, and other components within the simulation environments were created using the Trimble Sketchup® 3D CAD package. This CAD model is built to scale and represents all elements that help in cross-functional evaluation of PCB products.

Users have options to choose from three different kinds of virtual assembly environments which are (a) non-immersive, (b) haptic-based, and (c) fully immersive environment. In the non-immersive environment, the user can interact and make changes in the layout using mouse and keyboard. In the haptic-based environment, users can interact using a sense of touch, which is more natural and intuitive; a user interacting with the Geomagic Touch™ haptic device is shown in Fig. 12; the immersive environment was implemented using the HTC Vive™ in which the user interacts with the virtual environment by wearing a head-mounted display (shown in Fig. 4). Using these options, a user can interact with the virtual environment by modifying the layout and making changes to it using various interfaces; the most feasible alternative of accomplishing the component assembly can be compared, modified, and validated.

Three different PCB designs are considered to demonstrate the feasibility of this IoT framework; these three designs have 50% common components while the remaining components are unique to each PCB design category. This mix of common versus unique components creates the need to optimize the location of these component feeders. The assembly operation involves the robotic gripper arm picking up parts from feeders and placing them in various target locations (Fig. 5); the layout and the process elements including type of feeder, robot head, and general PCB layout configuration can be virtually modified and the resulting impact on the overall assembly can be studied interactively by teams of distributed engineers. These distributed teams can use mouse or haptic-based interfaces to study various SMT process layouts interactively using GENI-based networks; for a given PCB design where the final destinations of the various chips or components are given, the focus is on coming up with feasible process layouts which enable the assembly tasks to be completed without collisions; this analysis can be performed before any investment is made to purchase a given set of work cells or can be performed after these work cells are made available. By comparing the various layouts for the same placement cell as well as comparing layouts between two different placement workstations, the distributed teams can perform virtual process level analysis using the VR tools and networking technologies. Figure 5 shows a view of the VAE developed using the Unity 3D engine and C#. Figure 6 provides a view of the factory level simulation environment for the PCB factory.

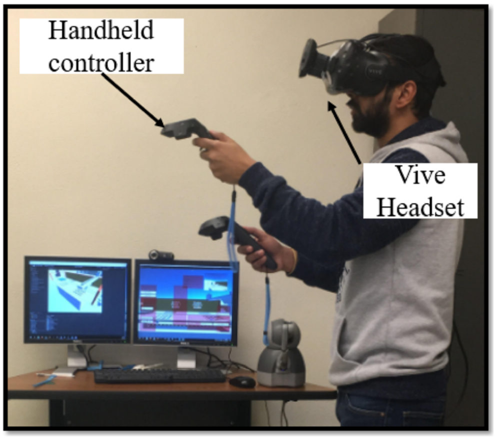


Fig. 4 A user interacting with the immersive virtual assembly environment (VAE)

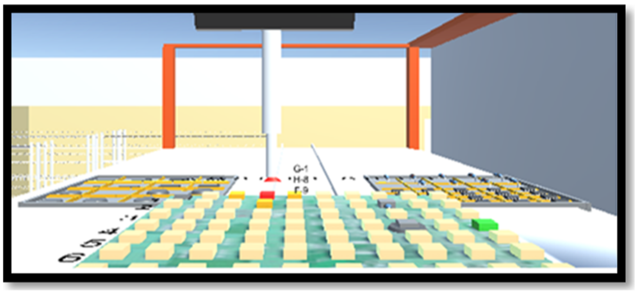


Fig. 5 View of the virtual assembly environment (VAE)

In this environment, the analysis of component placement mechanisms, layout options, feeder change over strategies, and work piece holding configurations and mechanisms can be accomplished. Figure 7 shows the virtual prototype (VP) view options to select various interactions and toggle between haptic/non-haptic modes available to users.

3.1 Path planning approach

In VAE module, a path planning approach was implemented based on the A* algorithm [36] to enable users to develop a collision-free path plan. The input to this module is the assembly sequence or assembly plan; currently, this assembly plan is input manually to the system. The long-term goal is to provide an automated assembly sequence alternative which can be generated by a sequence generating module. Currently, using the haptic interface, a given assembly sequence can be proposed; candidate assembly sequences can be compared. Using the path planning outputs, a given assembly plan along with

