# An Advanced Cyber Physical Framework for Micro Devices Assembly

J. Cecil, *Member, IEEE*, Sadiq Albuhamood, Aaron Cecil-Xavier, and P. Ramanathan, *Fellow, IEEE*

***Abstract*—The design and implementation of an Internet of Things (IoT) based cyber physical framework in the context of Industry 4.0 is discussed for the field of micro devices assembly. Such frameworks hold the potential to facilitate rapid and agile collaborations among distributed engineering partners. This paper outlines the key cyber and physical components which collaborate using cloud-based principles and emerging next generation global environment for network innovation Internet technologies. An information centric systems engineering approach is proposed to help design the cyber physical interactions, which provide a foundation for implementing this cyber physical framework. The cyber modules are capable of assembly planning, path planning, virtual reality-based assembly simulation, and physical command generation. The physical assembly activities are accomplished using micro assembly work cells. An IoT-based cyber physical test bed has been created to test and validate the design and implementation aspects of the proposed framework.**

***Index Terms*—Collaborative manufacturing, cyber manufacturing, Industry 4.0, Internet of Things (IoT), micro assembly, next generation Internet technologies, systems engineering, virtual reality (VR) based prototyping.**

## I. Introduction

WITH the rapid development of information technology as well as the advent of other technologies, advanced manufacturing is undergoing a revolution. A cyber physical system (CPS) can be described as a system of collaborating computational elements controlling physical entities [94]–[96]. CPS has also been depicted as a collection of transformative technologies for managing interconnected physical and computational capabilities [120]. CPS technologies have extensive application potential in various fields, including manufacturing, aerospace, automotive, healthcare, and transportation. Another emerging field involves the Internet of Things (IoT) networks, which can be described as a network of software and physical entities embedded within sensors, smart phones, and other devices which have software elements to perform computing or noncomputing activities [1], [2] These entities are the "*things*" referred to in the term "IoT" which can be capable of collaborating with other similar entities in the Internet at various levels of abstraction and network connectivity [23]. Examples of *things* are weather sensors, heart monitors, sensors in manufacturing facilities, software modules providing process feedback, and safety devices in a chemical processing plant, among others [9]–[12], [63]. Adoption of IoT principles and technologies can also help realize next generation CPSs and cyber manufacturing frameworks which require a higher level of collaboration and autonomy [1].

In this paper, an IoT-based framework for collaborative manufacturing in the context of Industry 4.0 is discussed for an emerging domain termed micro devices assembly (MDA). MDA refers to the assembly of objects with micro scale features, which are in the order of $10^{-6}$ m [3]–[7]. MDA-based products have a wide application potential ranging from biomedicine, sensors and electronics products [8]. As the physical micro assembly equipment and software tools used in MDA activities are expensive, it is not realistic for one organization to acquire or possess a diverse array of resources to support assembly of various types of MDA-based products. For this reason, collaboration among engineering and other partners is necessary. Such collaborations are also needed to function as a virtual enterprise (VE) to support changing customer requirements and while integrating and interfacing with distributed cyber physical resources [9], [10]. An IoT-based cyber physical framework holds the potential to address these needs. The described framework is multifaceted and involves concepts and technologies straddling several fields including Industry 4.0, CPSs, IoT, cloud computing, and virtual reality (VR)-based analysis techniques to support collaborative engineering activities.

One of the recent manufacturing initiatives involves Industry 4.0, which originated in Germany with an emphasis on promoting the computerization of manufacturing [93]. It emphasizes four key design principles including: 1) communication using IoT concepts; 2) information transparency; 3) CPSs principles; and 4) autonomy in decision making [1], [64]. The general underlying theme

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is that by linking machines and systems in manufacturing settings, intelligent networks can be developed along the value chain which are capable of autonomous control [64], [93], [94], [100], [106]–[115]. The potential of adopting IoT-based approaches and principles for various applications has been discussed by several researchers [60]–[76], including energy [40], [41], safety [42], [43], healthcare [44], [45], [54], [56], agriculture [47], [56], [57], big data analysis [52], [58], and information system [50], [51], [53], [55], [60]–[63]. In manufacturing, several research efforts have outlined conceptual models and frameworks involving IoT technologies [11]–[14] supporting factory automation.

Cloud-based technologies provide several benefits including lower maintenance costs, improved access, and enabling better collaboration. The use of cloud computing approaches in manufacturing has gradually been increasing in the past few years including support of smart manufacturing principles [16]–[25]. There has also been recent interest in the area of CPSs [100]–[102] and related approaches. Other researchers have discussed CPS principles in the context of manufacturing-related applications [94], [97]–[100], [104]–[105].

Several research efforts have explored a variety of research issues in the field of MDA ranging from automation of assembly tasks to innovative gripper design [59], [77]–[81], [87]–[90]. In general, VR-based simulation approaches help in planning and analysis in a variety of domains including manufacturing and healthcare [82]–[86]. The adoption of VR-based simulation approaches to aid in micro assembly tasks has been investigated in several research efforts [9], [10], [21]–[23].

A review of the various relevant research areas has led to the following key observations.

1) The IoT-based CPS framework discussed in this paper is one of the earliest implementation for advanced manufacturing applications. While there have been numerous papers outlining IoT, CPS, and Industry 4.0 concepts, few papers have discussed comprehensive CPS-based implementations for collaborative manufacturing contexts.
2) Prior CPS approaches have explored 3-D CAD-based modeling technologies; our approach extends this by adopting VR-based virtual prototyping techniques.
3) There has been limited exploration of emerging next generation networks including adoption of software defined networking (SDN) based principles in the implementation of collaborative manufacturing contexts.

Our previous work [9] discussed a preliminary framework involving collaborative components and technologies to accomplish a limited scope of MDA activities. Our current work outlined in this paper extends this initial framework by proposing a more advanced IoT framework, and expanding the capabilities of the cyber and physical modules hosted on the cloud. Multiple approaches and modules to perform assembly planning have been developed in the current framework to mimic a VE oriented scenario where more than one partner may be capable of performing the same engineering task. Our emphasis in considering more than one assembly planning module is to demonstrate the capabilities of the proposed IoT-based approach in supporting and interacting with diverse and multiple cyber resources to achieve the overall objective of assembling micrometer-sized devices. Another key element in our current approach is the adoption of global environment for network innovation (GENI) next generation networking principles which is used to support the collaborative VR-based assembly analysis from distributed locations.

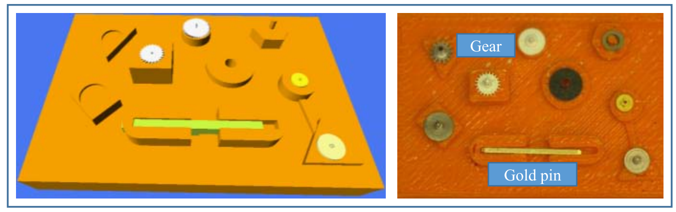



Fig. 1. Virtual and physical assembly views of a meso/micro design.

