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ARTICLE

(Smart CPS) An Internet-of-Things (IoT) based cyber manufacturing framework for the assembly of microdevices

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ABSTRACT

The emergence of Cyber-Physical Systems (CPS) based principles and technologies holds the potential to facilitate global collaboration in various fields of engineering. Micro Devices Assembly (MDA) is an emerging domain involving the assembly of micron-sized objects and devices. In this paper, a novel IoT based Cyber-Physical framework for MDA is discussed. The proposed IoT framework is the first of its kind for the process domain involving the assembly of micron-sized parts. Another innovation is the exploration of the feasibility next generation Software Defined Networking (SDN) principles to support distributed collaborations involving cyber and physical components within this framework. A unique information model-based monitoring approach is proposed to monitor and track the cyber-physical interactions. The advanced collaborative Cyber-Physical framework comprising of cyber and physical components linked using Next Generation Internet technologies has been developed to accomplish a targeted set of MDA life cycle activities which include assembly planning, path planning, Virtual Reality (VR) based assembly analysis, command generation and physical assembly. Genetic algorithm and modified Insertion algorithm-based methods have been proposed to support assembly planning activities. Advanced VR-based environments have been designed to support assembly analysis where plans can be proposed, compared and validated. The feasibility of the Cyber-Physical approach has been demonstrated by implementing an IoT Test Bed to assemble micro designs.

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KEYWORDS

Cyber-Physical Systems (CPS); Internet-of-Things (IoT); Advanced Manufacturing; Micro Devices Assembly (MDA); Next Generation Internet; Industry 4.0

Introduction

Micro Devices Assembly (MDA) refers to the manual, semi-automated and automated assembly of micron-sized parts (Cecil, Powell, and Vasquez 2007; Jain et al. 2015; Rabenorosoa et al. 2009; Zhang et al. 2010; Das and Popa 2010; Popa and Stephanou 2004). In MDA, parts are in the scale of 10^{-3} to 1 mm. MDA is an advanced manufacturing field specialised in providing technological techniques to handle the assembly of micron size devices/parts. Manual assembly of micron parts is tedious, hard and time-consuming which urge engineers to incorporate various techniques to automate or semi-automated the micron-sized assembly. The equipment and software resources in the field of MDA are expensive which dictates the need for collaboration and sharing of both cyber and physical resources. In general, a Cyber-Physical System (CPS) is defined as a system which involves collaboration between two classes of resources: software (cyber) entities and physical devices (which interact, interface or integrate with other physical devices or with the cyber components). CPS (Shi et al. 2011; Correll et al. 2009; Thiagarajan et al. 2011; Rajkumar 2012; Michniewicza and Reinharta 2014) is enabled through linking cyber (software components) and the physical (hardware components) together to support various engineering and other activities. CPS-based approaches are recognised to have substantial potential to support collaborative activities in advanced manufacturing including micro assembly and other fields. The recent emergence of Internet of Things (IoT) principles and technologies (Seo et al. 2016; Kelly, Suryadevara, and Mukhopadhyay 2013; Khaleel et al. 2015; Yang et al. 2014; Da Xu, He, and Li 2014) holds the potential to support Cyber-Physical interactions involving distributed components in various fields of engineering; in general, IoT can be described as a set of network entities (software and physical) embedded with computational and sensory capabilities. The emphasis of IoT is on exchanging of data to perform computing or non-computing activities. These entities can collaborate with other IoT entities as part of the Internet and other cyberinfrastructure at various levels of abstraction and network connectivity.

Virtual Reality (VR) based simulation approaches have been explored in manufacturing contexts to study process design issues and identify downstream problems early in the design cycle (Probst et al. 2009; Alex, Vikramaditya, and Nelson 1998; Ferreira and Hamdi 2004; Luo and Xiao 2006; Sun et al. 2005). In the field of MDA, there has been a focus on creation of automated methods for MDA (Alex, Vikramaditya, and Nelson 1998; Luo and Xiao 2006), design of novel gripping techniques (Sanchez-Salmeron et al. 2005; Cassier, Ferreira, and Hirai 2002; Popovic et al. 2002) and use of machine vision to support automated of MDA activities (Cecil, Powell, and Vasquez 2007; Alex, Vikramaditya, and Nelson 1998; Ferreira and Hamdi 2004; Luo and Xiao 2006; Rabenorosoa et al. 2009; Cassier, Ferreira, and Hirai 2002). VR-based environments have been used to facilitate micro-assembly tasks by several researchers (Probst et al. 2009; Ferreira and Hamdi 2004).

CPS-based approaches have been explored in various fields (Shi et al. 2011; Thiagarajan et al. 2011; Rajkumar 2012;

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Michniewicza and Reinharta 2014) including automating a garden (Correll et al. 2009). IoT-based approaches have been adopted in variety of fields from monitoring system to smart homes (Seo et al. 2016; Kelly, Suryadevara, and Mukhopadhyay 2013; Khaleel et al. 2015; Yang et al. 2014; Da Xu, He, and Li 2014). The importance of Industry 4.0 principles for next-generation manufacturing needs to be recognised (Khaleel et al. 2015) where the emphasis is on linking machines and systems in manufacturing settings to support intelligent networks facilitating autonomous control. Industry 4.0 principles will play a key role in supporting IoT-based collaborations for factory automation (Khaleel et al. 2015; Liu and Yu 2013; Bi, Da Xu, and Wang 2014; Da Xu, He, and Li 2014). Cloud computing techniques for manufacturing applications have been explored by various researchers as well (Xu 2012; Tao et al. 2014).