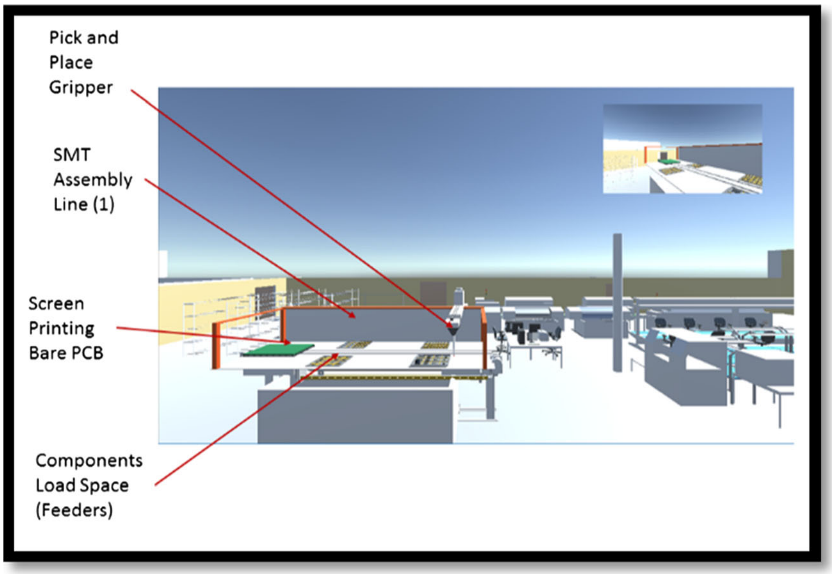
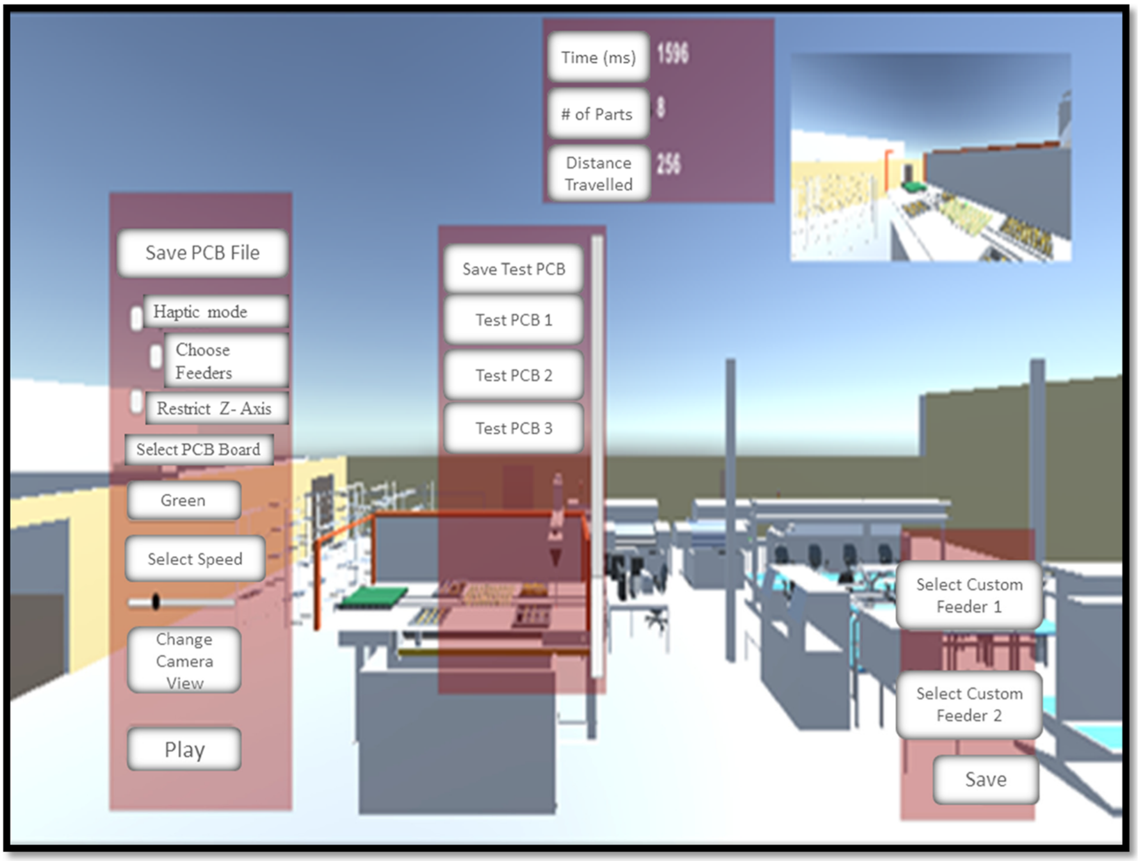


Fig. 6 View of the virtual factory environment (VFE)

the detailed plan can be virtually studied and validated in the 3D environment.

The algorithm uses the Cartesian coordinate plane of the printed circuit board and calculates the location of the obstacles already placed on the plane. From the starting node on a plane, it builds a tree of paths and growing these "paths" (alternatives) one step at a time, until one of its paths ends at the goal node. Each iteration in this algorithm needs to determine which of its partial paths could possibly expand into one or more longer paths. Based on an estimation of the cost to the goal node, A* selects the minimum path. The basic steps in the path planning approach are shown in Fig. 8.



