A CYBER PHYSICAL APPROACH AND FRAMEWORK FOR MICRO DEVICES ASSEMBLY

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Abstract: The emergence of Cyber Physical Systems (CPS) and Internet-of-Things (IoT) 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 dissertation, the focus of the research is the design of a Cyber Physical approach for the assembly of micro devices. A collaborative framework comprising of cyber and physical components linked using the Internet 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 potential of next generation Global Environment for Network Innovation (GENI) networking technologies has also been explored to support distributed collaborations involving VR-based environments. The feasibility of the cyber physical approach has been demonstrated by implementing the cyber physical components which collaborate to assemble micro designs. The case studies conducted underscore the ability of the developed Cyber Physical approach and framework to support distributed collaborative activities for MDA process contexts.

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CHAPTER I

INTRODUCTION

1.1 Overview of Micro Devices Assembly

Micro Devices Assembly (MDA) refers to the manual, semi-automated, and automated assembly of micron-sized parts [1-4, 10]. MDA is an advanced manufacturing field specialized to provide technological techniques to handle the assembly of micron size devices/parts. MDA applications range from assembly of simple designs involving basic parts to the assembly of complex designs involving sensors and devices which are composed of various materials. The economic potential of MDA is significant and estimated to reach 20 billion by 2020 [1]. The focus of this dissertation research is to investigate the design of an advanced Cyber Physical framework to support distributed collaborative activities in the field of MDA. This framework has been created taking into consideration the emergence of several recent technologies and principles which include Cyber Physical Systems, Internet-of-Things, and Next Generation Internet Technologies along with technologies such as Virtual Reality (VR) based simulation technologies.

1.2 Cyber Physical System (CPS) and Related Technologies

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 [19, 21, 87, and 93] is enabled through linking cyber (software components) and the physical (hardware components) together to achieve a set of valuable tasks. Interactions among CPS's components emphasize seamless integration of linked components.

CPS based applications hold the potential for integrating distributed activities involving both cyber and physical components in a range of industries including manufacturing, healthcare, transportation, energy, education, and public safety. CPS can improve safety, efficiency and automated interactions in various day to day contexts including designs of smart home technologies; CPS based frameworks can be used to monitor hazardous and high risk environments from remote locations. CPS based approaches are recognized to have substantial potential to support collaborative activities in advanced manufacturing including MDA and other fields [107].

1.3 Emergence of Internet-of-Things (IoT)

When the cyber physical components are linked to the Internet, they embrace another domain of interest known as **Internet-of-Things (IoT)** [20, 26,106,117]**.** IoT can be defined as a network of physical objects or "things" in the broader perspective, embedded with electronics software, sensors and connectivity. IoT emphasizes on exchanging data using the Internet to enable geographically distributed clients to control physical components without the need to physically attend and administer a process. IoT benefits in maintaining an ongoing process and providing collaboration among IoT devices. IoT provides a supportive platform for collaborative practices where geographically distributed partners have the opportunity to forge partnerships and build targeted products collaboratively. Collaborations among partners in advanced manufacturing will greatly benefit the field as it depends on collaboration between designers and producers to manufacture the desired products.

1.4 Virtual Reality (VR) based Simulation Approaches

One of the useful techniques for collaboration in engineering involves the use of Virtual Prototyping techniques which involve creation and use of VR based Simulation environments. VR simulation can be used to simulate the way equipment responds; emulate the way machinery works or to replicate soft skills such as human actions and behavior. VR simulation demonstrates its significance when there is limited resources or when equipment is scarce or expensive and/or accessing these resources is troublesome. Using VR simulation will be a perfect solution. By using VR based simulation environments, we can train a larger pool of trainees which will allow them to interact with fellows, follow best practice procedures or carry out fault finding scenarios; all without having to access and possibly damage the physical resources. In addition, complicated pieces of equipment, designs, processes or systems can be modeled efficiently.

1.5 GENI based Networking Technologies

The National Science Foundation (NSF) has established an initiative known as Global Environment for Network Innovation (GENI). GENI involves exploring network infrastructures that support high bandwidth and reduced latency for exchanging of data [121]. Latency and bandwidth are considered the main issues in slowing down the development of collaborative platforms. With GENI infrastructure, Virtual Enterprises (VE) that require exchanging of oversized data will prosper and high goals of collaboration will be supported.

1.6 Problem Statement

Microelectromechanical system (MEMS) is a technology that fabricates micron designs involving micron sensors and actuators. However, if the micron designs includes micron sized parts that have complex shapes and/or composed of various materials, then MEMS will not be able to fabricate them [1] and consequently, the use of MDA techniques is required. Manual assembly has many drawbacks and is considered unreliable due to high cost and longer time required. The automated assembly assumes significance as it automates the assembly process and saves on time and cost. The design and process of an MDA require better precision and higher accuracies due to sensitive nature of the micron sized parts.

Prior works involving the use of VR based simulation environments to support MDA have not explored the use of IoT or CPS based principles; this doctoral research investigates adoption of IoT based CPS approaches and principles in the field of MDA.

Other research efforts (as indicated in the literature review in this dissertation) have explored non-immersive VR based approaches to support physical MDA activities; this doctoral research explores the use of semi-immersive based approaches to facilitate assembly and path planning in a collaborative context.

Prior researches have also not explored the potential of next generation Internet technologies; this research explores next generation GENI networking technologies in supporting distributed collaboration in the field of MDA.

There is a need to develop a cyber physical frameworks for advanced manufacturing domains; in the context of MDA, such cyber physical frameworks can support collaborative engineering which encompass the main life cycle activities including assembly planning, path planning, VR based simulation and physical assembly. This doctoral research is the first major research initiative that addresses such a life cycle context in developing an innovative cyber physical approach along with building the first cyber physical framework that can demonstrate feasibility in accomplishing these life cycle activities resulting in the assembly of micron devices.

MDA resources are limited and expensive; unlike other manufacturing fields (such as general manufacturing involving prismatic or rotational parts to be manufactured using CNC machines) for a field such as MDA there is only a limited number of engineering and manufacturing organizations who have the expertise and resources to accomplish MDA planning and assembly activities. Further, the equipment and software resources in the field of MDA are expensive which in many ways underscores the need for collaboration and sharing of both cyber and physical resources; for these reasons, there is a need to develop collaborative approaches and frameworks which are based on CPS and IoT principles [20, 26,106,117] and technologies which will allow organizations to collaborate, share cyber/physical resources, and build MDA based products that address changing customer requirements. This is the primary motivation for this dissertation research outlined in this document.

Harnessing next generation technologies such as VR based simulation technologies, CPS, and IoT will benefit MDA activities and will reduce the time and cost of assembly. In addition, to support effective collaborations, a cyber physical framework can explore next generation GENI [50-51] technologies. A framework based on such smart technologies also holds the potential to support agile manufacturing principles in the field of MDA.

1.7 Goals and Objectives

The goal of the proposed research is to explore the design of a cyber physical framework to support assembly of micro devices using IoT principles and technologies. The life-cycle process context of MDA assembly process for this research includes assembly plan generation, path planning, VR based simulation and physical assembly.

To achieve the overall goal, the following objectives were achieved:

1. Develop an IoT based Cyber Physical approach which supports collaborations among geographically distributed cyber and physical resources and facilitate accomplishment of the life-cycle activities listed above.

   This IoT based approach and framework was developed using various tools (Unity 3D[134], SolidWorks, Blender), and programming languages (C#, Java, JavaScript). The cyber and physical components were linked by the Internet to support collaboration among distributed engineers.

2. Investigate use of alternative assembly plan generation methods to mimic a Virtual Enterprise (VE) context.

In a VE scenario, multiple partners may be capable of providing the same engineering service or function. For the assembly plan generation activity, two algorithm based planning approaches will be included for implementation. Demonstrate feasibility of approach using two approaches to generate assembly plans. Genetic Algorithm (GA) and Insertion Algorithm (IA).