MDA resources, in general, are limited and expensive; unlike other manufacturing fields, there is only a limited number of engineering and manufacturing organisations who have the expertise and resources to accomplish micro assembly planning and assembly activities. This underscores the need for collaboration and sharing of both cyber and physical resources; for these reasons, there is a need to develop frameworks to facilitate collaboration and sharing of cyber and physical resources to support MDA activities using a Virtual Enterprise (VE) model. A VE refers to a virtual partnership designed to facilitate co-operation and integration between the partners (Browne and Zhang 1999; Cecil 2003). The partners can be suppliers, designers, manufacturers, assemblers among others (Browne and Zhang 1999). This paper addresses the design and implementation of such a complex Cyber-Physical framework interacting through IoT concepts. Preliminary design and implementation of some of the Cyber-Physical components for supporting micro assembly have been discussed in our prior publications (Cecil et al. 2017; Cecil, Gunda, and Cecil-Xavier 2017; Cecil and Jones 2014; Gopinath, Cecil, and Powell 2007).

While the current Internet has become omnipresent in supporting wide range of applications, it has not been able to support applications requiring high bandwidth and low latency. In the US, the Global Environment for Network Innovations (GENI) is an initiative focusing to create the next generation networking technologies including software-defined networking along with facilitating multi-gigabit bandwidth and low latency (www.geni.net; www.protogeni.net) is underway.

Based on the literature review, the following voids have been identified:

(a) While there have been various research efforts focusing on conceptual ideas and approaches involving Cyber-Physical systems (CPS) and IoT-based frameworks in manufacturing, there has been less emphasis in the research literature on advanced implementation of such IoT based Cyber-Physical frameworks involving support of the life cycle of manufacturing activities especially in the emerging domain such as MDA
(b) Prior IoT and CPS related papers have not explored the adoption of Next Generation Internet technologies including Software Defined Networking (SDN) to support the collaborative exchange of complex data involving Virtual Reality based simulation and other Cyber-Physical interactions.

In this current paper, the capabilities of the assembly planning modules have been extended to mimic a Virtual Enterprise by supporting multiple assembly generation strategies. A more advanced VR assembly environment has been developed allowing more advanced distributed user interactions along with command generation capabilities to control the manufacturing activities in the automated work cells within this Cyber-Physical framework; another unique aspect is providing a haptic-based interactive capability where users can modify assembly layouts using haptic interfaces from various locations. The performance of the SDN networking approach implemented with respect to latency for both haptic and non-haptic interactions has been studied as well.

The use of such next-generation networking technologies has been explored to support the IoT-based framework outlined. In this context, there is a need to explore the design of IoT based Cyber-Physical frameworks for MDA which harnesses next-generation Internet networking technologies.

The life cycle of the cyber-physical framework

The life cycle of the Cyber-Physical interactions studied in this framework includes obtaining a data input for target micro-assembly tasks, assembly planning, path planning, and VR-based simulation of assembly tasks, and physical assembly of target microdevices. The cyber components of this IoT framework are shared through a Cloud hosting these collaborative resources (along with the cyber-physical interfaces to the manufacturing work cells) to enable geographically distributed users to access them. Figure 1 provides an overview of this IoT based cyber-physical framework.

Figure 2 provides an overview of the IoT interactions within the C-P framework. The process life-cycle of these interactions include generation of assembly plans, validation/modification using VR-based simulation analysis, generation of assembly commands based on simulation outcomes and final assembly of the micro parts; a collaborative Cyber-Physical Manager (CPM) and monitoring (feedback/tracking) module is also part of this framework.

Assembly Planning Module

The Assembly/Path Plan Generation Module takes an input of customer requirements, location of micron parts and feeders and generates a near optimal assembly plan. Users have options to generate assembly plans using Genetic or Insertion Algorithms (which are discussed in section 3).

VR Assembly Analysis Module

The VR assembly environment can be used to compare, propose and evaluate/validate candidate assembly sequences from distributed locations. After a candidate assembly sequence is analysed and determined to be feasible, it is then communicated to the Physical assembly components through the cloud interface where the assembly tasks are completed.

Command Generation for manufacturing tasks

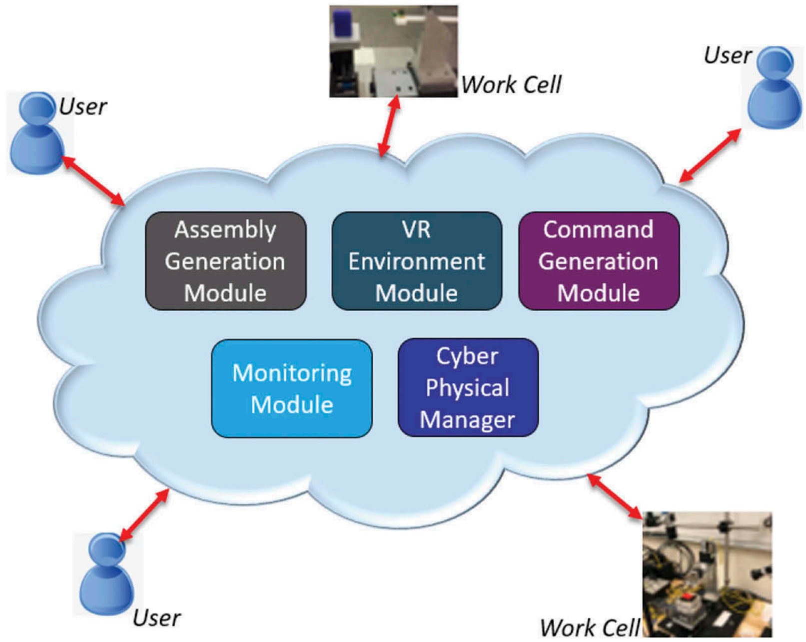

Figure 1. Overview of the IoT-based CPS framework.