Time (ms) 1596

# of Parts 8

Distance Travelled 256

Fig. 7 Some of the user interface options in the VAE

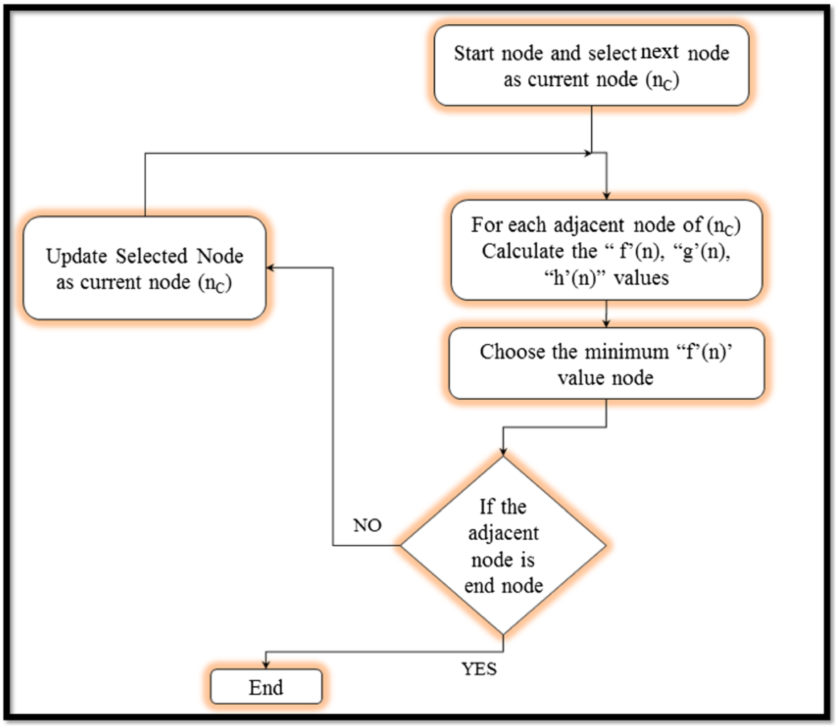


Fig. 8 The key steps in the A* algorithm-based approach for path planning

In general, an A* algorithm uses three parameters to estimate the path. The cost estimation is computed to compare possible alternatives when moving from one "cell" (Fig. 5) to the next using *F*, *H*, and *G* values.

Current estimated cost from current node *n*:

$$F^{'}(n) = G(n) + H^{'}(n)$$

$H'(n)$	heuristic value is the cost of the cheapest path from a specific node to goal node
$G(n)$	total cost of the path calculated from start node next node

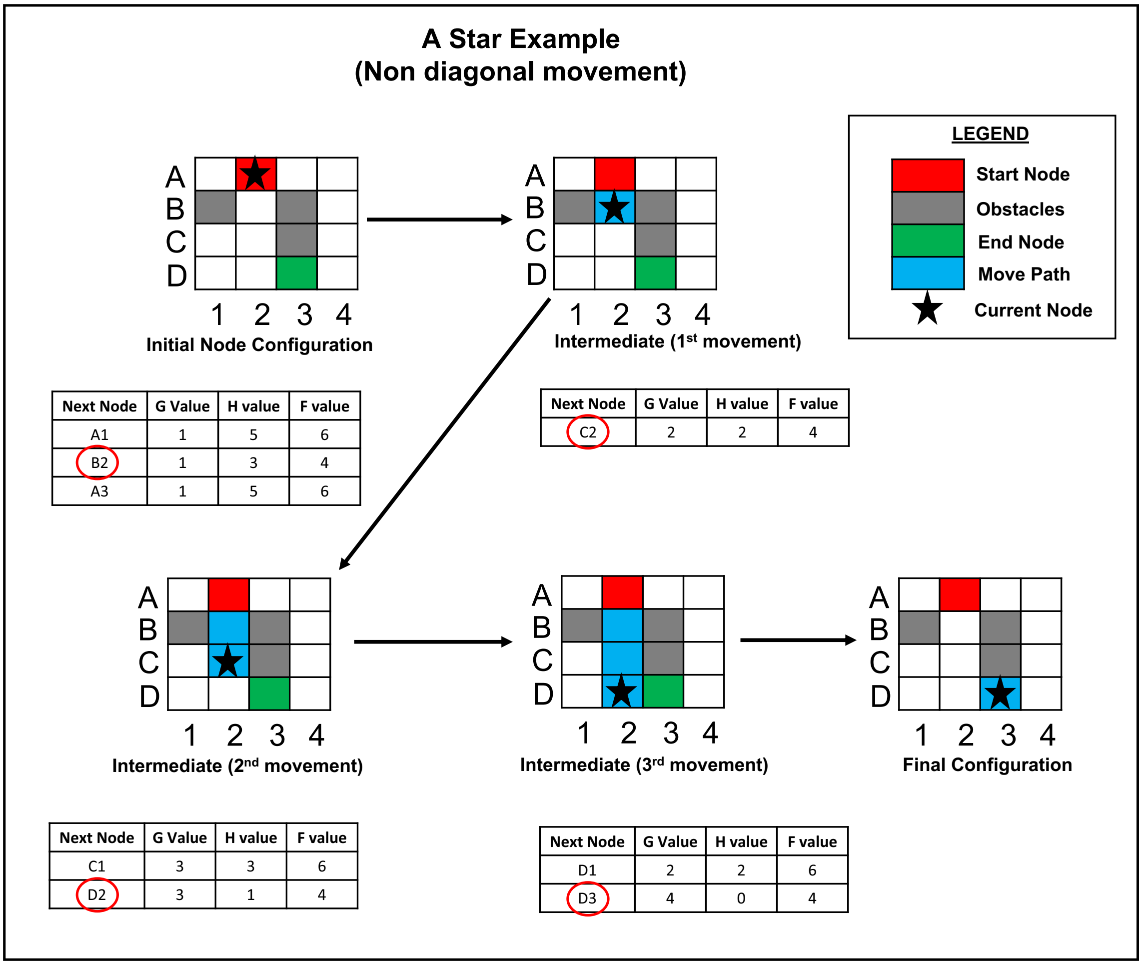
An example of this approach is illustrated in Fig. 9. The progress of the path plan generation is shown from the first stage (labeled initial node configuration) to the last stage (labeled final configuration); at each stage, the *F*, *G*, and *H* values are calculated and the adjacent node with the lowest cost value of *F* is selected to be the next current node (or position in the path plan). In situations where there are two low *F* values, the lowest of the *H* cost values is selected.