3. Develop a VR based approach and environments which will be used to demonstrate the cyber physical approach in the overall IoT based framework.

The development of advanced VR environments to support the feasibility analysis of assembly plans was investigated. The VR environments were built using Unity Game development software and two programming languages C# and JavaScript. The feasibility of using two approaches to generate assembly plans was demonstrated using GA and IA. The creation of VR environments was investigated using two levels of immersion: semi-immersive and non-immersive.

4. Develop a process to generate the physical micro assembly commands.

The assembly plans obtained from the VR environment were used to generate physical assembly commands interactively, these commands were used to perform physical micro assembly tasks and assemble target parts.

5. Explore the potential of next generation GENI networking to support collaborative interactions between distributed VR based assembly analysis environments.

In this research, the feasibility of GENI technologies to support such VR based collaborative interactions has been studied with an emphasis on latency related issues.

6. Demonstrate the feasibility of this cyber physical approach framework by creating and integrating modules which can perform: Assembly Planning, VR based Simulation (for assembly analysis), Command generation and Physical assembly.

1.8 Summary of Results

This dissertation research involves developing a CPS based approach for MDA to support collaborations among geographically distributed cyber and physical resources. A Test Bed was created to demonstrate feasibility of the proposed approach.

The CPS based approach envisions a VE where several geographically distanced partners can form an alliance to produce a product collaboratively. Two alternative assembly planning techniques were investigated to mimic a VE scenario based on Genetic algorithm (GA) and Insertion algorithm (IA). The two algorithms are used to show that multiple partners may have different feasible alternative assembly plans.

A path planning approach is used to return a collision free path during assembly using the A* algorithm.

VR environments were created to study the feasibility of assembly plans. Using the VR environment, unexpected collisions or near collision cases that can be avoided during the assembly of micron sized part can be identified. Partners can modify the generated assembly plan and propose alternatives. Non-immersive VR and semi-Immersive VR based environments were created.

Collaboration involving distributed VR environments were studied using emerging GENI technologies. The feasibility of GENI technologies to support collaboration between geographically distance partners was demonstrated.

A Command generation approach was developed for converting the feasible assembly plan into a set of physical commands based on the capabilities of the physical work cells.

One physical MDA work cell was used to assemble the parts using the generated physical commands.

1.9 Dissertation Outline

The dissertation is organized as follows:

- In chapter 2, we provide an extensive literature review of MDA along with relevant technologies that can handle and improve the lifecycle of MDA. The relevant technologies include CPS, IoT, VR simulations and next generation Internet. We highlight aspects of Industry 4.0 initiative and identify major research voids for MDA.
- In chapter 3, an overview of the overall framework and approach for MDA is provided followed by a discussion of the various cyber and physical components of the CPS based framework.
- In chapter 4, discussion of case studies including assembly examples are provided.
- In chapter 5, a summary of each chapter along with a discussion of future research is provided.

1.10 Summary

In this chapter, we highlighted the importance of MDA and identified several next generation technologies that an MDA should utilize. In the second subsection, a problem statement has been outlined and the goals and objectives are identified. Chapter 2 provides an in depth literature review of MDA along with reviews of next generation technologies such as CPS, IoT and GENI.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

We provide a literature review for various relevant research areas including research in MDA and Next Generation technologies. The following topics were reviewed: VR Technologies, MDA, CPS, Internet-of-Things (IoT), Next Generation Internet, Industry 4.0. A summary of Research Voids is also provided.

2.2 Review of VR Technology

The term VR was initially coined by Jaron Lanier who was the founder of VPL research. VR refers to 'simulation of artificial 3 dimensional world that is completely generated by computer which makes the users feel like it is a real world' [122].

Immersion in the VR environment can be categorized into three levels. Non-immersive VR, semi-immersive and fully-immersive VR.

Non-Immersive VR: Non-immersive VR is the type of VR where the 3D scene is displayed on a 2D screen. The screen can be a computer monitor, a projector screen or a large TV. Although being on the lower side in terms of cost, such VR can be useful for large group of people.

Semi-Immersive VR: Semi-immersive VR is the type of VR where the user is immersed in the virtual world to a certain level without losing the awareness of the real world. The examples of such type of VR is 3D TV, 3D movie screens and PowerWall™. Hololens is another example of semi-immersive VR where the user can view the real world and the virtual world at the same time. Figure 2 shows the non-immersive PowerWall™ .

Fully-Immersive VR: Fully-immersive VR refers to such VR where all references to the real world is removed and user becomes an active part of the virtual world. The user is completely surrounded by a virtual world in fully-immersive VR. VR cave, where the users are surrounded by walls is an example of such VR. Newer technologies such as HTC Vive(Figure 3) , Oculus Rift and Google VR are upcoming low cost fully-immersive VR alternatives for VR caves.

Full immersion involves deceiving the human senses (visual, sound, touch, smell and taste) to think that the environment as close as reality. Nevertheless, latest full immersive technologies are dealing with visual, sound and haptic only. Table1 categorizes these levels of immersion. Figure 1 shows the classification of current VR gadgets.

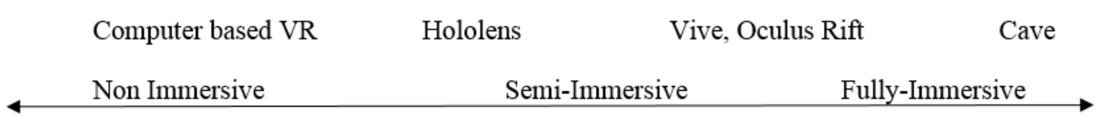


Figure 1: VR Immersion Continuum

Table 1: Classification of VR Gadgets

Features	Non-immersive	Semi-immersive	Full-immersive
Projection	Computer monitor	On a wall	Using headset
Field of view	Monitor based	90°	360°
Ability to isolate user from the world	Low	Medium	High
Interaction controls	Keyboard & mouse	Handheld controllers	Handheld controllers , gloves
Example	Computer based simulations	PowerWall™, HoloLens	Vive, Oculus Rift, Cave