## II. IoT-Based Test Bed and Framework for Cyber Manufacturing

An IoT cyber physical approach to assembly micro devices has been developed involving cyber components (supporting of planning and VR-based assembly analysis) and physical components (to perform assembly); an advanced IoT-based cyber physical test bed was created to support and validate the approaches and framework discussed in the subsequent sections. Various meso/micro designs were assembled using this test bed including components such as gears, cylinders, stepped shafts, and screws. The role of an information centric approach in designing the building blocks of this IoT-based framework is discussed (Section II) followed by descriptions of the cyber physical components. One of these designs involved a composite part with both micro and meso scale features as shown in Fig. 1. Although there is no universally accepted definition for meso scale, the meso scale description from [48] is followed where meso scale is described as including part sizes greater than 1 mm, with accuracies greater than 25 $\mu$m. In this example, a variety of gears, hollow cylinders, stepped shafts, and metal screw are micrometer-sized parts while the gold pin is in the meso scale range.

### A. *Designing the Cyber Physical Interactions Using Systems Engineering Approaches*

The lack of research on approaches and methods to facilitate the design of cyber physical interactions and activities based on the information/data exchange among the cyber and physical components in a CPS needs to be recognized. This is an important step which provides a foundation for further designing and integrating the various cyber and physical components in any CPS framework. Adopting the function modeling-based systems engineering techniques to design this CPS framework provided a better understanding of the entire IoT-based interactions and the functional relationships among its cyber physical components. Some of the modeling languages used

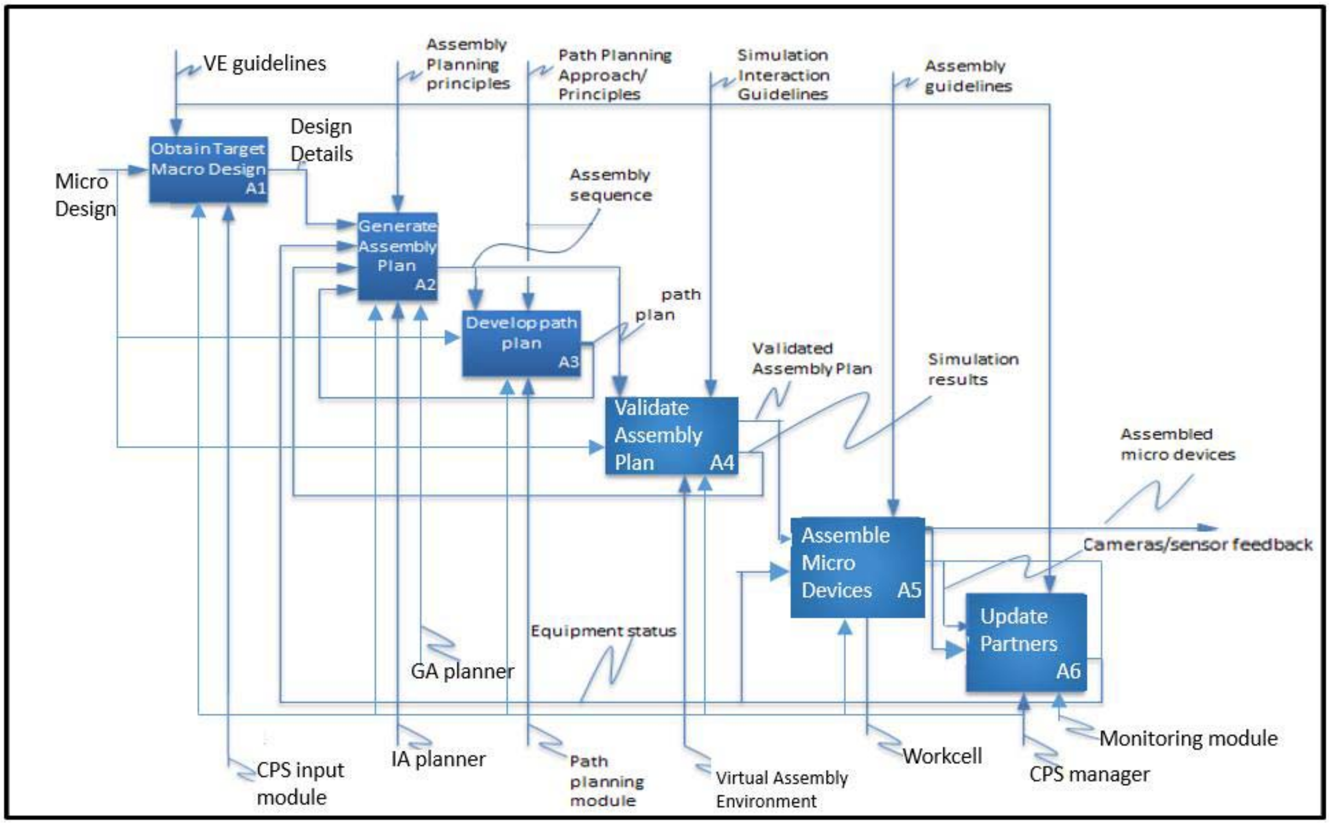



Fig. 2. Designing the IoT-based interactions involving cyber physical components using the IDEF-0 functional modeling methodology.

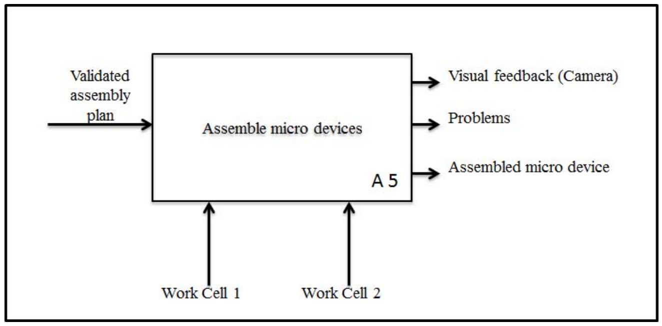
in systems engineering contexts include the systems modeling language [92] as well as activity diagrams (which are part of the unified modeling language); as the emphasis was on identifying the four major attributes associated with each cyber and physical activity in the collaborative MDA life-cycle, the IDEF-0 modeling methodology [116] was used to support this systems engineering activity [117]. These four categories of attributes included the following.

1) Information/data needed for each cyber or physical activity in the collaborative process.
2) The primary controlling entities influencing each activity.
3) The agents or modules responsible for accomplishing each activity.
4) The outputs or outcomes of each cyber or physical activity.