The outputs from the path planner is used to initiate the VR-based simulation showing the feasible path plan; users can also propose their own path plans and compare them to the plans generated automatically using the A* approach. Users (engineers) can also modify the layout of the assembly cell including introducing a diverse array of placement robots, feeder designs, etc. and then select the most feasible alternative as a team.

4 The design of the virtual factory environment

While the VAE focuses on helping to study the assembly sequences and layout of the individual assembly cells, the virtual factory environment (VFE) focuses on analyzing flow and utilization for the overall factory. The placement level outcomes can be realized on the shop floor to physically complete the corresponding assembly/manufacturing activities. However, the simulation outcomes from the VAE are first input to the VFE, where the overall impact on production outputs and utilization are studied virtually.

In this PCB factory context, the major inputs to the DES are assembly and other processing times at each work cell or machine, number of personnel assigned to each work cell or machine along with relevant process information such as use of material handling equipment to help with other tasks in the factory. The DES module was created using Simio™; for the 3D layout-based simulation activities, the relevant 3D CAD models were created using Trimble Sketchup™ and imported into Simio software. The time-related data is defined in tables inside the Simio model and linked to corresponding data output tables in the ERP system. Figure 10 displays a view of this DES module with respect to links to ERP system data, along with the output reports that show the results of a scenario analysis for a set of



Next Node	G Value	H value	F value
A1	1	5	6
B2	1	3	4
A3	1	5	6

Next Node	G Value	H value	F value
C2	2	2	4

Next Node	G Value	H value	F value
C1	3	3	6
D2	3	1	4

Next Node	G Value	H value	F value
D1	2	2	6
D3	4	0	4

Fig. 9 Example path planning using A* algorithm-based approach

scheduling constraints at each station. Various reports can be generated using the DES engine such as the customer expectation status, machining time for each part, shipping time, and lead time, among others. Using the DES, the potential impact of a decrease in processing time attributed to benefits of the collaborative efforts using the virtual prototypes can be captured.

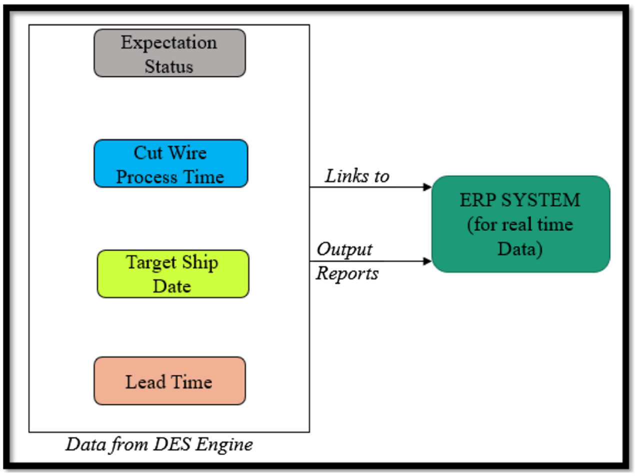


Fig. 10 Output reports from DES engine for analysis

5 Adoption of next-generation Internet technologies

With the current Internet having bandwidth and latency issues, several initiatives are underway globally to design and develop the next-generation of Internets [33, 37]. One of these initiatives is the Global Environment for Network Innovation (GENI), which focuses on exploring future Internet networking principles including software-defined networking (SDN) and adoption of cloud-computing technologies. These networks facilitate seamless exchange of information across heterogeneous platforms among distributed partners enabling reduced latency and improved bandwidth that can support technologies involving sharing of VR-based environments. Other similar initiatives in Europe include the Future Internet Research and Experimentation (FIRE) project. In this IoT framework, the distributed collaborative interactions were achieved using GENI networking technologies; some of the interfaces include haptic interfaces to interact with the assembly level simulation activities among distributed users. A cloud-based repository of resources is linked to distributed sites to support engineering and simulation collaborations.