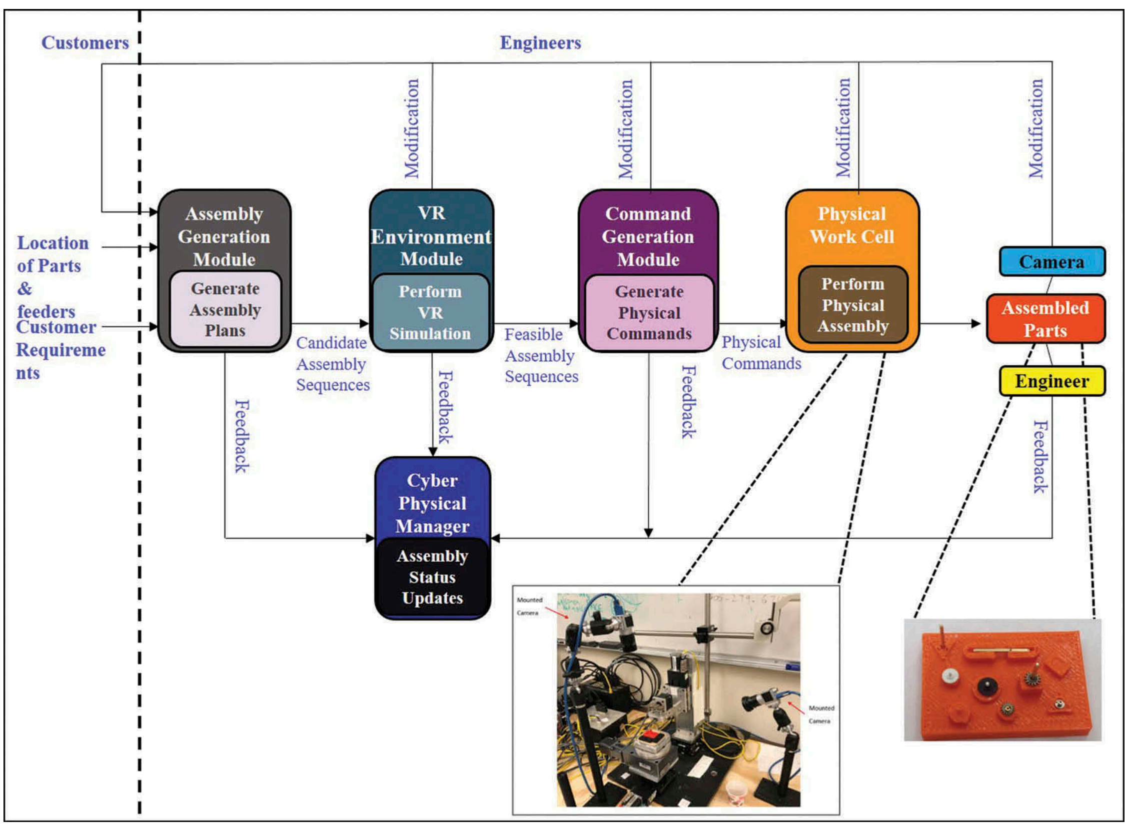

Figure 2. The cyber-physical interactions in the IoT-based framework.

The feasible assembly sequences from the VR-based assembly analysis module is the basis for generating machine-specific controller level commands which are then relayed to the appropriate physical work cells.

Cyber-Physical Manager (CPM)

The collaborative IoT-based life-cycle is coordinated by a Cyber-Physical Manager; as the cyber and physical activities progress, they are monitored by this CPM and communicated to distributed locations. Monitoring cameras provide tracking information and feedback to this CPM to ensure progress of physical activities. This CPM maintains overall control of the various interactions among the various modules discussed using the feedback data. An information model-based monitoring approach is proposed to monitor and track the cyber-physical interactions (discussed in section 6).

Assembly generation module

Obtaining a near-optimal sequence of given micro-assembly plans is supported by this IoT framework taking into consideration a Virtual Enterprise (VE) oriented context where more than one potential enterprises is interested in being part of the collaborative partnerships and there is more than one potential way to generate these assembly sequences (through different approaches from each organisation). To mimic such a VE-based theme, two assembly sequencing modules have been designed and made available which are implemented based on two approaches: The first is Genetic Algorithm GA-based approach and the second is a modified Insertion algorithm IA-based approach. The use of two algorithms shows the importance that the CPS can handle VE type scenarios were partners can provide different sequences based on different approaches; these candidate sequences can be compared and validated in the Virtual Reality based assembly environments.

Genetic algorithm (GA) based assembly sequencing

GA (Muhlenbein 1992; www.obitko.com/tutorials/genetic-algorithms; mnemstudio.org/genetic-algorithms-algorithm.html) is a heuristic search algorithm that harness the idea of evolutionary of the fittest chromosome. It follows the natural selection of the best chromosome based on genetic operations performed on parents that should yield better children that can survive harsh tests. GA approach exploit randomised search which tries to narrow down the search space by directing the search to better regions within the search space. The fitness score represents the distance of traversing all the points in the sequence. Figure 3 shows the flow chart of the main GA steps.

The following is a summary of the main steps of the GA-based approach:

(1) Generate random population of parents for the first iteration
(2) Calculate or Measure the fitness score of the population (corresponding to the assembly distance)
(3) Perform the following process
    a. Select parents randomly from the population
    b. Perform crossover on randomly selected (two) parents and generate new child sequences
    c. Perform mutation on one random parent; generate new child sequence
(4) Calculate the fitness score for each of the generated children sequences; select these children sequences from both cross over and mutation outcomes as the new parents. The GA heuristic adopted generates 70% of new children using cross over operation and 30% of new children using mutation operation.