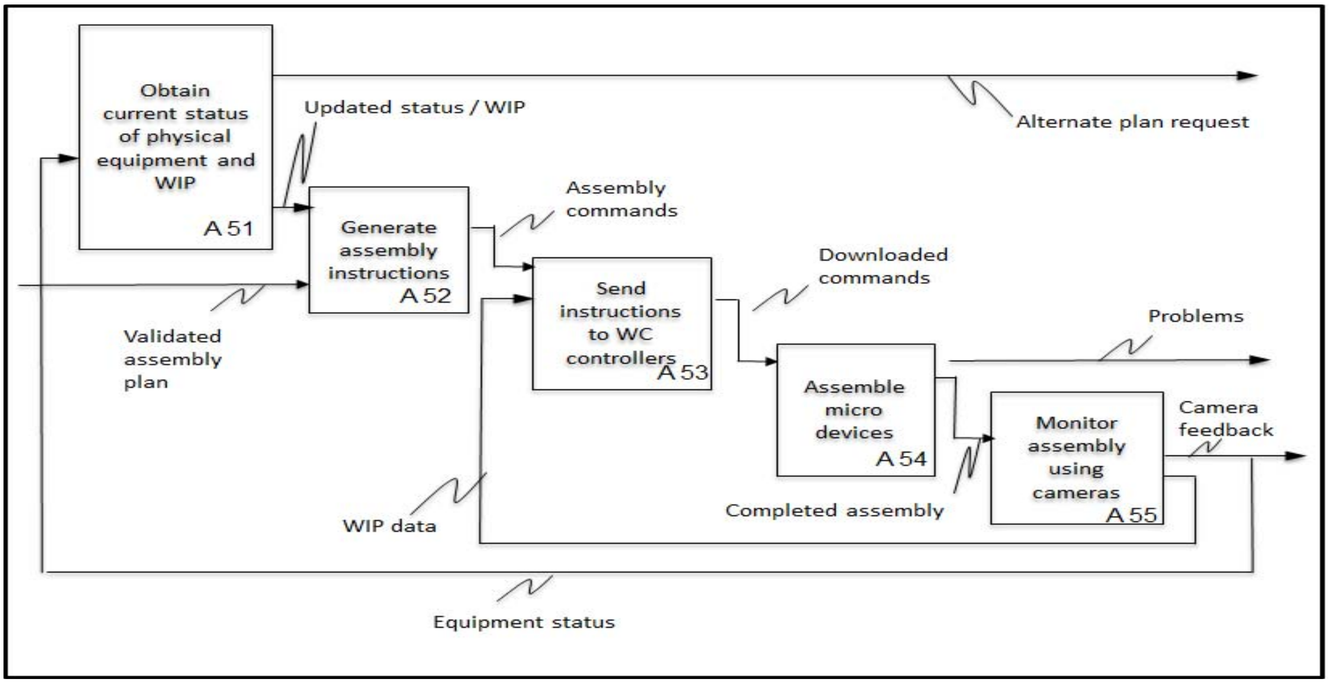
These information centric function models helped the project team comprising of engineers and software specialists (programmers) to understand and design the collaborative approach; the IDEF-0 model was information oriented and scalable in terms of modeling different levels of abstractions. This approach provided a structured foundation to propose, modify, and finalize a given set of CPS interactions. As these interactions formed the core essence of the cyber physical collaborations (that were carried out by both cyber and physical resources), it served as a blueprint for analyzing and integrating the various CPS components functionally apart from providing a basis to link these components using advanced cyber networking. The entire collaborative lifecycle for the micro assembly activities was modeled hierarchically as a set of functional units (responsible for a given cyber or physical function) along with the associated information attributes (information/data inputs, controls, performing agents, and outputs) for these units, along with the functional dependencies among the collaborating components.

The collaborative process context for the IoT framework developed involves a "mini" *micro assembly life cycle* which begins with a user submitting a target design to be assembled; subsequently the assembly plan is generated along with a detailed path plan; after virtually analyzing/modifying these plans collaboratively using VR-based assembly environments, a feasible assembly plan is selected. Subsequently, the physical assembly commands based on the feasible assembly plan is generated; these commands associated with a specific micro assembly task is downloaded to a physical work cell, where the target designs are assembled by robotic resources. During the physical micro assembly activities, the assembly tasks can be monitored by cameras and shared with distributed users in various locations through the cloud. A cloud-based framework supports the sharing of resources and modules used in this life cycle is shown in Fig. 4.

The four types of attributes modeled is shown in Fig. 2 and included information inputs (shown by arrows going from west to east in each activity box in Fig. 2), controlling factors (represented by arrows going from north to south), mechanisms or resources involved in a certain task (indicated by arrows




(a)




(b)

Fig. 3. (a) Elided decomposition of activity A5 "assembly target micro devices." (b) Decomposition of information/data exchange during micro assembly activities (corresponding to A5).

going south to north) and outputs (from each task or activity, indicated by arrows from west to east). As shown in Fig. 4, the various cyber and physical components collaborate to accomplish the overall objective of assembling target micro designs. Fig. 3(a) and (b) provides additional information in the form of decompositions of activity A5 (in Fig. 2) including key data/information flow relevant to the activity "assemble micro devices."

This modeling approach can be applied to manufacturing of less or more complex designs; it provides an information centric foundation to design effective IoT-based approached and frameworks. The decompositions are elided and only the inputs, mechanisms and outputs are shown in Fig. 3(a) and only the inputs and outputs are shown in Fig. 3(b).

The primary input to accomplish target micro assembly activities is the validated assembly plan (as shown in Fig. 2), which is an outcome of three key cyber components (assembly planning module, path planning module, and VR simulation module) working together.

The physical resources available are work cells 1 and 2, which includes micro positioners, grippers, and cameras. The cameras provide real-time feedback as the specific assembly activities progress, along with specific problems encountered during the realization of assembly activities.

The activities were also decomposed as necessary to provide additional understanding; for example, a decomposition of activity assemble micro devices [A5 in Figs. 2 and 3(a)] is shown in Fig. 3(b) provides a more detailed understanding of the data/information exchange in accomplishing this activity. For a given (validated) assembly plan, the physical micro assembly commands are generated by the command generation module (A52) and downloaded to the specific micro assembly work cells (A53). The assembly monitoring module keeps track of the status of the physical equipment as well as monitors the work in progress (WIP) during the micro assembly activities (A55); any equipment breakdown in a given work cell are reported back (as problems, A54) to the collaboration module. Alternate assembly plans can be generated depending on the micro design and the availability of the second work cell. The cameras provide continuous feedback to the distributed users and teams through the cloud (A55). The primary input to accomplish target micro assembly activities is