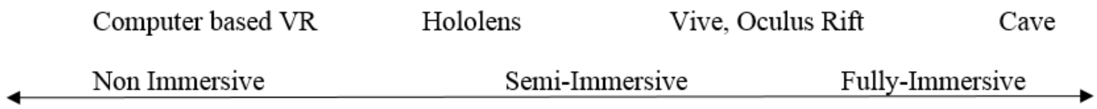


Figure 1: VR Immersion Continuum

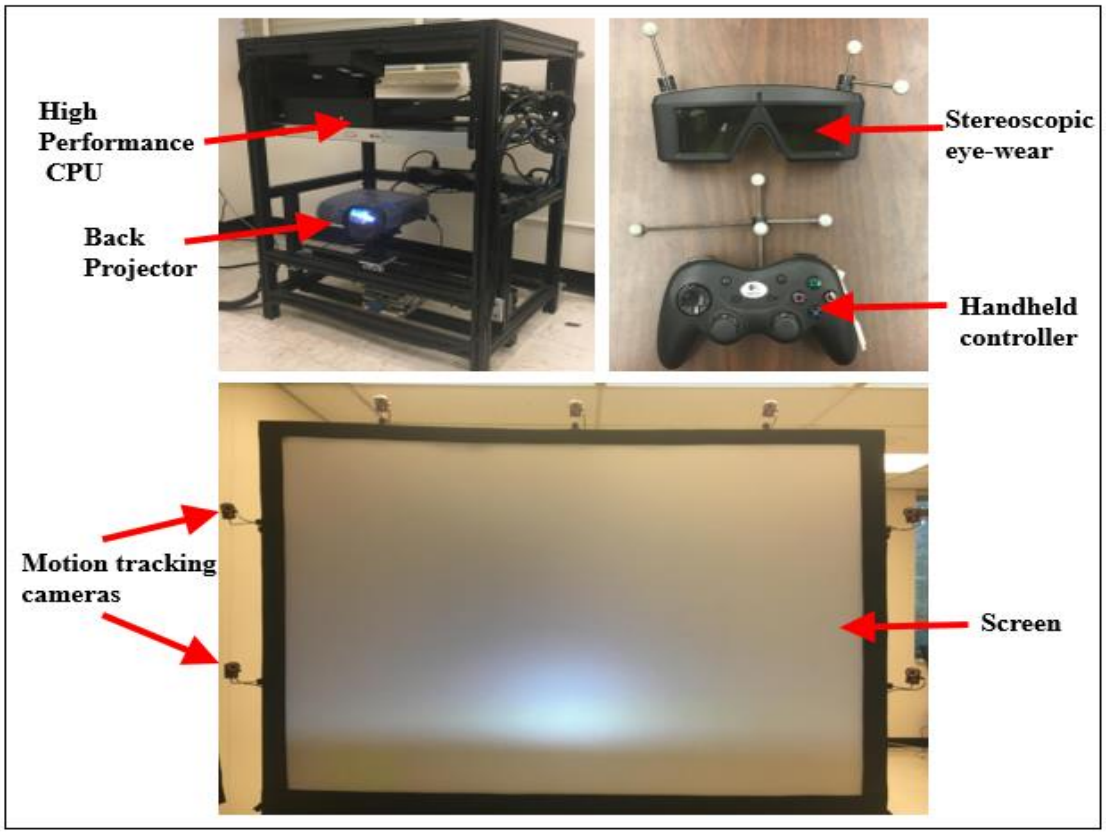


Figure 2: Semi-Immersive PowerWall™

There are two emerging technologies evolve from VR which are known as Mixed Reality and Augmented Reality. Mixed reality also known as hybrid reality which allows merging of real and virtual objects to co-occur in the simulation scene. HoloLens is an example of a mixed reality technology. Figure 4 shows the HoloLens.

Augmented reality takes real world objects and augments/supplements them virtually. This requires set of wearable sensors to allow user interactions. Daqri Smart Helmet is an example of an augmented reality technology. Daqri Smart Helmet augments dangerous situations to inform the user about possible dangerous situations. Figure 5 shows Daqari Smart Helmet.

Figure 3: Fully-immersive HTC Vive

Figure 4: Mixed Reality Microsoft HoloLens device [124]

Figure 5: Augmented Reality Daqri Smart Helmet [121]

Monferrer et al. [81] outlined a system to control robots performing difficult or dangerous tasks using a VR based framework. A set of guidelines was proposed to define an ideal user interface that would use VR to help an operator control an underwater robot. The authors also highlighted the role of human users in the design of VR based collaborative environments.

Cecil et al. [120] proposed a virtual simulator for training medical residents. Discussion of VR based technology provided. Along with the description of the Virtual Surgical Environment (VSE). The VSE is utilized for practicing an orthopedic surgery process. Training medical residents in an orthopedic surgery process is critical and the VSE supplements other training methods. Initial results were discussed along with outlining the tools used for the creation of the VSE.

Collaboration among partners can be carried out in a VR simulation where distributed partners can investigate designs, propose alternatives and exchanges ideas. VR simulation is considered a vital feature in determining the feasibility of an approach and serves as a collaboration platform for distributed clients.

Zhang et al. [41] proposed a cloud-based monitoring system that monitors activities of different sectors using the help of VR. The proposed system allows users at different locations to collaborate by sharing and managing data remotely. The proposed system's capabilities were demonstrated by monitoring coal-mining equipment.

Mahdjoub et al. [42] proposed a collaborative design for usability approach supported by a VR environment and a Multi-Agent System. The details of a collaborative workstation design approach are discussed at length, and a Multi-Agent System (MAS) running on a VR platform is used to undertake this collaborative design approach.

Wu et al. [43] proposed a prototype system using a virtual environment to solve the complex assembly issues. The prototype is coupled with various techniques such as collision detection and parallel rendering to provide a cutting-edge Distributed Parallel Virtual Assembly Environment (DPVAE). Using DPVAE, geographically distributed users can collaboratively carry out assembly operations and conduct verification and evaluation of the assembly simultaneously. The collaborative VR environment allows participants at different locations to interactively assemble complex products.

Lee et al. [44] discussed the idea of large-scale virtual manufacturing environments, along with how a heuristic construction method and collaborative construction is needed to create such a VR environment.

Other VR environments focused on education, medical training and entertainment [45-48].

There has been limited cases where the exploitation of the semi-immersive and full-immersive environment are used in analyzing and validating a manufacturing process. In addition, most of the reviewed works focus on adoption of non-immersive environments that do not support collaborative interactions.

2.3 Review of MDA

MDA has been identified to be a critical technology in advanced manufacturing.

Jain et al. in [2], presented a novel design of micro manipulation system along with a discussion of piezoelectric micro gripper. Following the discussion, the authors presented the novel design that is capable of handling miniature parts and controlling the misalignment during peg-in-hole assembly. This is accomplished through the use of a piezoelectric actuator which has the capability of producing the displacement measure in micron range and generating the force needed for alignment.

Rabenorosoa et al. [3] presented a reconfigurable micro assembly station for the assembly of 3D MOEMS (Micro-Opto-ElectroMechanical Systems). The reconfigurable micro assembly station is introduced to accommodate complex MDA designs. For insuring the reconfigurability of micro-benches, a micro gripper is proposed. The proposed micro assembly station is developed with an eight Degree Of Freedom DOF configuration and nanometric resolution which will ensure precise positioning of parts. The micro station is validated and demonstrated to assemble MOEMS via a mirror and lens.

2.3.1 Gripping Techniques of MDA

Sanchez et al. [4] reviewed gripping techniques for automating the assembly process of micro parts. The authors introduced state-of-the-art industrial micro work cells along with specifications such as DOFs, accuracies, load and speed. Then the authors categorized the gripping techniques into four categories and draw comparison of their capabilities, materials they handle, applications and accuracy. The four gripping categories are: friction, pneumatic, magnetic and other techniques.

Petrovic et al. [5] presented a vacuum gripper for micro parts and two types of mechanical grippers. The goals for these grippers include handling different shapes, dimensions, and to precisely position the gripper in designated locations. The gripping system is integrated with a force sensing and a vision guide. The vision guide is used for position measurements. The system features controls and alarms for detecting collisions.

Popovic et al. [6] presented some of the final results from supported participants of a European grant targeting, handling and assembling of micron parts. Results were in the area of : adaptation of high precision positioning stages to the needs of handling and assembly of micro parts; development of tools for handling the assembly methods for automation; combination of different technologies in one fabrication process for batch assembly purposes; and joining techniques;

Ballandras et al. [7] designed and fabricated micro grippers using a specific technique known as LIGA technique. Few micro grippers have been designed based on general design considerations and then validated through examining the mechanical behaviors of the micro grippers.

Cecil et al. [8, 10] provided a comprehensive review of research in MDA including review of papers in factory automation, gripping techniques, modeling of interactive forces coming into play during, MDA as well as VR based approaches to facilitate assembly tasks.

Hassani et al. [9] reviewed several micro grippers and a set of parameters to examine their effects on gripping techniques. These parameters include: material specification, displacement amplification factor, gripping range and stroke, jaw motion characteristic, normally open and normally closed gripper, ideal shape of tips, aspect ratio, number of degree of freedom and micro actuator specifications. Examining these parameters and their effects on gripping will help in optimizing the micro gripping techniques and, therefore, the authors proposed an algorithm for designing micro grippers.

Zhang [62], presented an autonomous microassembly for pick and place with three goals: high accuracy, reliability and speed. The microassembly is equipped with a three-pronged micro gripper designed to overcome adhesive forces.

Xiong [63] outlined an assembly of micron parts on a single substrate. A two-batch electrical assembly is proposed to assemble square parts with electrical connections. Capillary force used for the assembly and substrates depends on hydrophobic sites for electrical connection. Proposed VR simulation is used to detect collisions while assembling the micron parts.