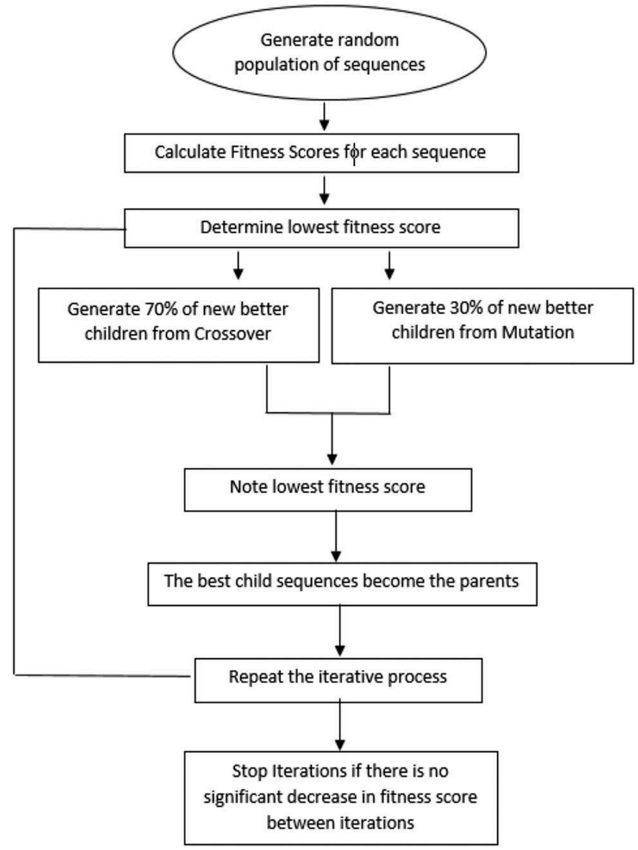

Figure 3. The main steps of the GA-based assembly planning approach.

(5) Repeat step 3 using the children sequences with lesser assembly distances as the new parents; repeat this process until there is no significant decrease in the fitness score of the children sequences. The near-optimal sequence generated is noted and used in the analysis of the assembly plans by the VR-based analysis environment.

Modified insertion algorithm (IA) based approach

IA (http://web.tuke.sk/fei-cit/butka/hop/ConstructiveHeuristicsForTheTSP.pdf) is considered one of the leading approximation algorithms that provide near optimal results at minimal cost. Analysis of the algorithm evaluates its outcome to be less than two times of the optimal sequence plan. An inclusion of the feeder distance is a must due to the special case of the assembly of micron-sized parts where a robot needs to pick an object from a feeder then places it into the designated location. These conditions dictate modification of the IA (hence, the term modified insertion algorithm). Figure 4 shows the flow chart of the main steps of the IA.

The following is the steps of the proposed modified IA for the MDA:

(1) Define an initial sequence that begins with home position and ends with it. [Gripper–Gripper]
(2) Insert a target part into this sequence preceded with travelling to its corresponding feeder into the subsequence which yield least increase of distance among all

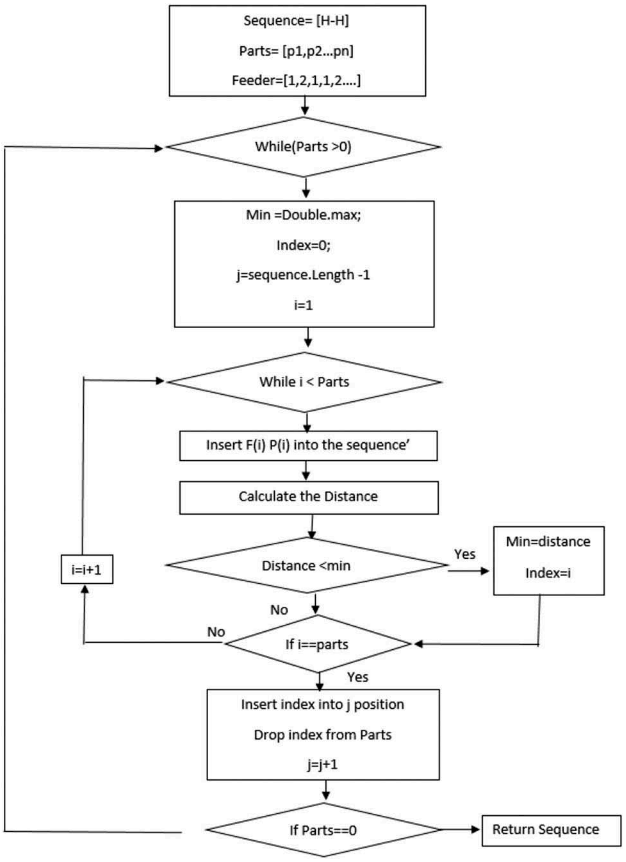

Figure 4. Key steps in the modified IA-based approach.

parts. (e.g. Part 3 can be inserted into the subsequence if it yields the least travelling distance compared to visiting any other device [Gripper -[Feeder, Part P3]-Gripper]

(3) Repeat this process with another part Pn which needs to be assembled in the micro design.

(4) To accomplish step 3, measure the cost of insertion of remaining objects into the subsequence and insert objects with the least cost of increase in the subsequence.

(5) Sub Sequence will appear as: [Gripper, [feeder1 part1], (inserting position1) [feeder1 part3] (inserting position2) [feeder2 part3], Gripper]

(6) Repeat this process until all parts appear in the assembly sequence.

Results received from GA and IA assembly plan generating components contain assembly sequences that are input to the VR assembly analysis environment. Examples of these assembly sequences are shown in Figures 5 and 6 for an assembly involving 10 micro parts and 2 feeders. The results show that GA-based approach generated an assembly sequence with an assembly travel distance of 115 mm. On the other hand, the IA-based approach generated an assembly sequence with a distance of 121 mm; however, the IA-based approach generated the assembly sequence in a faster time frame. There will always be a trade-off between time and distance in such scenarios. The IoT framework involving multiple assembly plan generation capabilities provides the users flexibility in deciding the assembly sequence based on either assembly time or plan generation time. During the calculation of the assembly sequence, the assembly distance is calculated using a Path Planning Module which determines a collision-free path between two consecutive pair of micro-part destinations. The intent is to employ one of the existing methods for path planning; a path planning approach has been adopted based on the A Star (A*) algorithm (Ferguson, Likhachev, and Stentz 2005; Dechter and Pearl 1985).