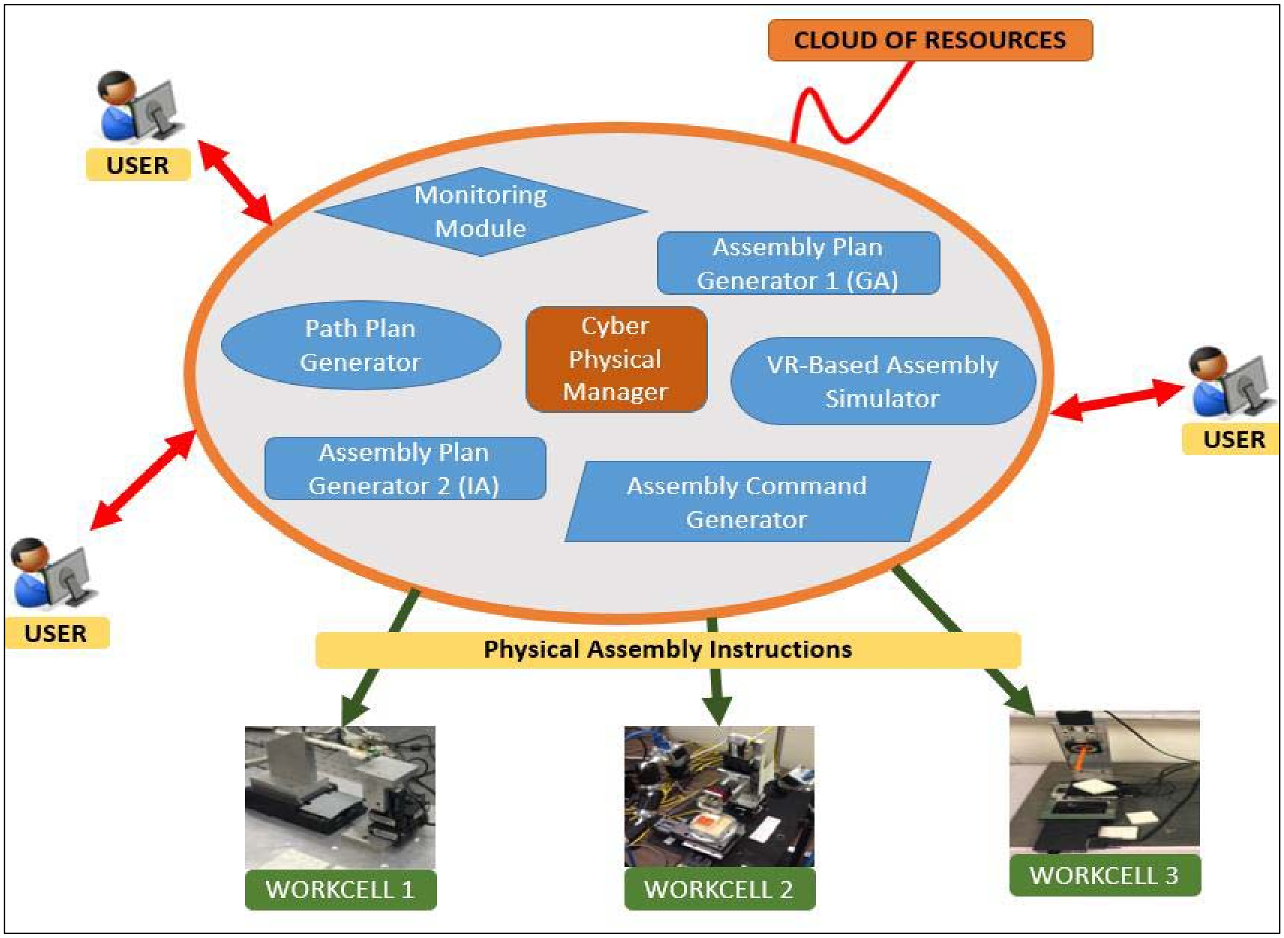



Fig. 4. IoT-based cyber physical framework to support MDA.

the validated assembly plan [as shown in Fig. 3(a)], which is an outcome of three key cyber components (assembly planning module, path planning module, and VR simulation module) working together. The physical resources available are work cells 1 and 2, which includes micro positioners, grippers, and cameras. The cameras provide real-time feedback as the specific assembly activities progress, along with specific problems encountered during the realization of assembly activities.

Fig. 4 provides an overview of the IoT-based cyber physical framework. The framework is composed of a coordination entity called the cyber physical manager (CPM), a cloud to support the collaboration, the cyber components, and the cyber physical interfaces and the physical equipment; the cloud hosts the cyber components which can be categorized into coordination, planning, simulation, and interface components. The planning components deal with developing assembly and path plans for given part designs. The simulation components enable users to assess assembly alternatives using VR environments and equipment. The interface components provide seamless communication between the cloud and physical equipment; these include assembly command generation tasks whose outputs are sent to appropriate physical work cell controllers where assembly tasks are completed. The monitoring provide vital feedback from the physical world to the collaborating partners and sites through the cloud components.

The collaboration among the cyber and physical modules is coordinated through a CPM (Fig. 5) which keeps track of the progress of the life cycle activities using a state chart that updates the various cyber and physical activities. For example, at any given instant, each of these activities can have a token status of not started (NS), in progress (IP), or completed (CO). This allows partners and users to be aware of the overall progress of the cyber physical activities. Fig. 18 shows a view of this state chart for a sample of the physical micro assembly tasks.

Apart from the adoption of IDEF-0 methodology, the collaborative interactions among the cyber and physical modules were modeled as UML communication diagrams (Fig. 6). Communication diagrams, in general, are used to model basic relationships between software classes in a system and provide a top-level view of a group of collaborative objects [27]. While these communication diagrams have been developed for the MDA domain, a similar approach can be adopted to support the design of collaborative activities for manufacturing of other products.

UML-based class diagrams [27] can also be developed as part of the software system design supporting IoT interactions. Such class diagrams describe the structure of a software

| Modules | Input | Output |
|---|---|---|
| Assembly Plan Generation | Part destination coordinates and feeder position coordinates | Assembly plans |
| Path Plan Generation | Assembly plans and obstacles | Collision-free path plan |
| VR-Based Assembly Simulation | Assembly and path plan | Feasible assembly plans and modifications |
| Assembly Command Generation | Feasible assembly plan | Robotic assembly commands |
| Machine Vision Based Monitoring | Real time images of physical work-cells | Assembly completion or work in progress updates |
| Physical Assembly | Robotic assembly commands | Completed physical assembly |

Fig. 5. Inputs and outputs involving various cyber physical components (or modules) in the IoT framework.

system by showing the system's classes, their attributes, operations (or methods), and the relationships among objects.

## III. Cyber Physical Components

In this section, a description of the various cyber physical components in the IoT framework is provided.

### *A. Assembly Plan Generators*

The assembly planning modules aim at determining the feasible assembly sequences for a target micro assembly task. The outcomes of the assembly plan generated is the input to the VR-based assembly simulation environment. For the assembly planning activities, two modules are available for use to mimic the functioning of a VE. Users can generate assembly plans by both these modules, compare them virtually and decide on which plan to use for the physical assembly tasks. One of the modules uses a genetic algorithm (GA) based approach to determine the assembly sequence while the second module adopts a modified insertion algorithm (IA) based approach. The emphasis is not to focus on the optimal generation of the assembly sequences but to demonstrate how multiple cyber modules are available to mimic a VE scenario where engineering partners are capable of performing the same function but using different approaches; in a VE context, these components modules can belong to two or engineering organizations who are part of a newly formed VE partnership that has been formed to respond to an emerging customer need. A discussion of both GA- and IA-based assembly planning approaches follows.