Beyeler et al. [64] discussed a MEMS gripper and an ultrasonic manipulator device. The gripper moves using the electrostatic actuator. Force feedback is provided during manipulation. The ultrasonic device is used to release micron parts that stick to the gripper.

Mayyas et al. [65] presented a joining technique for micron parts. This technique utilizes a system on a chip actuator which permits placement of micro parts with zero force. Assembly performance is improved due to frictionless grasp and release of micron parts.

Zhong et al. [66] discussed creating a VR environment for modeling of solid objects. Engineers can create precise solid models by incorporating some constraints. Constraints are used for object definition, creation and rendering. Finally, experimental results were discussed.

Valentini [67] presented an Augmented Reality virtual assembly. Augmented Reality is activated using a head mounted display and hand gloves with sensors. The head mounted display is utilized for projection of the VR environment whereas the hand gloves equipped with sensors to interact and manipulate objects.

Abulrub et al. [68] discussed educational goals of engineering using VR environments. A VR environment helps engineering students to conceptually understand complex engineering activities in the industrial field. Engineering students will be able to practice, apply and validate theoretical ideas in a VR environment without the need to go to industrial sights.

Lining et al. [69] presented an approach for detecting collisions in a VR environment based on "Fixed Direction Hull" method. A robotic master hand is utilized to get a virtual force feedback.

Subramaniyam et al. [70] presented a design for automated work cell. A micro factory system is presented with high precision, high throughput and low cost goals. The micro factory system is designed using VR environment. A proposed layout is compared against an existing layout which shows improvements in time.

Chang et al. [71] presented a visual-servo system for peg-in-hole micro assembly. The system is armed with few modules that help in placing micro objects with accuracy, efficiency and robustness. A monitoring interface is used to examine the assembly progress.

Das et al. [72] presented a design for an automated MDA with path planning and collision avoidance goals. Experimental results show improvement for precise path planning but it is not the shortest path that exists.

Popa et al. [72] presented a robotic assembly system for MDA with precision goals. The system's goal is to reduce the cost using three approaches : Multiscale manipulation, Parallel manipulation, and Modularity.

Claverley et al. [74] discussed the production technique of the micro-scale parts. Two methods for assembly are presented. First is assembly from MEMES and second is assembly by micro elector-discharge machining. Finally, Claverley presented a micro-scale coordinate measuring machine system.

The rest of MDA's literature revolves around automating self-assembly [11, 12], gripping techniques [13], precision assembly and handling adhesive forces come into play when assembling micron devices [14, 15, 16]. Few cases are harnessing vision guided assembly or exploit visual servoing techniques to help precise the assembling of micron parts [17, 18]. Literature review of MDA indicated limited uses of VR to simulate the physical assembly and determine the feasibility of an assembly plan. Also, there has been only a limited number of research initiatives in MDA that have investigated adoption of collaboration approaches involving distributed resources.

2.3.2 VR for MDA

Several researchers have explored the role of using VR based approaches to support MDA. Probst et al. [1] presented a 6 DOF microassembly that assembled biomedical systems. The microassembly is equipped with an advanced vision and illumination modules. The microassembly work cell is integrated with a VR based environment to ensure the assembly process is carried out correctly and then operated on the physical microassembly. In addition, the benefits of using VR for MDA has been presented along with the examples demonstrating such benefits. The VR environment helps assembling complex bio medical devices for medical monitoring.

Alex et al. [53] highlighted the complexities of assembling micron sized parts and the need for automated operations for the assembly. Then authors presented a VR environment coupled with high resolution visual servoing technique to guide the assembly.

Ferreira et al. [54] introduced microphysics-based models of rigid body dynamics, deformation, friction and micro domain physics in a non-immersive VR environment. The operator could practice, explore and prevent the problems that might occur during the implementation. Assembly work cell is virtually simulated and an example of micro-task teaching is given. The implementation includes view tracking using virtual force feedback, visual and audio rendering in virtual microenvironment.

Luo et al. [55] analyzed forces coming to play while assembling micro/nano scale parts. Specifically insertion in optical fiber assembly. Several contact forces (e.g adhesion or friction) are modeled and simulated in a non-immersive VR environment and analyzed using a haptic device.

Cassier et al. [18] presented a VR environment coupled with vision servoing for semi-automated microassembly. The combination of vision servoing techniques and VR-based simulation system allowed to plan the manipulation tasks and to insure the guided-movements of the micromanipulators. Therefore, preventing any collisions, and improve safety and reliability of the assembly work cell.

Tan et al. [57] presented a VR environment integrated with force feedback and visual feedback for micromanipulation. The system realizes vision and force close-loop to improve the micromanipulation process.

Sun et al. [58] presented a non-immersive VR environment to detect collision in peg-in-hole microassembly. Haptic and force interactions are integrated with the VR environment. Authors outlined a model to respond to the collisions by measuring the virtual force and corresponding displacement occurred.

Gobinath et al. [119] developed a non-immersive VR based environment linked to a robotic work cell for the assembly of micron parts. The architecture of the VR environment includes various modules such as part initialization module, user interface module, navigation module and assembly manager. These modules complete an integrated physical and virtual assembly approach using a non-immersive VR environments.

Cecil et al. [60] presented a non-immersive VR based simulation environment to simulate MDA process. Using such VR environment, the users would be able to propose, modify and determine the feasibility of the assembly plan. Once an assembly plan is virtually analyzed it could be downloaded to the robotic work cell for physical assembly.

Sulzmann et al. [61], presented a non-immersive VR based environment along with a vision feedback for micron accuracy and manipulation of micro systems. Users can interact with the VR environment and sees the robotic work cell as looking through a microscope. Table 2 summarizes the approaches of the VR applications reviewed.

Estevez et al. [26] developed a positioning system for the precise location of a working table for a haptic micro-manipulation system which had 6 degrees of freedom and used magnetic forces for precise positioning. The conceptual design of the system was developed for handling delicate and fragile micro-parts with sensitivity and repeatability.

Table 2: Use of VR in MDA

Publication	MDA/domain	VR/Immersion
Probst et al. [1](2009)	Assembling and manipulation of biomedical devices	Non-immersive VR environment with visual feedback , collision detection
Alex et al.[53] (1998)	Automated operations for MDA along with visual servoing	Non-immersive VR environment integrated with high resolution vision system
Ferreira et al. [54] (2004)	Manipulation of micron parts involving rigid body dynamics, deformation, friction and micro physics	Non-immersive VR environment integrated with Visual servoing and virtual force feedback
Cassier et al. [18](2002)	semi-automated of complex hybrid MEMS devices using visual teleported micromanipulation	Non-immersive VR environment coupled with vision servoing
Gobinath et al. [119] (2007)	Micro manipulation of micron parts of (60 to 400 μm)	Non-immersive VR environment to analyze an assembly plan
Luo et al.[55](2006)	Assembly of optical fibers for automated MDA in the scale of nano/micro parts	Non-immersive VR environment along with haptic feedback

Cecil et al. [60](2014)	Rapid assembly of micron parts with different shapes and sizes	Non-immersive VR environment for determining the feasibility of an assembly plan
Sun et al. [58](2005)	Manipulation of micron objects especially peg-in-hole microassembly	Non immersive VR environment simulate motion plan before the actual manipulation and detect collision
Tan et al.[57](2004)	Micromanipulation robot with high precision to increase success rate. Master hand is used to measure force feedback.	Non-immersive VR environment integrated with visual and force feedback. Collision detection and task planning are featured
Sulzmann et al. [61](1995)	Manipulation of microsystems with high precision of 1 micrometers	Non-immersive VR environment along with a vision feedback
This dissertation	Semi-automated MDA is processed with the help of integrated set of cyber and physical modules to produce a feasible assembly plan	Non-immersive and Semi-immersive VR environments involving collision detection , collaborative , command generation

The literature review of VR in MDA indicated that there have been no cases where exploiting of semi-immersive and/or full-immersive environment are used in analyzing an assembly plan. Most of the research on MDA involves the use of non-immersive VR based simulation environments. Our framework exploits the use of semi-immersive VR to propose, analyze and modify an assembly plan for MDA. Another contribution of our work is to automatically generate the physical assembly commands based on the simulation outcomes to control and complete the physical assembly tasks. The semi-immersive environment uses the PowerWall™ (see Figure 6) from Mechdyne ™ to develop this simulation environment.