VR-based assembly analysis environment

An advanced VR environment has been designed to study the feasibility of an assembly plan in a virtual environment. The VR environments are 3D graphics simulation environments built using Unity Game development software which uses two programming language C# and JavaScript. Figure 7(a) shows a view of one of the VR environments for one of the work cells and Figure 7(b), which shows a view of that corresponding physical work cell. Through the VR environment, users can either use the assembly plans generated by IA or GA or can manually propose their own assembly plans and compare it with the automated generated plans and select the most preferable plan. Subsequently, the validated assembly plan is converted into physical commands that can be downloaded to a computer linked to the physical Work cells, where target parts are assembled.

GENI-based framework to support distributed VR environments

The Global Environment for Network Innovation (GENI) initiative involves the design and deployment of advanced networks and approaches that have several innovative

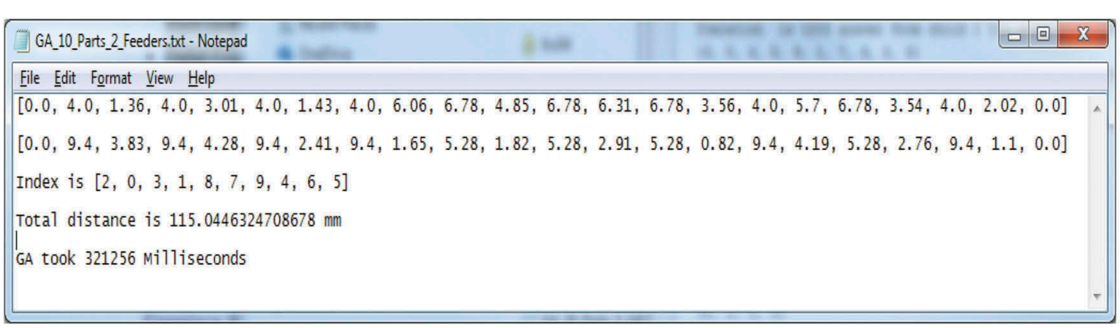

Figure 5. Example (output) of a GA-based assembly sequence.

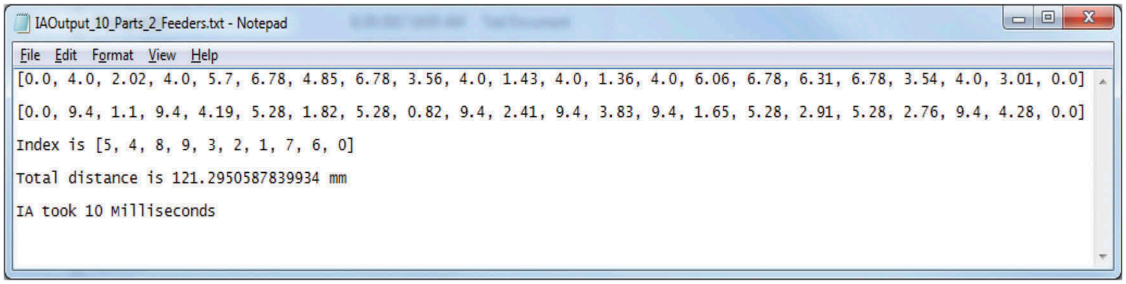

Figure 6. Example (output) of an IA-based assembly sequence IA sequence.

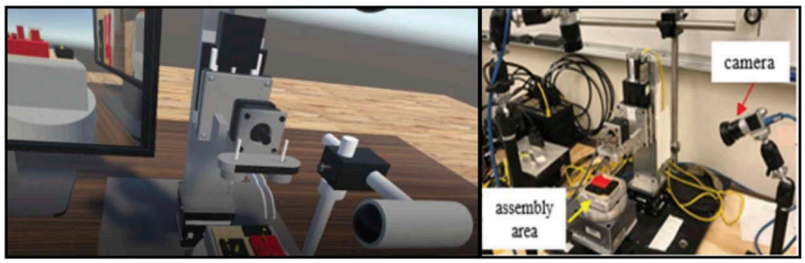

Figure 7. (a) VR environment for workcell (left) and (b) Corresponding Physical work cell.

aspects including Software Defined Networking (SDN) and adoption of cloud technologies. The current Internet has several drawbacks to supporting distributed collaboration including lack of resiliency to server failures (http://www.geni.net; www.ict-fire.eu; Berman, 2014). In this approach, Software Defined Networking (SDN) principles have been used to increase resiliency to simulation server failures. In general, SDN enables network control to be directly programmable; this enables networking operations to be more agile, centrally managed, open standards-based and vendor-neutral. SDN not only reduces the complexity seen in today's networks but also helps Cloud service providers host millions of virtual networks without the need for common separation/isolation methods (www.opennetworking.org/sdn-resources/sdn-definition). Consequently, improved collaboration between distributed locations to access and share resources especially involving high bandwidth data and low latency is facilitated; the rationale for using such networking approaches to enable sharing of VR-based environments data (involving rich 3D VR data) across heterogeneous platforms as well as support low latency-based collaborations between distributed users.

The VR-based simulation interactions between distributed users and sites were using Unity 3D, Virtual Reality engine. As the Unity-based architecture can experience single point failure of the Unity Server, in situations where the Unity server fails and/or if network connection to this server fails, the entire system will fail.

In the distributed collaboration context of the MDA life-cycle, the participants are the engineers at different locations who can collaborate and propose assembly alternatives, modify the assembly layouts using Geomagic Touch™ haptic devices, study their feasibilities, compare the alternative plans and identify the most feasible assembly plan. They can be viewed as engineering clients ECs. Only one EC has a 'token' for modifying a state (e.g. perform an assembly simulation or analysis task); the other clients in other locations can observe the changes being made by this client who has the control token, which can be transferred from one client to another.