Figure 11 shows the framework of GENI-based collaborative interactions. A master server is created on the GENI node at one of the many GENI racks. The users situated at distributed locations are provided with their instance of the VR environment. When the users first launch the VR environment, they will be prompted to join as a client. After the users have joined as clients, the instances of the simulation environments are synchronized to support distributed collaborative interactions.

Performance of the GENI-based network with respect to latency was also studied. Network latency between the distributed locations was measured using Internet Control Message Protocol (ICMP) ping.

Table 1 shows the latency data for two samples measured 2 h involving interactions between the users at two different locations. The latency was found to be stable at 43 ms which is considered acceptable for our framework.

6 IoT-based cyber physical interactions

The virtual assembly environment assists in providing the collaborative training interface through haptic interactions along with inputs from a part planner and a pathfinding algorithm (A* algorithm). The haptic devices used are the Geomagic Touch (Fig. 12) which allows users to interactively modify the layout of the virtual environments. The group-based interactions are linked through GENI where the users join as clients, and interact with the VR environment collaboratively.

The outputs from these collaborative interactions such as assembly processing times, and modified assembly sequences are transferred to the DES module for scenario analysis. The DES module also receives data from the physical work cells in the facility through IoT interfaces. Comparing these data streams through simulation over a period, the DES is used as a facility planning tool in evaluating the benefits of collaborative training over existing setups.

A typical physical facility consists of one or more work cells connected with material handling systems such as conveyors and automated guided vehicles. The work cells in the facility could be manned or unmanned depending on the type of process and equipment's used in the work cell. The data collection devices in this IoT framework are cameras and sensors from the PCB factory floor and assembly work cells; they play an important role in the real-time data exchange among the cyber physical components in this overall IoT approach.

The cameras in the assembly and other work cells can be used to monitor the progress of the assembly and other SMT activities on individual assembly lines in the factory. This enables remote monitoring as well as up to the minute detailed data collection on work in progress (WIP), assembly, and other tasks completed. As the production activities continue, the physical production (completion) data can be compared to the simulated data and used that as a basis for further validating the outputs of the simulation results from the DES module. The production-related data such as tracking status of a product in the assembly line is captured using bar code scanner. The data from bar code scanners are dependent on the assembly worker's input instead of automated data collection.

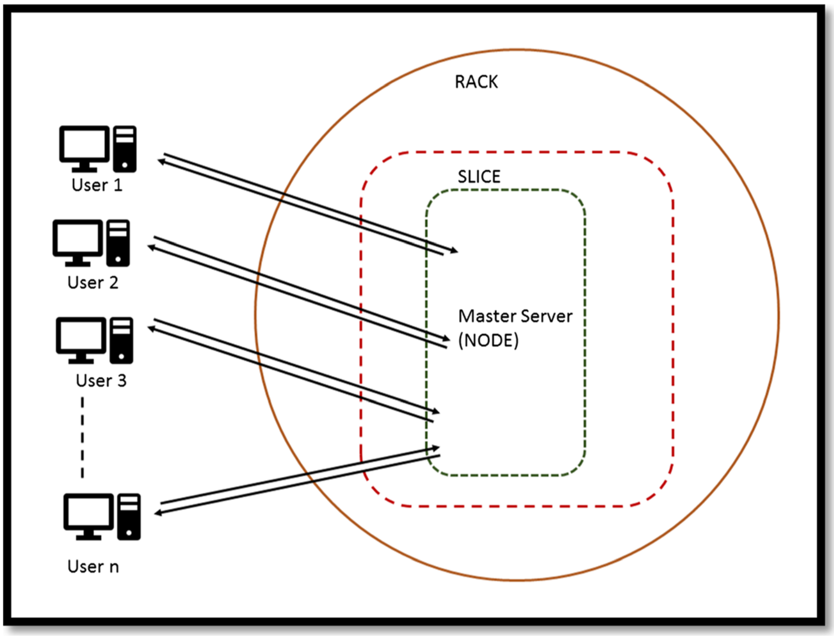


Fig. 11 GENI-based collaborative framework

Table 1 Latency during the interactions using GENI network

2 users	Latency (ms)		
	Max	Min	Average
Sample 1	62	39	43.97
Sample 2	59	35	43.43

The automated assembly process of the SMT pick and place machine collects process-related information for different types of printed circuit board (PCB) product assembled in the machine and sends the data to a cloud server. The IoT sensing layer in the SMT pick and place is a host of speed/rpm sensors integrated into the machine drive system. These speed sensors will record three states of the machine: machine on/off state, idle time where the drive runs at low rpm, and run time where the drive mechanisms run at the rated maximum rpm. These three states are monitored by the machine CPU for each batch of PCBs assembling on the machine and this continuous stream of data is sent to the networking layer. The networking layer transfer this data to the cloud server where a machine-specific application (Fig. 13) helps to facilitate the functions of the service and interface layers.