*1) GA-Based Assembly Planning:* GA is an evolutionary algorithm which derives its behavior from evolutionary theory [28]–[30]. The general principle is that after beginning with a random assembly sequence, a better assembly sequence can be generated using genetic operators for the next generation. This process is continued until there is no significant improvement in the assembly sequence. The fitness value is used to guide in the selection of new children sequences. In this GA-based approach, the chromosome is represented as an assembly sequence (comprised of a linked list of part positions) for the physical assembly robot to complete using the gripper and cameras. The inputs to this module include information about the layout of the micro assembly area, the feeders' positions, and destinations of the micrometer-sized parts. The fitness value is the traveling distance involved in completing tasks in an assembly sequence by the robotic gripper. A typical sequence will involve going first to the feeder containing a given part and then going to the destination to insert or manipulate the part, which is then repeated until the entire assembly is completed.

Fig. 7 provides an overview of the key steps of this GA-based assembly approach. The first step involves generating $n$ number of random assembly sequences (called parent sequences). For a sequence containing $n$ parts, the first step involves randomly generating n assembly sequences. To ensure that the assembly calculations are accurate, a 3-D path planner is used to determine collision free path plans which in turn enables to determine the traveling distance used to compute the fitness value. In the first iteration, the sequence (with the lowest distance) is noted. In the subsequent iteration, a next generation of children sequences are generated using genetic operators (using the parent sequences). In our approach, the new children sequences which are better than their parents are generated by 70% cross over and 20% mutation and 10% hybrid operators (which use cross over and exchange operators). The fitness value of the child sequences are compared with the parents and the $n$ child sequences that are better than their parents are selected. The child sequences subsequently become the parent sequences for the next iteration; this process is continued for a large number of

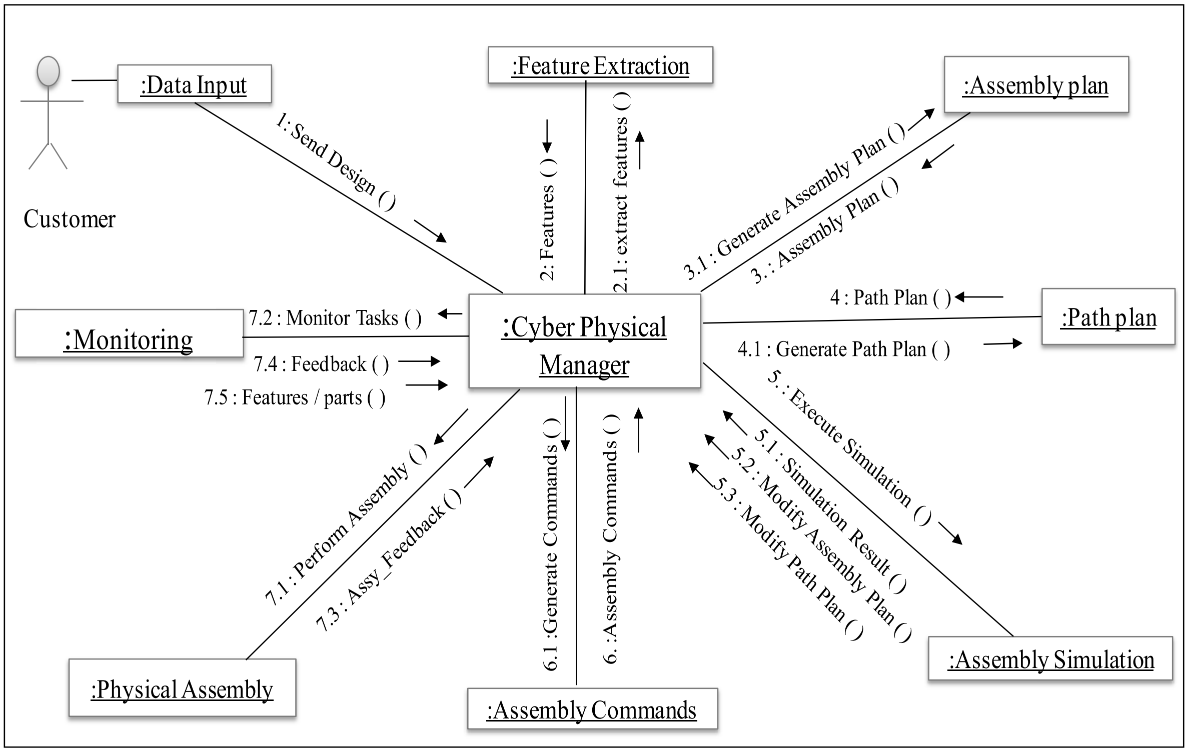



Fig. 6. Communication diagram illustrating the collaborative relationships in the IoT framework.

iterations until there is no significant improvement in the child sequences.

One of the operators used to generate new child sequences is a hybrid cross over operator that uses both cross over and exchange operators. Fig. 8 provides an illustration of how this operator works using four parent sequences containing four parts (A, B, C, and D). The cut point is indicated as $k$ for the cross over operation. The reversal operator is used for the second set of parents (which exchanges the positions of parts C and A in parents 3 and 4) which is followed by a cross over operation (between child 1 and 2) as shown. A part of the child sequence is generated by a combination of a reversal operators (which switches the positions of two parts in parents 3 and 4) followed by a cross over operation (between child 1 and 2). During cross over, if a part already appears in the assembly sequence, the next part from the parent sequence is selected; in Fig. 8, this occurs during the cross over involving child 2 where part D is already present in the first half of the sequence; for this reason, part C is selected followed by part B. The new child 3 is the outcome of this hybrid cross over and exchange operator (which is named ACX after the third author who proposed it).

*2) Modified Insertion Algorithm-Based Assembly Planning:* The IA is used by one of the assembly generators to determine a feasible assembly plan. As indicated earlier, the emphasis is not on generating the best assembly sequence but rather have each assembly module generate a near optimal feasible sequence. These sequences can then be compared in the VR environment and subsequently the distributed users can select a feasible plan. The MDA imposes special requirements on the IA relating to picking up a part from a feeder which precedes placing it into its designated location. The main steps of this modified IA is shown in Fig. 9.

The benefit of adopting a VE-based approach is that multiple partners can propose assembly plans based on their proprietary approaches or algorithms; the CPS manager can compare these sequences based on shortest assembly time as well as process constraints (proximity to obstacles, avoiding paths close to sensitive parts, etc.). Consider an assembly case study involving ten parts and two feeders is shown in Fig. 10; for this design, the GA-based planner generated an assembly sequence with an assembly distance of 115.04 mm while the IA-based generator identified a sequence with an assembly distance of 121.29 mm.