Figure 8 shows the SDN-integrated architecture of the surgical application. There are r redundant simulation servers (SS) in this architecture. In this architecture, it is possible to tolerate the failure to connect to up to r-1 SS; this is possible as the clients do not connect directly to the simulation server. Instead, each client connects to the servers through proxies realized through OpenFlow switches; in OpenFlow (an SDN standard) network controllers can decide the network path packets across the network of switches. If there are m Open Flow Proxies (OFPs), then the engineering clients are partitioned into m groups; each group connects to the simulation servers through one of the proxies (which offer failure resiliency without introducing much latency).

The performance of this GENI based networking approach in supporting this IoT-based framework was studied for multiple scenarios involving distributed locations in the US (Tulsa, Oklahoma; Washington D.C.; Stillwater, Oklahoma and Madison, Wisconsin).

The command generation module converts the VR simulation details into physical work cell commands that can be communicated to the physical work cells to implement the assembly plans. A set of Sliders in the VR environment provide users to propose alternate assembly routes interactively. Five sliders (Figure 9) support interactively studying assembly plans virtually including operations such as gripper action, movement along an axis, rotating the assembly plate, by users as part of completing a target virtual assembly inside the VR environment.

Physical work cells in the cyber-physical framework

The Physical Assembly equipment in various work cells is used to complete the physical assembly tasks. Three physical work cells are available as part of this Cyber-Physical framework. The assembly

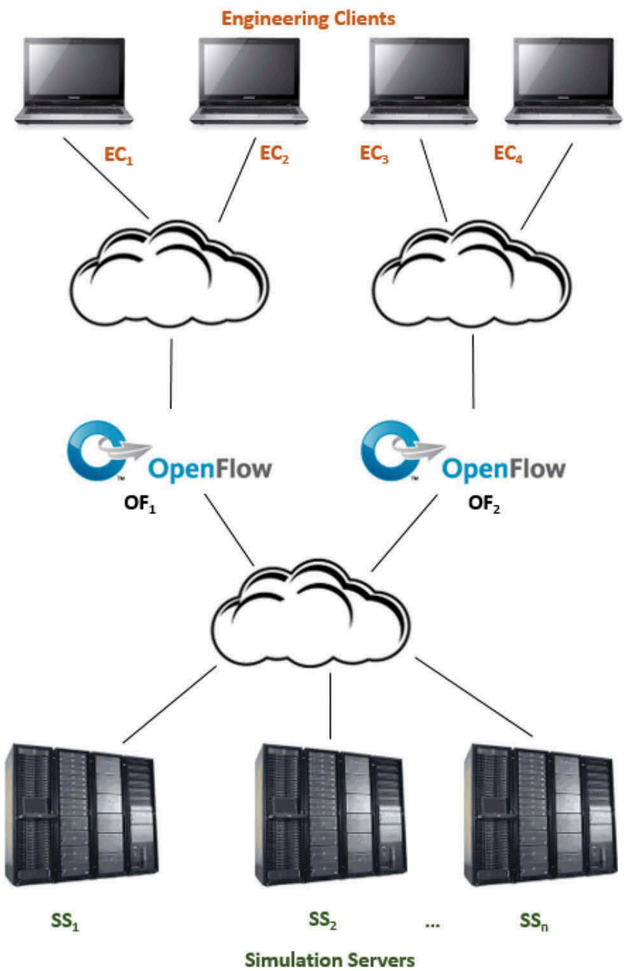

Figure 8. SDN-based framework to support collaborations among distributed sites.

plans are used to generate the physical commands using the Command Generation Module. Consequently, the converted physical assembly commands act as an input for the physical work cell to assemble microdevices. For example, the physical work cell in Figure 10 has 4 degrees of freedom with the assembly plate capable of rotation and the gripper can move along the z-axis; it is versatile and capable of assembling parts from 30 microns to 1 mm. Two cameras are available for assisting in the assembly activities as well as for monitoring progress of the assembly tasks. Figure 11 shows a snapshot of the progress of an assembly via the mounted cameras (seen on the web through the cloud interface).

The status of the various Cyber-Physical interactions can be monitored through a CPS status web page; the work cell performing the physical assembly has cameras mounted on it.

An information model-based monitoring approach was proposed and implemented to serve as the basis for tracking and monitoring the progress of the various IoT-based cyber and physical tasks. There has been a lack of research approaches focusing on a structured approach to support tracking and monitoring of the Cyber-Physical activities; this is the first reported approach in the literature of adopting such an information-centric tracking approach to support IoT-based interactions. For brevity, in Figure 12, only an elided view of this information model has been shown; the top-level process units (corresponding to PU_i in Figure 12) in the IoT life-cycle are shown (each of these processes were decomposed to support a more detailed tracking of each lower level task within that process; these are not shown for brevity); junction boxes were used to design and map the various IoT interactions and also used to model the synchronous or asynchronous nature of their temporal relationships at all levels. Each of the process units (PUi) has an associated set of (i) information or physical inputs, (ii) major constraints which need to be satisfied and (iii) cyber or physical resources (termed as Performing Modules (PM_i) in Figure 12) to accomplish a given process unit or task. The task outcomes can be Physical Outcomes (PO_i which refers to the physical outcomes occurring in the life cycle of the micro assembly process) or Cyber Outcomes (CO_i) which refers to possible cyber outcomes such as generated assembly sequences, updated plan and any other non-physical outcomes. Some process units can have both Cyber and Physical Outcomes (CPO_i) after a given task is successfully completed; assembly completion or plan