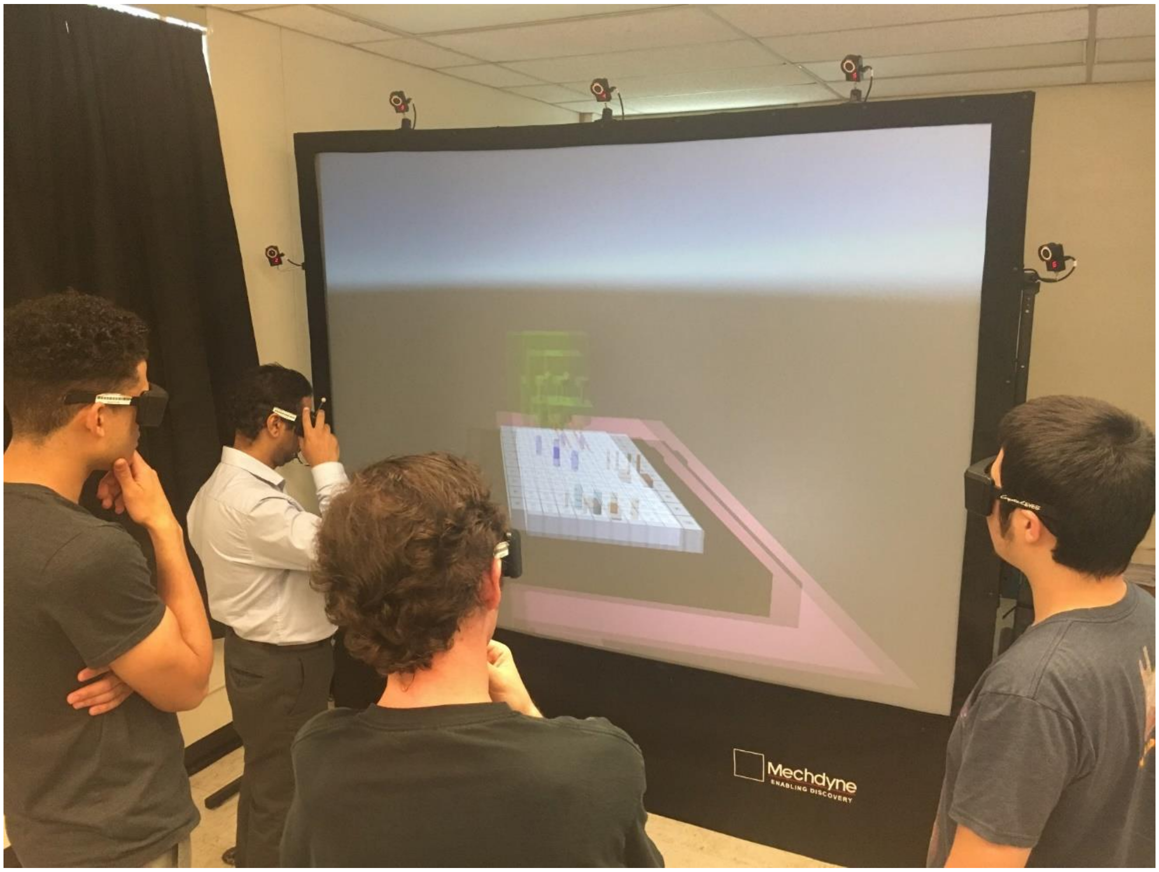


Figure 6: A Semi-Immersive Environment

2.4 Cyber Physical Systems (CPS)

Research in CPS has explored the adoption of CPS approaches to a variety of fields from an automated garden to helping plan taxi driving routes.

Shi et al. [115] introduced benefits of CPS and highlighted research areas of CPS involving energy and secure control, transmission and management of CPS and model based designs. Several classical applications that are utilizing CPS based principles were surveyed. Surveyed applications are categorized into three categories: health care and medical domains, electric power grid, and integrating roads with unmanned vehicles. Several research challenges were discussed.

Correll et al. [19] presented a group of robots that service garden plants. Each plant in the garden has sensors to help the robots monitor and sustain the plants. The goal of this project is to accomplish a sustainable greenhouse based on autonomous robots and sensors. The emphasis of this project is on scalability and robustness. The architecture of the CPS can be classified as group of robots and plants. Each robot is outfitted with a 4-DOF arm with force sensor, water pumping and a camera. The plants have an infrared docking station, wireless router and humidity sensor. The robots' jobs are seeding, watering, inventory and harvesting whereas the plants' jobs are to sense the humidity and request water from robots.

Thiagarajan et al. [21], used cellular data obtained from a cell phone to project an accurate path that is followed by a taxi driver. GPS and Wireless fidelity use a significant amount of cellphone power and therefore if not used, it will save cellphone power. Ctrack proposed a CPS that uses only cellular data to project a path that a specific taxi driver followed. The mapping happens by taking a sequence of raw position samples from cellular GSM and producing the most likely path followed. Nevertheless, cellular data lacks accuracy and cannot produce accurate mapping because it has average error of over 175 meters. Ctrack coupled this approach with a cyber module that uses a novel Hidden Markov Model which can process the cellular data and produce meaningful trajectory of the taxi driver path. Ctrack can detect movement (acceleration) and turns (compass direction). Ctrack is proven to retrieve over 75% of accurate mapping on average.

Rajkumar [87] presented the aspects of Cyber-Physical Systems and the potential of changing the future by utilizing CPSs. Few examples of the CPS were presented that includes: fully autonomous vehicles, smart power grids, agricultural cyber-biological system. Impacts on society, and educational were discussed afterward.

Michniewicza et al. [93] introduced a CPS involving robotics. The robots are equipped with smart devices that enable communication with cyber modules. The communication allows efficient utilization and re-configurability of the robots which are used for assembly. Using a set of cyber modules, the robots can be automatically programmed, reconfigured and optimized.

Wang et al. [86] presented CPS trends, latest advancement of CPS, and how it will shape the future researches if its principles are applied to manufacturing. In addition , an introduction of cross domain technologies are presented and compared with the characteristics of CPS. These technologies include System of System (SOS), IoT and Cloud technology. A brief outline of relevant initiatives such as Industry 4.0 and Industrial Internet were introduced.

Ollinger et al. [90] outlined a model driven engineering method followed by referencing an architecture that defines services for controlling tasks. The method is implemented to serve a CPS design for agile automation. The design is coupled with service oriented procedures to address customers' changing requirements. The service oriented procedures contain design guidelines for suitable structuring and definition of services. The outlined model driven engineering method has shown that the control procedures can be performed easily once the equipment services are established.

Kao et al. [91] presented a framework and outlined a methodology for developing an automation interface for CPS. A five level implementation architecture is described for CPS in manufacturing and automation field. A self-learning health monitoring approach is then presented which demonstrated accurate cyber representation of a monitored machine.

Monostori in [95] introduced a CPS along with potential and expectations of future researches. Cyber physical Production System (CPPS) which consists of autonomous, cooperative components and sub-systems that are linked together and dependent on each other was introduced. Convergence of cyber and physical modules was discussed. The need for modelling cyber and physical operations along with forecasting emergent behaviors were discussed. Challenges realizing CPPS were introduced.

Lee et al. [116] discussed current trends in developing Medical Cyber-Physical System (MCPS). The trends included reliance on software to deliver a network connectivity in MCPS and continuous monitoring of patients. Challenges of MCPS were summarized and research directions were discussed. Lee et al. emphasize on the importance of modeling and model driven engineering to lead the development of MCPS.