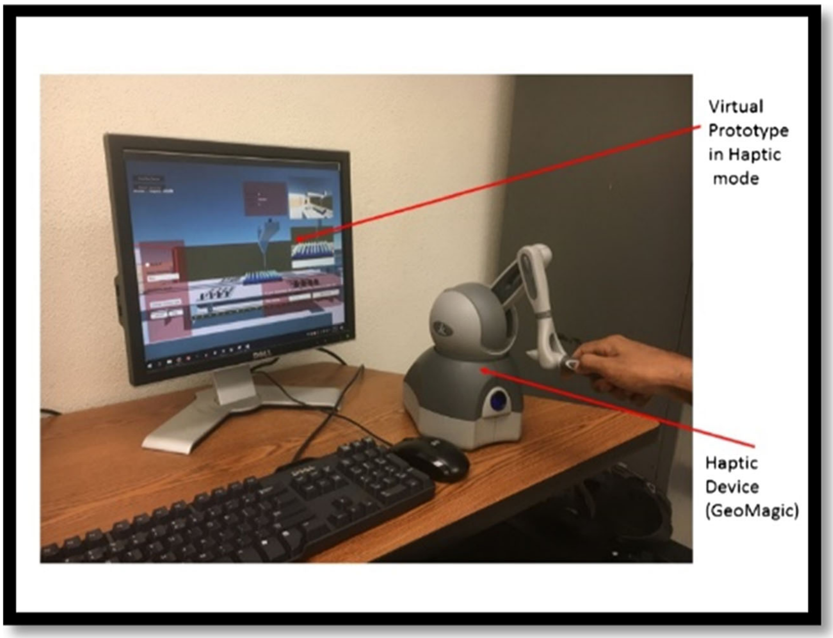
Apart from the data from various machines and work cells on the factory floor, the operator of the machine uses a bar code scanner to stamp the time at the beginning of as well as at the end of the assembly. This data is collected as part of manufacturing process data and stored in the ERP database. Based on the comparison of data from the SMT machine and the bar code scanner, there is an average loss of 72% in process time. Since the bar code scan data is dependent on the manual input of the assembly worker and is subject to human error, issues related to lack of training in machine setup as well as operation and assembly sequence. This bar code data is also collected and stored in the ERP system. The data in the ERP system is used to capacity planning and scheduling of the products in the system. Discrete event-based simulation software is used to assist in the scheduling of the PCBs by their due dates to the customers.

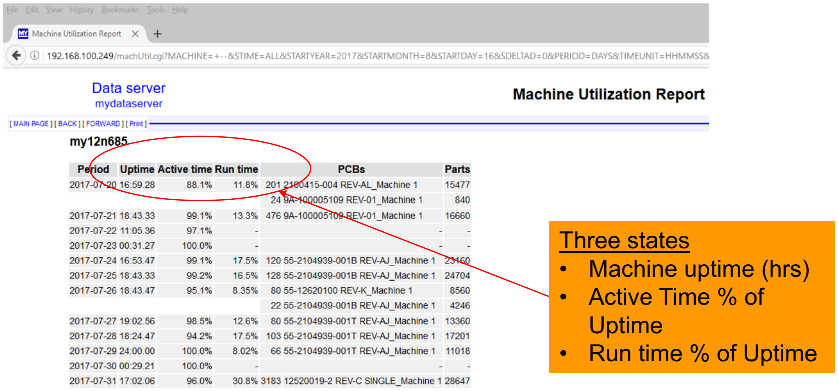
The second IoT interface is through the use of cameras focused on the assembly work space of the surface-mount technology pick and place machine; this data feed along with a monitoring module would help with the identification of the issues related to the assembly of the particular product. It would act as a feedback loop to validate the effect of training and planning using the virtual prototype. Figure 14 shows an image taken from one of the PCB assembly work cells from a factory. Given the complex nature of these IoT-based cyber physical interactions, the tracking module uses a state chart type of an approach to represent the progress of the various activities (outlined in Fig. 2, shown earlier); the state chart indicates whether a given cyber or physical task has not been started, completed, in progress (WIP), or has encountered any problems. It uses a color-coded scheme shown in Fig. 15 indicating the status at any given instant.

7 Discussion

The IoT-based CPS framework proposed for PCB assembly will enable the manufacturers to collaborate using cyber physical resources and enable them to respond in a more agile manner. The IoT technologies using embedded sensor data from equipment as well as streaming camera images help to understand the benefits achieved through collaborative

Fig. 12 A haptic device-based interface to support collaborative process design interactions





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Data server
mydataserver

Machine Utilization Report

my12n685

Period	Uptime	Active time	Run time	PCBs		Parts
2017-07-20	16:59.28	88.1%	11.8%	201	2100415-004 REV-AL_Machine 1	15477
				24	9A-100005109 REV-01_Machine 1	840
2017-07-21	18:43.33	99.1%	13.3%	476	9A-100005109 REV-01_Machine 1	16660
2017-07-22	11:05.36	97.1%	-		-	-
2017-07-23	00:31.27	100.0%	-		-	-
2017-07-24	16:53.47	99.1%	17.5%	120	55-2104939-001B REV-AJ_Machine 1	23160
2017-07-25	18:43.33	99.2%	16.5%	128	55-2104939-001B REV-AJ_Machine 1	24704
2017-07-26	18:43.47	95.1%	8.35%	80	55-12620100 REV-K_Machine 1	8560
				22	55-2104939-001B REV-AJ_Machine 1	4246
2017-07-27	19:02.56	98.5%	12.6%	80	55-2104939-001T REV-AJ_Machine 1	13360
2017-07-28	18:24.47	94.2%	17.5%	103	55-2104939-001T REV-AJ_Machine 1	17201
2017-07-29	24:00.00	100.0%	8.02%	66	55-2104939-001T REV-AJ_Machine 1	11018
2017-07-30	00:29.21	100.0%	-		-	-
2017-07-31	17:02.06	96.0%	30.8%	3183	12520019-2 REV-C SINGLE_Machine 1	28647