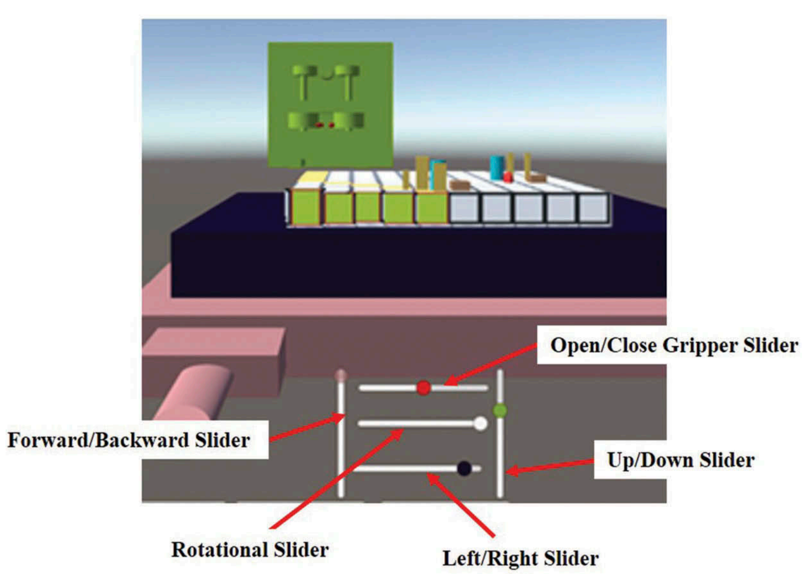

Figure 9. Sliders to propose assembly movements manually in the VR assembly environment.

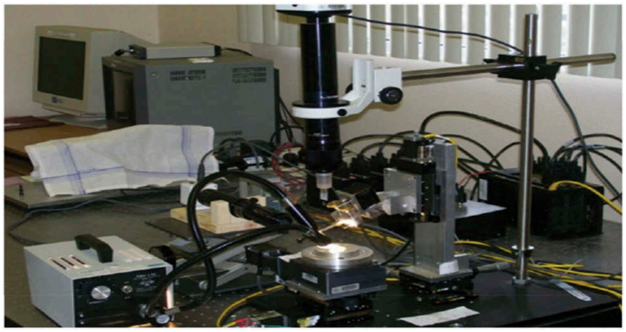

Figure 10. One of the Physical Work Cells in the IoT framework.

generation status are examples of WIP data monitored by the IoT framework and communicated with the Cyber-Physical Manager. In general, the outcomes can be tracked effectively as the life-cycle of the cyber-physical activities progresses. A cyber outcome can lead to new information being created or modification of existing data/information; for example, once an assembly plan was generated, a new information entry is noted (corresponding to a successful generation of an assembly plan, which is an information or cyber outcome); if after the VR-based assembly analysis, an assembly plan needed to be modified or updated, this is tracked using the feedback links and communicated to the assembly plan generator (which is another cyber component, as shown in Figure 12). In addition, when an information or physical outcome affects the start of more than one process, the synchronous or asynchronous nature of this subsequent process or task can be indicated in the IoT process map using the appropriate junctions (as shown in Figure 12), which is used to trigger the relevant succeeding process units. This information-centric modelling approach was used as the foundation to monitor and track the progress of the various IoT based Cyber-Physical activities at any instant. At the top or decomposed levels, the progress of each process or task can belong to one of these four states: Not Started, in Progress, Completed or Problems Encountered.

Discussion

An IoT Test Bed for MDA was built to demonstrate feasibility of the IoT based Cyber-Physical approach and framework discussed in this paper. A variety of micro-meso scale parts were assembled. The assembly tasks involved manipulation of meso/micro part designs where some of the target parts may be in the mesoscale while others are in the microscale range. Mesoscale refers to including part sizes greater than 1 mm, with accuracies greater than 25 μm. Figure 13(a) shows an assembly scene where the gripper is placing a target gear in its location. Figure 13(b) shows a partial view of an assembled micro design which involve assembling gears, sensors and pins.

The SDN-based network latency was measured for both haptic and non-haptic based interactions involving several distributed locations and users (and was measured using ICMP ping) (Figures 14 and 15). Figures 14 and 15 provide a graph involving the measured Latency (millisecond) plotted against time (minutes) for both haptic and non-haptic interactions; as shown, Latency is stable at around 46 and 48 ms respectively. These experiments underscore the potential of adopting SDN based next-generation networking principles to support distributed interactions such as in the proposed IoT framework for collaborative manufacturing activities.

Conclusion

In this paper, the design and implementation of an IoT based cyber-physical approach involving both cyber and physical components were discussed for the emerging domain of

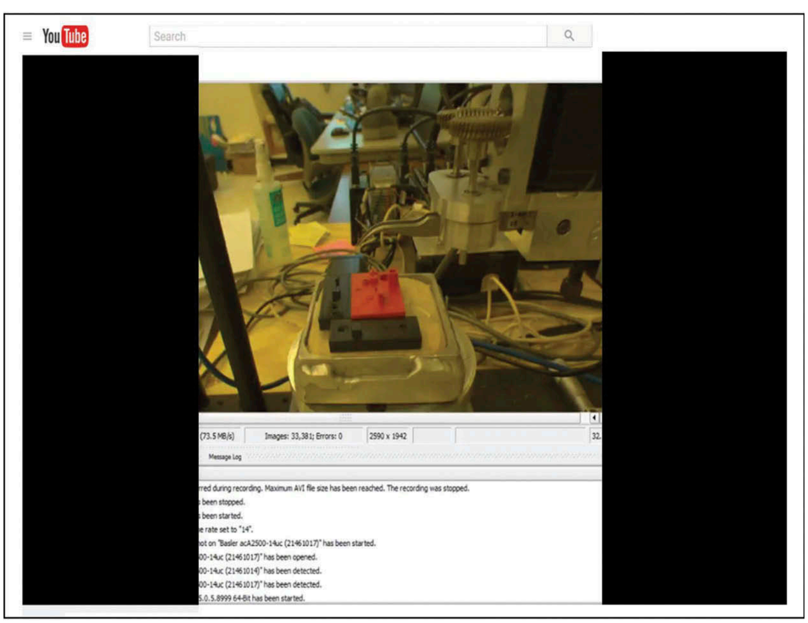

Figure 11. View of a snapshot of a live stream of the physical assembly activities through an IoT monitoring module on the cloud.