Dworschak et al. [89] presented CPS research findings on competence needs in manufacturing fields. The results are drawn from surveys indicating that degree of implementation in CPS was low in manufacturing firms.

Literature review of CPS indicated limited examples of CPS approaches where a CPS principles are fully exploited. Most of CPS approaches revolve around limited few examples including robots and assembly machines. In addition, there is limited known approaches that explore the scalability of the system or exploit an advance network among the components of the CPS.

2.5 Internet-of-Things (IoT)

The IoT allows automating and controlling the tasks that are done on a daily basis, which leads to avoiding human intervention where Machine-to-machine communication helps to maintain transparency in the processes. The IoT can lead to uniformity in the tasks, maintain the quality of service, and take necessary action in case of emergencies.

Seo et al. [22] implemented a monitoring system based on IoT for alerting the public about food contamination possibilities. An android based smart phone is used to do the analysis which can send the results to the Internet for public notification. Seo et al. have demonstrated the use of mobile device for protection against consumption of contaminated food via IoT based approach. The system uses Immuno-analysis of pathogenic bacteria and shares the results using the mobile device with public. Several institutes have worked on measurement of physical vital signals, for instance; temperature and heart beat through the use of smart phone, nevertheless, the measurement of biochemical analytes (proteins and bacterial) based on antigen –antibody are difficult due to lack of technological advances in this field. The paper exploit the use of image sensor for observing and detecting the signal produced from an immuno analytical system which eventually determine the contamination of the food sample in the question. Using an android based application in a smartphone, a sample can be monitored, controlled and analyzed. The contribution of the paper is considered one of the first exemplification of pathogen monitoring via IoT for healthcare.

Jeong et al. [117] discussed that as more and more modern devices are growing in power and functionality, it becomes important to reduce their cost of operation. IoT can serve as a common platform for interaction with these devices over the Internet for the reduction of the cost. An interactive framework of visualizing and authoring IoT for indoor environment was described. The framework consists of virtual sensors and actuators. These virtual sensors and actuators abstract physical things and their virtual behaviors on their physical networks. Web based visual authoring tools are used to abstract and program their behaviors. Even a casual user can utilize the visual authoring tools to monitor and define behaviors of sensors and actuators. The user does not have to know about the underlying connection while using the authoring tools. An experimental study was also conducted to assess the usability of the visual authoring tools and the results showed that the tools are easy to use and understandable. The users preferred these tools compared to the typical text-based script programming.

Kelly et al. [20] outlined an intelligent home automation system which consists of clusters of sensors that collect different types of data regarding the residents and utility consumption at home. The intelligent system demonstrated an effective low-cost and flexible solution for condition monitoring and energy management in home. The operations include remote management and control of domestic devices such as electric lamp; water heater etc., unobtrusive monitoring of domestic utilizations and providing ambient intelligence to reduce the energy consumption. The system consists of (1) ZigBee Wireless Sensor Network, (2) Sensing units (smart sensing devices), (3) IoT gateways, (4) Internet Server.

Hsieh et al. [106] proposed a tentative architecture that combines IMS (IP Multimedia Subsystem) network and IoT to provide an infrastructure for high-quality ecosystem applications for smart living. The system mainly focuses on mobile network quality improvements on behalf of IoT development in Ecosystem. In order to gain quality, two types of networks i.e. IMS and Electronic Product Code Information Services (EPCIS) have been integrated and agent-based scheme (software modules) has been used to improve the Quality of Service (QoS) of the network. The agent utilizes a Q learning algorithm to measure and monitor the networks. The agent learns the behaviors of the network through patterns and improves the efficiency and resolves the problems in network. Several tests have been conducted and several graphical data of the tests were analyzed.

Shancang et al. [23] discussed IoT devices that may use different protocols for communication with other IoT devices, that include different object identification, information representation and data transmission. This raise a problem of processing information from several heterogeneous devices. In addition, few challenges have been recognized in current IoT based services. Therefore, a distributed consensus algorithm was developed for decision making for IoT oriented devices when information is insufficient or overloaded.

Qingping et al. [24] proposed a reconfigurable interface device to enhance sensors' capabilities in IoT devices by parallel reading of data and higher speed reading. The reconfigurable interface integrates data collection, data processing and wired/wireless transmission.

Khaleel et al. [25] provides an IoT based approach for car manufacturing industry. The approach includes several devices including a wireless sensor and actuator network for industrial machines monitoring and a radio-frequency-identification -based system for operator management, locating, and authorization.

Lihong et al. [29] showed challenges rising from large volume of data in storage, managing data, handling different data types, and accessing of data information for IoT devices. Consequently, a framework for efficient storage of massive data of IoT devices was proposed. The framework handles unstructured data by implementing a management version and data isolation method which improved processing massive IoT data information.

Shifeng et al. [30] introduced a novel Integrated Information System (IIS) based on IoT for monitoring the environment. The ISS combined IoT cloud computing, geoinformatics such as GPS and e-science for environmental monitoring and management. A case study involving regional climate change and its ecological responses was presented and results showed that the IIS was beneficial in environmental data collection, monitoring, and decision making.

Zhuming et al. [33] provided a comprehensive literature review for IoT, opportunities, and challenges when adopted by manufacturing enterprise. The impact of IoT on enterprise systems in modern manufacturing was overviewed and technological gaps with next-generation manufacturing paradigms was explored. Zhuming et al. concluded that IoT brings great opportunities to advance manufacturing enterprises. Nevertheless, the IoT for manufacturing enterprises was considered in its early ages.

Yuan et al. [27] developed a rehabilitation system based on IoT, combined with an ontology-based automating design methodology. The ontology helps computers analyze the patient's symptoms and medical resources data which are used for early disease diagnosis and resource allocation. Test results showed that the rehabilitation system is effective and efficient due to two important features: quick construction and easy sharing of domain knowledge in which ontology was used as a base in building the rehabilitation system.

Guangyi et al. [34] proposed a user interoperability framework for heterogeneous IoT devices. Heterogeneous IoT devices generate data in different context which prevents efficient utilization of interaction between IoT devices. The framework addresses the problem of interactions between heterogeneous IoT devices. The proposed solution allowed heterogeneous devices with different context to interact with consistent syntax and semantics. The framework enabled a set of heterogeneous IoT devices to be transformable to a set of common devices and then personalized to users' semantic context. The bases of the framework is a bi-directional transformation between real devices, common devices and virtual devices. Devices are mapped syntactically and semantically.

Other IoT researches have extended services to IoT technology. Kai et al. [35] proposed a model to protect the privacy and security of the users in the IoT by determining the trustworthiness of an applications. Ling et al. [29] proposed a three-layer quality of service (QoS) scheduling model for service-oriented IoT in heterogeneous network. Wu et al. in [30] presented a novel using IoT and cloud computing to resolve some challenges caused by the increasing transportation issues. Boyi et al. in [31] presented a model to store and interpret IoT data in heterogeneous environment for emergency medical services. Geng et al. in [38] provided in-home healthcare platform based on IoT that involves intelligent medicine box and intelligent pharmaceutical packaging enhanced with connectivity. Finally, Li Da et al. in [39] reviewed current research of IoT, major industrial applications of IoT and challenges.

2.5.1 IoT in Manufacturing

In the context of manufacturing, Chengen et al. [28] discussed an automated system for the assembly of complex shapes and harnessed IoT and cloud computing to help solve complex assembly plans for assembly of aircraft engines and other complex shapes. The IoT approach support decision making at various processes of assembly.

Fie et al. [31, 32] investigated application of IoT technologies in cloud manufacturing (Cmfg) and presented a classification of manufacturing resources, services and relationships based on IoT for intelligent perception and access of manufacturing resources.

Wenxiang et al. [26] proposes a manufacturing-assist system for packaging and printing production based on IoT techniques. Genetic algorithm for scheduling subtasks is used to optimize the system.