Three states
- Machine uptime (hrs)
- Active Time % of Uptime
- Run time % of Uptime

Fig. 13 View of some of the IoT data (collected by the ERP system from a SMT placement work cell)

interactions at a facility level. This framework was implemented using next-generation GENI-based networking technologies linking distributed workstations which were used to accomplish process layout modifications for the assembly environment using both haptic and non-haptic interfaces.

Using a PCB assembly industrial organization, this case study was also implemented using both the assembly level simulators and the discrete event simulation models of the entire factory (for this industrial organization). The IoT sensors including cameras were used to collect and monitor assembly and process data which was used to compare the simulated data with the actual physical outputs from the PCB factory.

The process cycle time collected through IoT interfaces revealed that the machine/work station idle time was averaging around 67% for each PCB product that was assembled. The high idle times can be attributed to two factors: lack of adequate training necessary in becoming proficient in setting up a new PCB product for assembly especially in a high product variety and low-volume manufacturing context. Using the DES module, an analysis was conducted for a 3-month period with three types of PCB assembly products; it indicated a reduction in idle time to 33% would reduce the overall facility lead time by 41%. This continuous improvement effect attributed to the benefit of using collaborated approach could be validated through the camera feedback and monitoring system which records the start and end of each process cycle.

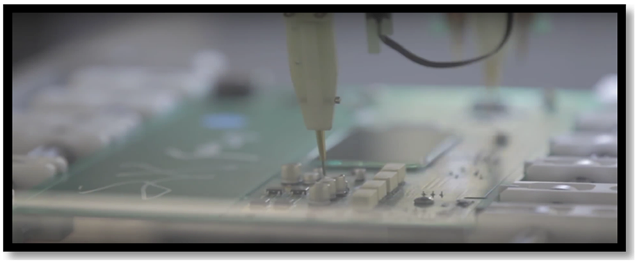

Fig. 14 Close-up camera view of an assembly level placement task in progress

Reviewing the recorded videos helps operators and trainers to identify opportunities for improvement in the assembly process. In general, when process design changes are proposed by operators and engineers, the feasibility of these changes can be studied using the collaborative VAE environments; additional analysis on the overall production throughput can be studied using the DES engine. Hosting the cyber components on a cloud-based server has several benefits including being capable of being accessed "on demand" 24/7 from distributed locations. The physical machines and workstation cells at different locations can be monitored using focused cameras as well as shop floor cameras along with machine sensors. A single electronics manufacturer with multiple locations or a consortium of manufacturing companies can form a collaborative partnership on large projects and could interact with physical resources in different locations.

The collaborative virtual environments (VFE and VAE) played an important role in the analysis of component assembly and path plans. Virtual environments provide a powerful means for distributed teams to identify problems, as well as propose and compare solutions. As the next-generation Internet technologies continue to evolve, our study underscores the feasibility of using such emerging technologies.

The framework and the various component outlined in the paper can be used by designers and manufacturing engineers as well as PCB contract manufacturers to integrate process design and manufacturing activities in the area of PCB manufacturing. The primary emphasis in this paper has been on proposing a new way for such collaborations to occur using emerging IoT principles