### B. Path Plan Generator

The path planning module is used to ensure that the assembly path is collision free when the gripper is performing its assembly tasks. It returns also the exact distance computed after determining a collision free path for candidate assembly sequences (which is needed to compute the fitness value in the assembly plan generation task). The path planner uses breadth first search (BFS) and Dijkstra's algorithm. BFS is a tree search algorithm which begins at the root node and traverses through all the neighboring nodes in the form of waves in the water. Nodes connected directly to the root node have a distance of unit 1, and its neighboring nodes have the distance of unit 2, etc. When the distance between any two nodes is equal, BFS is used which ensures reaching a destination using the minimal distance. If the distance between

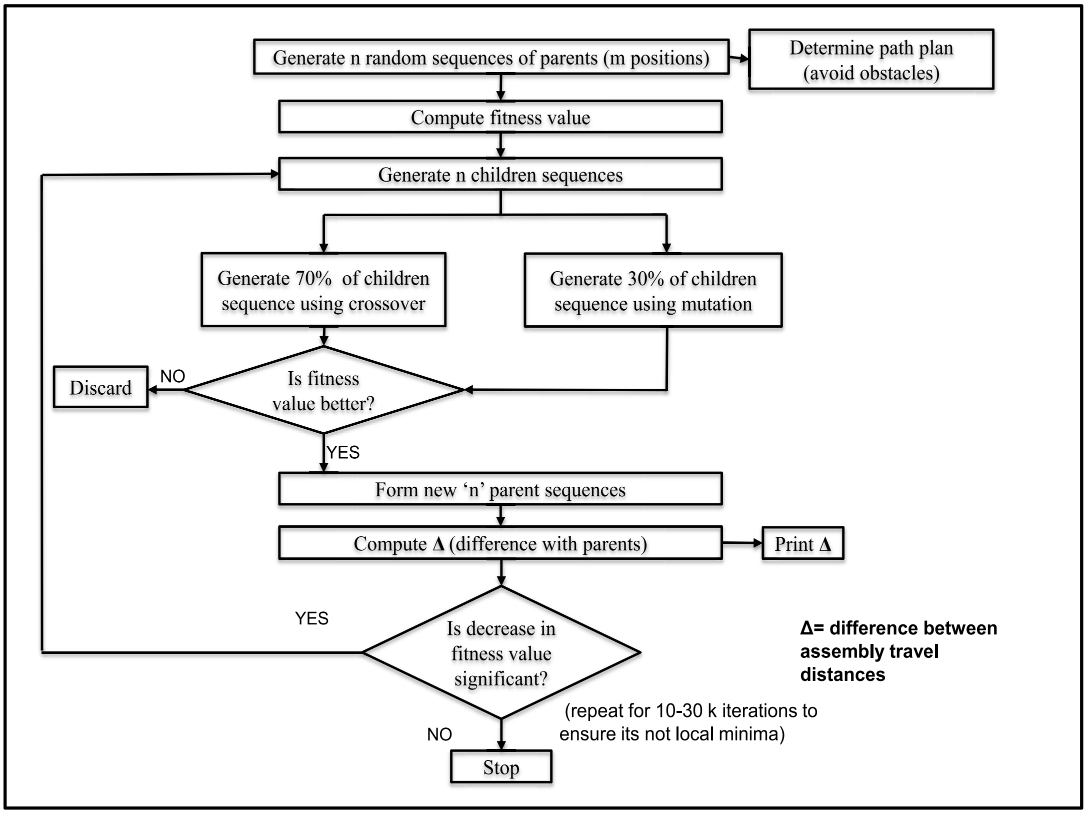



Fig. 7. Flow chart of GA-based assembly approach.

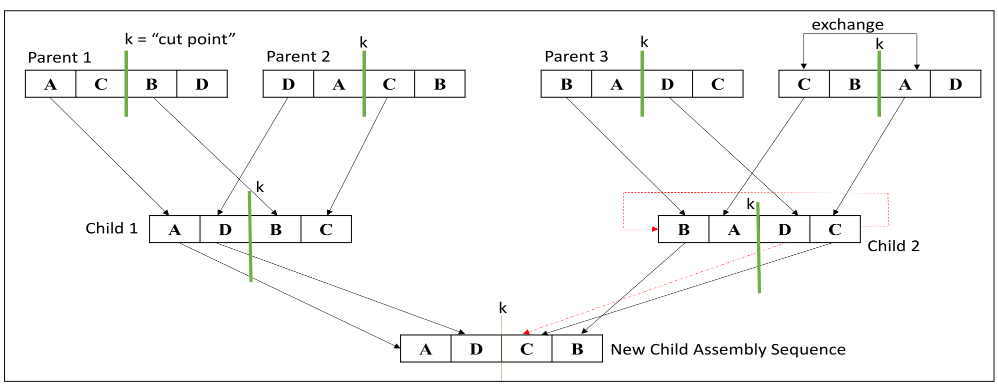



Fig. 8. Hybrid cross over and exchange operator used in the GA-based approach.

the neighboring nodes is varying, then Dijkstra's algorithm is used. The algorithm starts with the source node. All the nodes start with an initial distance of infinity. The source node distance is zero. The neighboring nodes of source distance are compared with its own distance. If the distance of a node is more than the distance from its parent node then the distance is updated. In this way, the algorithm explores all the neighboring nodes till it reaches the destination node. Fig. 11 illustrates the functioning of this path planner. The complete assembly area is divided into a floor map (where the $z$-axis is ignored for brevity) depending on the size of the obstacles which can be sensors and other parts already assembled on the micro part design. The start or source is node 1 ($X$) and the destination is 203 ($Y$). The obstacles are in blue (202, 102, and 103). The collision free path is 1->2->3->4->104->204->203.

## *C. Virtual Reality-Based Simulation Environments for Assembly Analysis*

Three categories of simulation environments with different interaction capabilities were developed to support assembly analysis. These environments include both non-immersive simulation environment, a semi-immersive environment (running on the Powerwall) and a fully immersive Vive-based VR environment. In the semi-immersive and fully immersive environments, users can navigate the 3-D environments using controllers and trackers. The VR-based simulation environments were built using the Unity3D platform to assist the analysis of the assembly/path plans interactively by engineers from different locations. Inputs to this environment are assembly plans and 3-D path plans generated by the assembly planning and path planning module discussed earlier.

1. Define a sub sequence as [Gripper, [feeder1 object1],(*inserting point*) [feeder2 object2],Gripper]
2. Loop and determine the objective function (travel distance) of insertion of remaining objects into the sub sequence.
3. Insert objects with the least travel distance in the sub sequence as follows: [Gripper, [feeder1 object1], (*inserting position1*)[feeder1 object3](*inserting position2*) [feeder2 object2],Gripper]
4. Subsequently, object4 and its preceding feeder need to be placed in position 1 or position 2 according to the least travel distance.
5. Repeat this process until the completion of the entire assembly sequence

Fig. 9. Main steps in the modified IA for MDA.

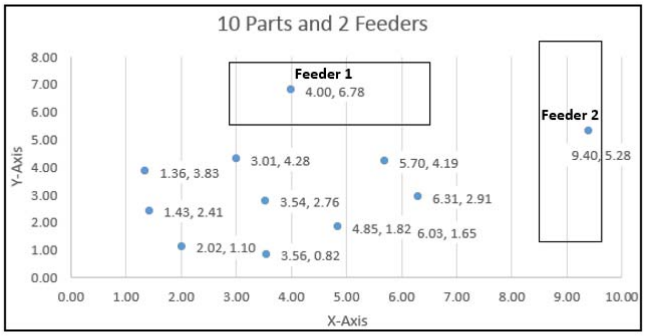



Fig. 10. Layout of parts and feeders.