2.6 Next Generation Internet Technologies

The current Internet capabilities are outdated and cannot serve next generation applications that demand exchanging of large sized data, reduced latency and higher bandwidth. The Internet began in the eighties for researching networks with limited number of users and economical potential. In the nineties, the Internet has been widely spread out and led to traffic explosions which put pressure on network capabilities. Current Internet has become the cornerstone of innovative applications such as cloud based software, Internet of things and others. These applications require next generation networking capabilities which led to the creation of GENI and FIRE [50,51]. Global Environment for Network Innovation (GENI) is funded by the NSF to establish next generation Internet and serve future applications' need. Future Internet Research and Experimentation (FIRE) is a European commission funded initiative to explore and experiment next generation networking and service paradigms at low cost and at scalable level. Latency and bandwidth problems in current Internet are enhanced by using next generation Internet. Latency and bandwidth are some of the main issues which next generation technologies seek to address. Next Generation Internet technologies hold the potential to address these issues in support of collaborative manufacturing activities.

Anan et al. [104] showed the concerns over today's Internet capabilities and presented a cloud based monitoring system that can streams video data over the network. This system designed to provide, monitor and enhance video streaming service using TCP protocol by combining it with OpenFlow testing environment built in the GENI test bed. Experimental results showed that the TCP protocol used for many years as inadequate for handling video streaming capabilities. The proposed approach is able to meet complex requirements of streaming videos when enhanced with the cloud-based monitoring system. The advantages of software defined networking (SDN) where highlighted in light of the development of the monitoring system.

Abdelhadi et al. [102] implemented a localization algorithm that utilizes WiFi networks over GENI in which they demonstrated a use case of the mobile w-iLab.t robot test bed. This test bed demonstrated the importance of GENI and several tools that researchers need to prototype and advance researches. The test bed is for indoor positioning systems for robots.

Albrecht et al. [103] outlined the complexity of deployments of software modules to different network platforms and presented an application manager (Gush) for managing distributed applications that can ease on challenges associated with dealing with many resources which consume developer’s time. These challenges include deploying, configurations and controlling experiments applications on various networking platforms including GENI in the US, FIRE in Europe and other countries.

Angu et al. [105] shared their experience of using GENI in transferring large data files. Authors created a dynamic circuit network service in GpENI (Great plains Environment for network Innovation) which is a programmable test bed based on GENI in participating Midwest universities of US. The dynamic circuit is then linked to a Mid-Atlantic Crossroads (MAX) of Washington to create inter-domain circuit. Authors demoed their approach by submiting large scientific data.

Bashir et al. [109] introduced the problem of large flow of data between data centers which requires identifying and proper addressing. Monitoring and identifying a large flow of data among heterogeneous applications with existing approaches have limited visibility or associated with high overhead making it hard to detect and therefore no proper handling is taking. VirtMonE, a lightweight detection software was presented to detect the large data flow. Evaluations of the VirtMonE were carried out on GENI testbed.

Berryman et al. in [118] demonstrated the potential use of GENI infrastructure in advance manufacturing. Use cases and early results were discussed. High speed networks and the use of cloud infrastructures to build future Internet serveries have shown exciting potentials which can bring together manufacturing, developer, and consumer to improve the functionalities of products.

2.7 Industry 4.0

Industry 4.0 [45] is a recent initiative which originated in Germany that recognizes the emergence of next generation technologies to support distributed and collaborative manufacturing. In industry 4.0, manufacturing resources are integrated with an emphasis on adoption of emerging technologies and concepts related to CPS, IoT and Cloud Computing.

The term "Industry 4.0" originates from an initiative led by the German government to promote computerization and introduce highly technologies to the manufacturing factories. Factories will be integrated and connected to achieve seamless cooperation and improve efficiencies and provide better adaptation to changing customer requirement. Adopting industry 4.0 principles will lead to creating smart factories which is the fourth industrial revolution.

Jazdi et al. [83] discussed the development, reliability, security, and data protection of CPS in the context of Industry 4.0. Jazdi et al. highlighted the importance concept behind the industry 4.0 with an application. The application involved industrial coffee machine.

Lee et al. [84] outlined several perspectives on CPS themes and depicted CPS-based manufacturing and service innovations as two inevitable trends and challenges for manufacturing.

Brettel et al. [85], discussed the transformation of the manufacturing landscape by virtualization, decentralization and network building from an Industry 4.0 perspective.

2.8 Summary of Research Voids Identified

1. Prior works involving the use of VR to support MDA have not been explored the use of IoT or CPS based principles; this doctoral research investigates adoption of IoT based CPS approaches and principles in the field of MDA.

2. Other research efforts (as indicated in the literature review in this chapter) have explored non-immersive VR based approaches to support physical MDA activities; this doctoral research explores the use of semi immersive based approaches to facilitate assembly and path planning in a collaborative context.

3. Prior researches have also not explored the potential of next generation Internet technologies; this research explores next generation GENI networking technologies in supporting collaborative VR based analysis for assembly planning.

4. None of the past researches in MDA have focused on developing a broad collaborative framework which encompasses the main life cycle activities in the field of MDA including assembly planning, path planning, VR based simulation and physical assembly. This doctoral research is the first major research initiative that addresses such a life cycle context in developing an innovative cyber physical approach along with building the first cyber physical test bed that can accomplish these life cycle activities resulting in the assembly of micro devices.

2.9 Summary

In this chapter, relevant literature relating to MDA approaches and technologies, research in CPS and IoT technologies as well as emerging next generation Internet technologies have been reviewed. Aspects of Industry 4.0 was introduced. The major research voids (based on this literature review) have been summarized as well.

CHAPTER III

CPS APPROACH AND DESIGN OF CYBER – PHYSICAL COMPONENTS IN THE PROPOSED FRAMEWORK

3.1 Introduction

The life cycle of the cyber physical components studied in this dissertation research framework includes obtaining a data input for target MDA tasks, assembly planning using two methods (IA and GA), path planning, and VR based simulation of assembly tasks, command generation and physical assembly by physical work cell. The components of the IoT framework are placed on a Cloud to enable geographically distributed users to access them. Figure 7 shows an illustration of the layout of the IoT based framework.

Figure 8 shows the interactions of cyber and physical components of the IoT based framework. For a given data input file (for a target MDA tasks), the first phase is to obtain an assembly plan which can be generated using two approaches discussed in this chapter. After the generation of the assembly plan, a path plan is developed to avoid the obstacles during the assembly process. Subsequently, a VR based simulation is developed to determine the feasibility of an assembly plan. Finally, commands are generated through the Command generation module for a physical work cell to carry out the assembly. A detail discussion of modules is presented in the subsequent sections of this chapter.