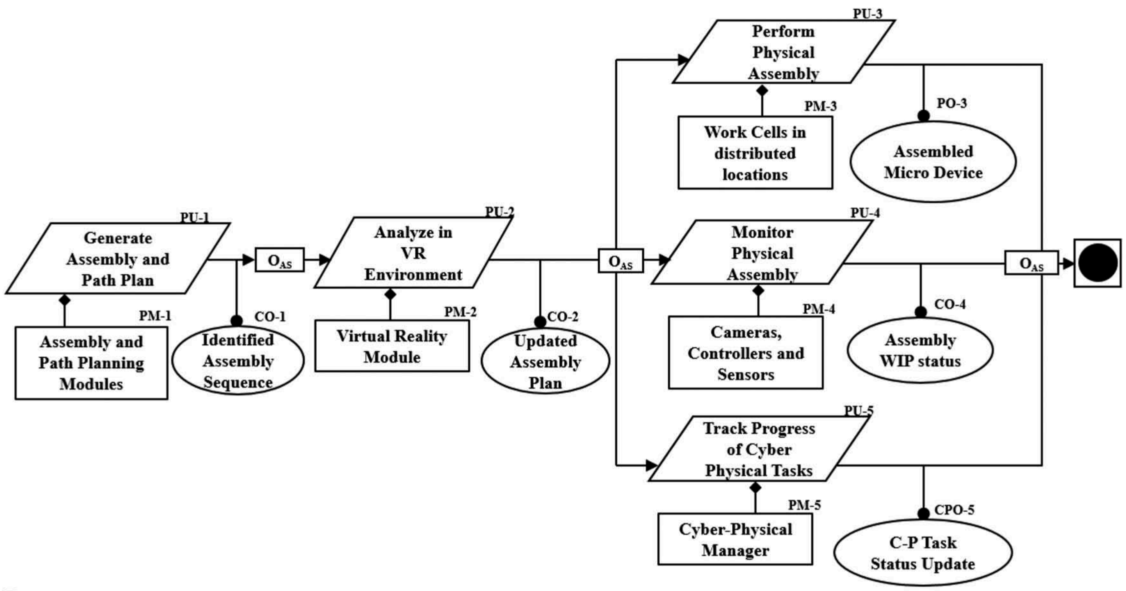

Figure 12. Information-centric model used to design the tracking and monitoring activities during the cyber-physical activities.

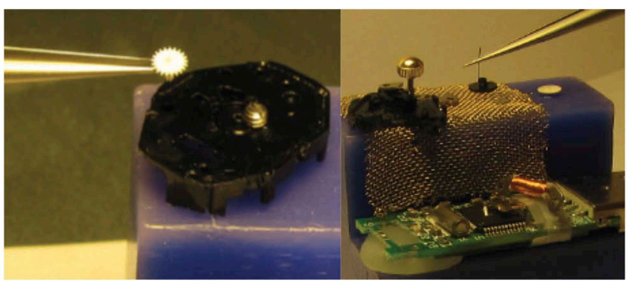

Figure 13. (a). Close-up view of gripper performing assembly and (b) Micro-assembly parts assembled.

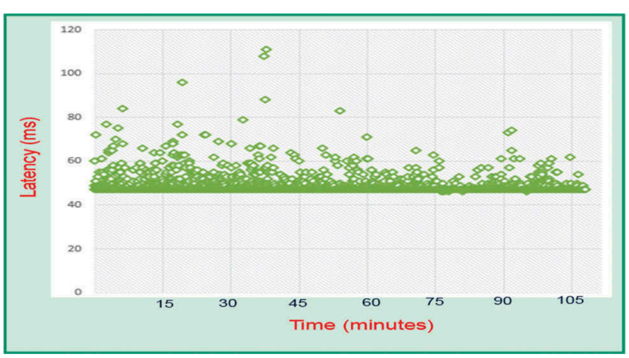

Figure 14. Latency data for distributed haptic interactions.

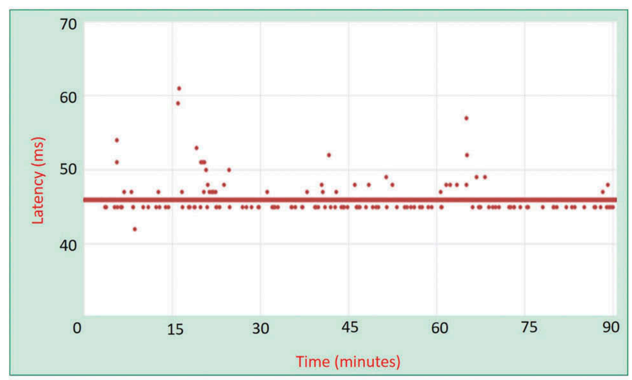

Figure 15. Latency during the distributed non-haptic interactions.

microdevices assembly. The life cycle of collaborative activities was accomplished using Next Generation SDN technologies and included assembly planning, VR-based simulation, command generation and physical assembly of target micro-components. The Assembly Generation task mimicked a VE oriented approach where multiple planning approaches can be used to generate assembly plans. The assembly plans can subsequently be compared, analysed and modified in the collaborative VR environments linked through SDN networking technologies. Various Physical Work Cells can be controlled through cyber-physical interfaces to assemble microdevices (after the assembly alternatives have been analysed virtually). A Cyber-Physical Manager is used to coordinate the overall task activities. Several meso-micro designs were assembled using a Test Bed created to demonstrate feasibility of the proposed approach. Additional research is continuing expanding the scope of the collaborative activities.

This research discussed has several innovative aspects; it is one of the first efforts aimed at developing and demonstrating a complex IoT based cyber-physical framework for advanced manufacturing and especially for the field of Micro Devices Assembly (MDA); the second innovation is the adoption of Next Generation Software Defined Networking (SDN) principles to support distributed collaborations with reduced latency. The third innovation is the information-centric approach proposed to monitor and track the Cyber-Physical interactions.

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