The CAD models of the various entities (e.g., robots, grippers, etc.) were first created using ProE/SolidWorks and then imported into Unity to create the virtual assembly (simulation) environments. These environments can be described as virtual prototypes or 3-D digital mockups that have behavioral and analysis characteristics that serve as the foundation for the collaborative simulation-based interactions involving the virtual work cells (or assembly environments); multiple users from different locations can interact and collaborate during analysis of candidate assembly and path plans. Depending on the micro design requirements, a specific digital mockup (or virtual prototype) can be selected for the simulation of the identified assembly tasks. Fig. 12 provides a view of one of these virtual environments which is used to "virtually" propose, compare and analyze assembly alternatives. The assembly simulations enable the users to assess the feasibility of the assembly plans, which are shared among the distributed users (and teams) through the cloud. The primary benefit of using such simulation environments is to allow users to study assembly alternatives, validate/modify or identify problems (such as collisions, infeasibility of a path plan, etc.) as well as make changes to the assembly layout to improve the overall assembly process.

In general, users can use one of the three VR environments. However, only the nonimmersive environment is networked for real-time distributed collaboration. The Vive-based system can be used as a stand-alone environment for analyzing assembly plans; subsequently, these models can be brought into the cloud-based environment for distributed interactions using the GENI technologies (discussed in Section IV). A view of the Vive-based immersive environment in use is shown in Fig. 13.

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|---|---|---|---|---|---|---|
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| 301 | 302 | 303 | 304 | | | |
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Fig. 11. Path planning approach to avoid obstacles.

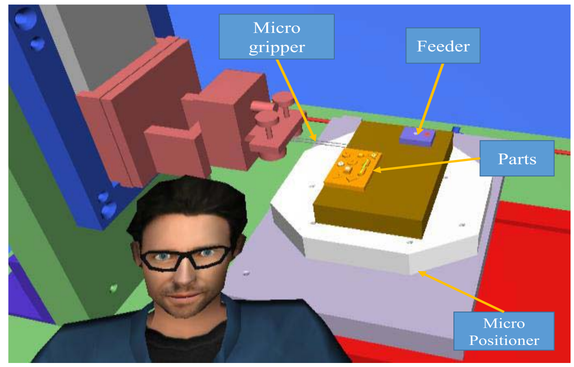


Fig. 12. View of virtual environment for micro assembly.

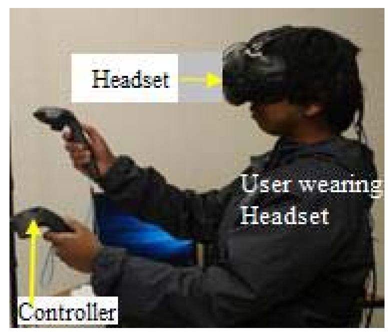


Fig. 13. User interacting with the Vive-based assembly analysis environment.

The Vive™ (Fig. 13) is fully immersive [118] and comprises of a headset (with a 110° field of view) and two wireless handheld controllers (to navigate and explore a target environment). Users can navigate, walk around, and study assembly alternatives; they can also modify the layout of the assembly area by using the controllers (Fig. 13); the trackers are mounted on stands near the user. A view of the simulation environment that a user sees is shown in Fig. 12.

### *D. Physical Command Generator for Robotic Assembly*

The function of the command generator module is to use the feasible assembly and path plan validated in the VR-based simulation environment and then generate the detailed physical assembly commands for the respective micro assembly work cells.

Depending on the dimensions of a given part design and the capabilities of the three work cells, an appropriate work cell can be selected for the assembly analysis; after the assembly plans are compared and validated, the corresponding work cell commands are generated. The commands are downloaded to

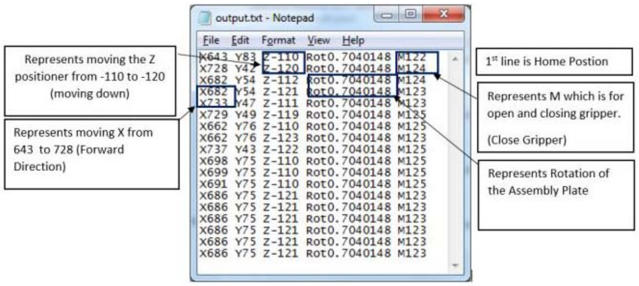


Fig. 14. Part of a complete program to perform micro assembly tasks using a work cell.

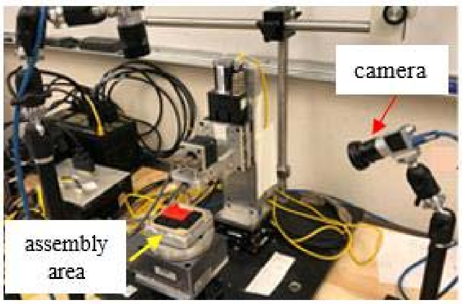


Fig. 15. View of a physical work cell.

the work cell controller where it is assembled. This activity involves a human user also monitoring the work cell in reference during the physical assembly. Additional measures and capabilities are under implementation to ensure safe operation of these robotic resources.

Fig. 14 provides an example of the robotic micro assembly commands used in work cell 2 (Fig. 15); these commands are a part of a larger program to accomplish a target assembly.

### *E. Physical Micro Assembly Components and Resources*

Physical micro work cells are used to support the IoT-based approach for collaborative manufacturing. They typically comprise of work tables, micro positioners, micro grippers, fixtures, feeders, and cameras. These components have sensors and can be viewed as *things* which can transmit relevant data of a WIP or assembly completion to the cloud which is communicated to other resources and partners. Each work cell has multiple cameras and engineers can remotely monitor the assembly status of other micro work cells in different locations.

Figs. 15 and 17 show views of one of these physical micro work cells; it is equipped with the assembly plate with two linear and one rotation degrees of freedom; it is capable of supporting different grippers for assembling 30 $\mu$m to 1 mm. Two cameras are available for assisting in the assembly activities as well as for monitoring the progress of the assembly tasks. The gripper is mounted on a micro stage capable of motion in the $z$-axis. Feeders are positioned around the target assembly part.

### *F. Monitoring and Machine Vision Module*

In the IoT-based approach, a monitoring and machine vision module keeps track of the physical micro assembly activities

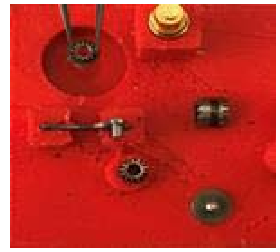

Fig. 16. Camera view during assembly.

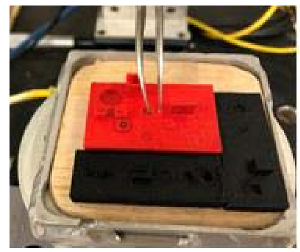

Fig. 17. Close-up view of the assembly area in a work cell.

in the work cells (Fig. 16). This module was developed using OpenCV, which is an open source computer vision and cross-platform library [32]. It is used to help identify part positions and gripper movement during assembly as well provide updates on the overall assembly tasks IP to the CPM and distributed partners.