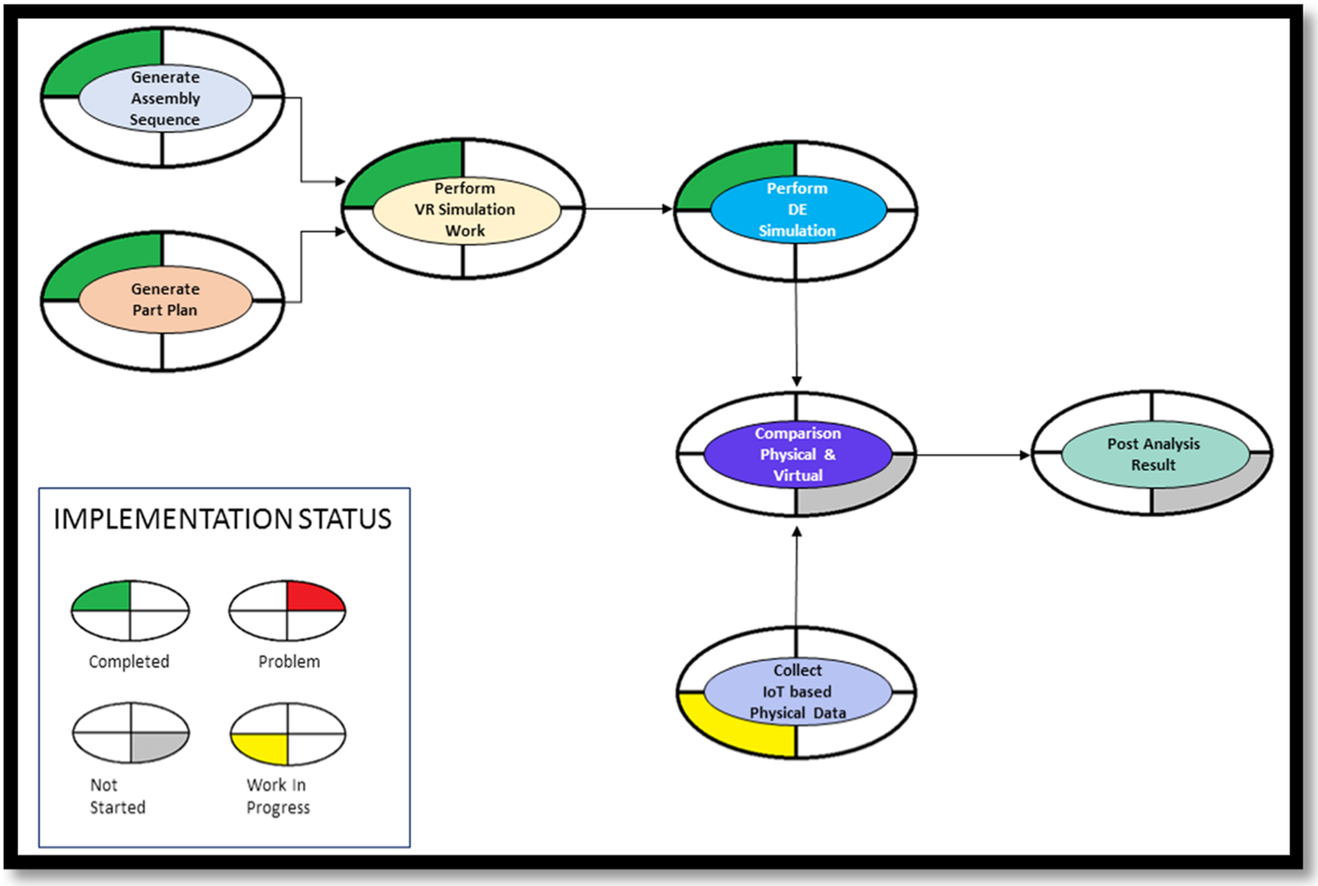

Fig. 15 Tracking the status of various activities within the IoT framework

and smart technologies involving VR-based environments. The general principles underlying the proposed approach can be adopted for various manufacturing domains. We have demonstrated feasibility of this approach by studying an assortment of PCB layouts and assembly alternatives in general; when a new or different PCB placement machine is considered, they can be modeled and a new virtual prototype reflecting those characteristics can be built; they can then become part of the relevant simulation modules where various process design alternatives can be studied. This is in contrast to traditional approaches where assembly plans and process design details are validated using physical machines; the time and cost to such traditional approaches is very high compared to using the simulation-based approaches outlined in this paper.

The scope of our IoT-based collaborative framework is being extended as part of the next phase of our planned activities; additional cyber and physical components will be introduced as part of the collaborative framework to support other engineering analysis activities. Further, new IoT interfaces/sensors will be incorporated into the cyber physical environments for the PCB assembly factory. Data collected over a larger period will be used to study patterns and trends in the overall manufacturing activities and production cycles.

8 Conclusion

The focus of this paper was to discuss the design and development of an IoT-based framework for PCB assembly activities. The cyber environments were VR-based simulation environments with two levels of abstraction: the first was an assembly level simulator (VAE) focusing on process design of SMT-based placement activities at the work station level; the second was a factory level simulator (VFE) which was integrated with a discrete event simulation (DES) engine for performing production analysis for entire shop floors. Sensors and cameras provided the needed data into the IoT framework and an ERP module which enabled the comparison of simulated and physical production data. The VR-based simulation environments and other cyber modules have been networked using next-generation GENI technologies. Users can interact with the virtual environments using haptic-based interfaces to propose plans and to compare alternatives as well as to identify infeasible steps within the assembly process. The scope of the IoT framework is currently being expanded to include other work cell level analysis and simulation activities in the PCB assembly context.

While such IoT frameworks hold a significant potential to support collaborative manufacturing activities as well as facilitate enterprises to respond in an agile manner, there is an equally strong need to research methods that will enable the structured design of such IoT-based collaboration and frameworks. Such methods should provide a strong foundation that will enable engineers to understand the complex data and information-based interactions as well as recognize the need to address semantic interoperability issues [38]. The general principles in the design and implementation of this IoT framework can be extended to other manufacturing domains such as precision optical assembly and semiconductor manufacturing as well automated shop floors comprised of computer numeric controlled machining work cells.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interests.

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