Fig. 16 shows a view from the monitoring camera during assembly. A state chart table (Fig. 18) is used to keep track of the assembly activities which is communicated to the CPM; a similar chart is used for cyber activities as well. Each cyber or physical activity can have a token status (or state) of NS, IP, or CO.

## IV. Next Generation Networking Supporting Collaborative Interactions

The cloud networking approach implemented enables users to interact from different locations. GENI networking principles have been used to support users collaborating and analyzing assembly plans from different locations. The GENI [27], [37], [58] initiative explores the design of the next generation of Internets including the deployment of software designed networks and cloud-based technologies (among others). SDN reduces the complexity networks, as well as help cloud service providers host large numbers of virtual networks without common separation isolation methods [67], [114]. These and other initiatives (such as U.S. Ignite) highlight the emergence of the next generation computing frameworks which have an important role along with other technologies in supporting global IoT-based advanced manufacturing practices.

The VR-based simulation application is built on top of Unity, which is a multiuser gaming and simulation platform. In the architecture implemented (Fig. 19), a user is associated with a simulation client (SC). Through a command interface, a user interacts with an SC and thereby participates in the simulation. The simulation server (SS) has several critical

| Nature of Interaction | Physical Task | Status or Outcome | Visual Feedback images (from camera monitoring module) |
|---|---|---|---|
| Physical | Gripper Moves to feeder | CO |  |
| Physical | Pick up part | CO |  |
| Physical | Move along x-axis | IP |  |
| Physical | Gripper moves to part destination | NS |  |

Fig. 18. Snap-shot of the state chart (at a given state) used to keep track of physical activities.

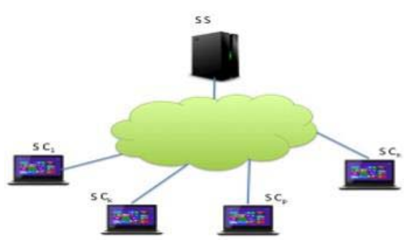


Fig. 19. Multiplayer MDA architecture in Unity. SS is the simulation server, and SC(s) are the simulation clients.

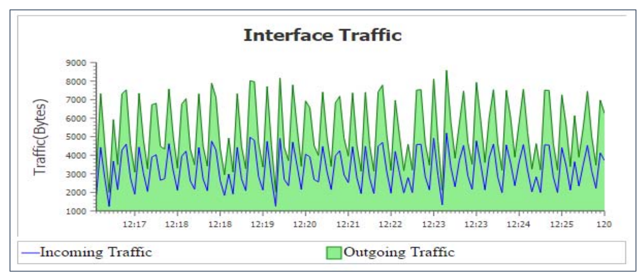


Fig. 20. Data traffic during the IoT interactions.

coordination roles in this architecture. A client joins by first registering with the SS. If the simulation is already ongoing when an SC joins, the SS exchanges a sequence of messages with the new SC to synchronize the state of the SC to that of the other SCs. The SS also exchanges periodic heartbeat messages with each SC. If the SS does not a get heartbeat response from an SC, it deregisters the SC from the simulation. Through this mechanism, users can enter or exit the simulation at any time of their choosing without disrupting the other SCs. The SS also assists in keeping all the clients synchronized. Specifically, a client can use the Unity application programming interface to ensure the changes in its state are made visible to all SCs. It is completely flexible in the sense that an SC decides when and what state changes should be visible to other SCs. Due to communication delays, there may be latency in propagating changes from one SC to the others. Emerging Internet architectures such as GENI networks have the ability to reduce such latency. In this regard, the IoT framework has taken advantage of the SDN capabilities of GENI.

In the MDA application context, the users or engineers are referred to as MDA client. To maintain consistency, at any given time, only one MDA client has a control "token" that gives him/her the right to modify the state (e.g., to modify assembly plan); the other clients can watch the changes being made by the MDA client who has this control token. A command interface allows an MDA client (with the control token) to pass the "control" to any other MDA client during distributed collaborations.

## V. Discussion

Various meso/micro designs were assembled using this IoT-based cyber physical test bed. This cyber physical test bed was used to accomplish the MDA life cycle activities involving users and partners in Washington, DC, USA, Stillwater, OK, USA, and Madison, WI, USA. Other collaborative interactions were carried out between Stillwater and Aix-En-Provence France. The performance of the GENI-based network in supporting this IoT-based framework was studied for multiple scenarios involving distributed locations. Performance measurements of traffic was performed using GENI desktop (Fig. 20). The network latency between these multiple locations was measured using ICMP ping (Fig. 21). As can be seen from Fig. 21, the latency is stable at around 46 ms. These experiments indicate the feasibility of the overall GENI-based network to support distributed interactions using the IoT framework discussed in this paper.

Adhesive forces come into play during assembly and may cause the part to stick to the gripper surface; modeling and simulating the effects due to the presence of these forces is continuing as part of efforts to expand the

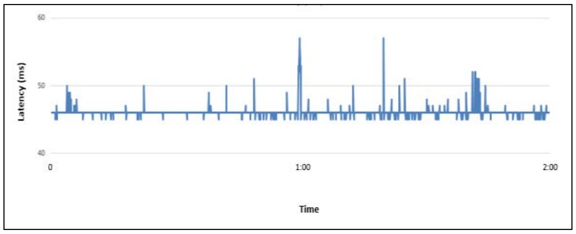


Fig. 21. Latency during the IoT interactions (2-h period).

simulation capabilities within the IoT-based collaborative framework.

The adoption of an information centric systems engineering approach enabled the project team to design the cyber physical interactions by modeling the functional relationships and data/information integration "hooks" essential for collaboration. This information centric approach, the use of VR-based simulation environments and the adoption of next generation networking technologies are core elements of this IoT-based framework which can be applied to process contexts; the core elements of this innovative framework have been used to support IoT-based practices in electronics manufacturing [115] as well as VR-based simulation activities to train orthopedic surgical residents [119].

## VI. Conclusion

In this paper, an IoT-based cyber physical framework and approach for collaborative micro assembly was discussed. A mix of cyber and physical components collaborate to accomplish assembly planning, path planning, VR-based simulation, command generation for assembly, and finally physical assembly of micro parts. An IoT-based cyber physical test bed was implemented based on the proposed approach. An information centric systems engineering approach was adopted to design the functional interactions involving the cyber and physical components. Using this test bed, users among geographically distributed locations were able to interact and collaborate using next generation GENI-based networking technologies. Experiments and assembly activities completed demonstrated the feasibility of the proposed IoT-based framework for collaborative micro assembly.

This advanced test bed is the first major implementation involving IoT-based technologies supporting collaborative manufacturing practices. The collaborative framework implemented is also the first reported implementation in manufacturing contexts involving the adoption of GENI-based next generation networking principles. The underlying approach and framework outlined in this paper for the domain of micro assembly can be applied to other manufacturing and nonmanufacturing domains as well.

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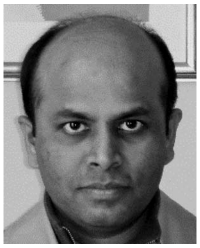

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