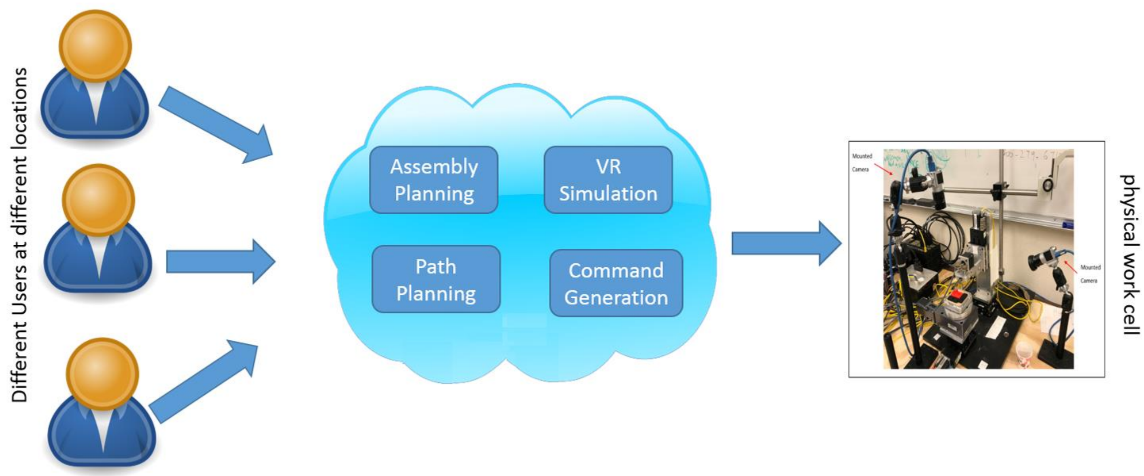


Figure 7: Layout of the IoT based framework

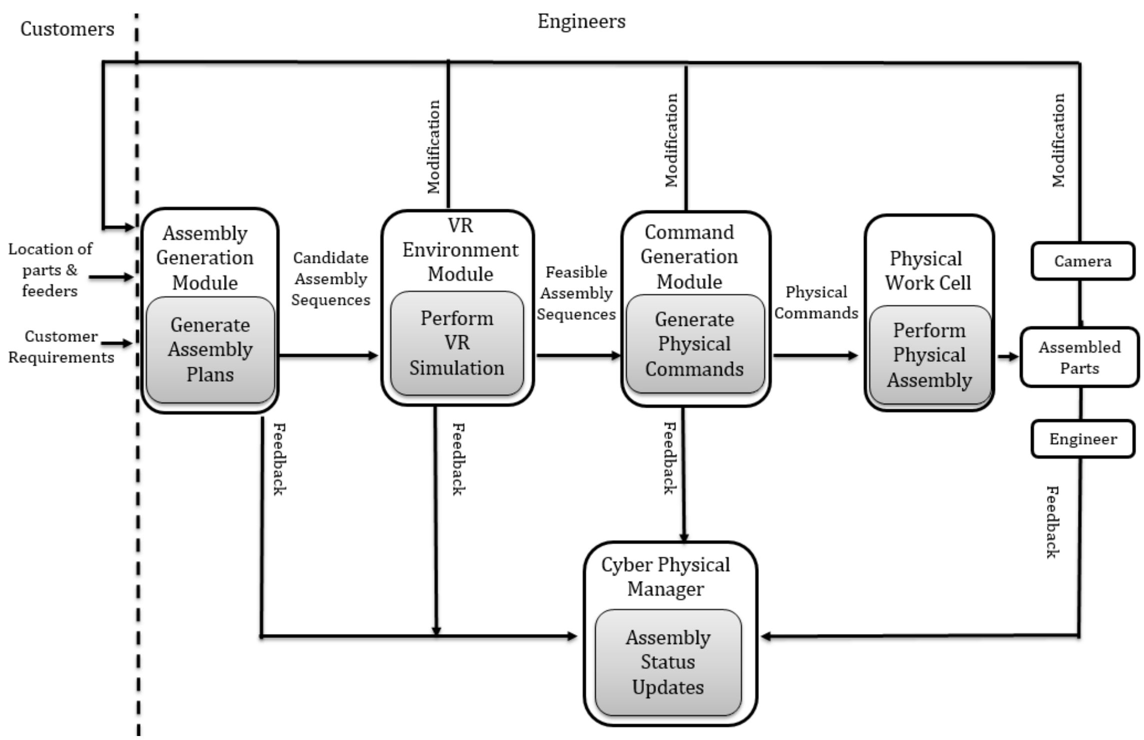


Figure 8: Interactions of the Cyber and Physical components

The customers provides designs and several engineers interact with the CPS framework. The Assembly/ Path Plan Generation Module takes an input of customer requirements, location of parts and feeders. It generates candidate assembly sequences (using GA and IA based approaches) and performs Path Planning (using A* algorithm) between each consecutive pair of the generated sequences. Progress feedback will be provided to the Cyber Physical Manager (CPM).

VR based Assembly Simulation Environment (VRASE) takes candidate assembly sequence (which contains the collision free path) as an input for determining its feasibility of assembly. If the candidate assembly sequence is analyzed and determined to be feasible, then it will be outputted to the Command Generation module, otherwise, a request for modification will be sent to the CPM.

Using the VRASE, users can also propose their own assembly plans and compare it with the automated generation assembly sequence and select the one that is most feasible. If collisions are detected or other problems identified such as near collision cases where van der wall forces are present, then these are communicated as feedback to the CPM and modifications to the assembly sequence is requested.

The Command Generation Module will take the assembly sequence as an input and will convert it to micro-positioners movements in the syntax of the physical work cell. The Command Generation Module will generate an output file containing the physical commands.

The Physical assembly module receives the physical commands, which is used as the basis to complete the physical assembly tasks. During assembly, monitoring cameras provide feedback to the CPM of the work in progress as the assembly progresses.

A CPM maintains overall control of the various interactions among the various modules discussed using the feedback data. Detailed discussions of the various modules of the collaborative approach are in the following subsections.

In this CPS approach, van der wall forces and human errors are not taking into consideration.

Figure 8 shows the importance of Information modelling techniques that can be harnessed to design collaborative CPS activities. Information modelling helps with the software engineering aspects of creating a CPS approach.

3.2 Part Design Input

The lifecycle of an MDA begins with a customer providing a sketch design of an MDA along with an input file containing the coordinates of the parts and feeders. The user is directed to upload the input coordinates file into the IoT based framework using the Cloud that hosts the framework. Figure 9 shows the graphed input of MDA layout with feeder and part positions. Figure 10 shows the input file for the part design.

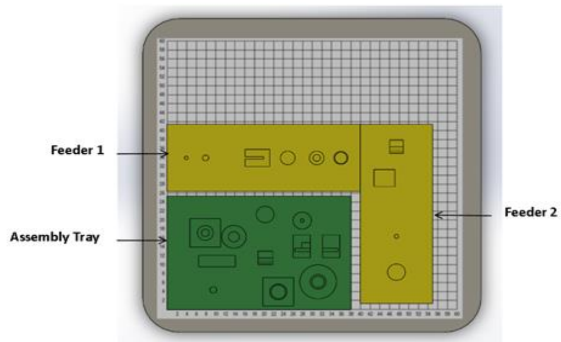
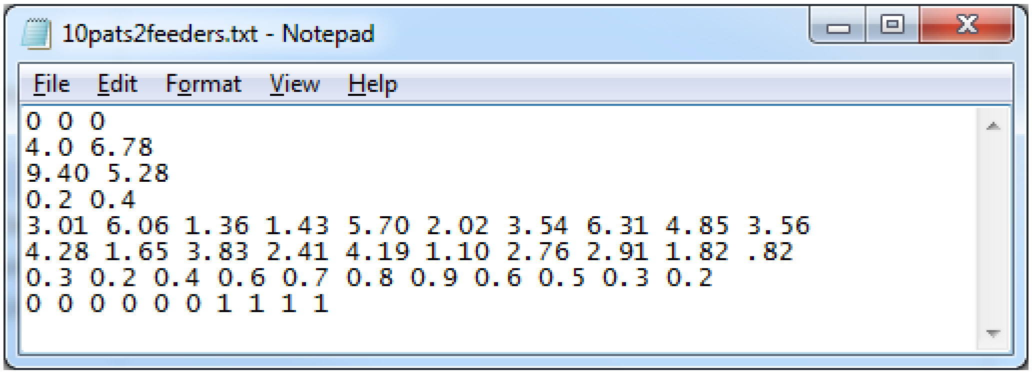


Figure 9: Graphed input of MDA layout.




```
0 0 0
4.0 6.78
9.40 5.28
0.2 0.4
3.01 6.06 1.36 1.43 5.70 2.02 3.54 6.31 4.85 3.56
4.28 1.65 3.83 2.41 4.19 1.10 2.76 2.91 1.82 .82
0.3 0.2 0.4 0.6 0.7 0.8 0.9 0.6 0.5 0.3 0.2
0 0 0 0 0 0 1 1 1 1
```

Figure 10: Input file for the part design

In the part design file shown in Figure 10, the first line represents the coordinated of the gripper, first is for X axis, second for Y axis and third for Z axis. This line will be read by the Assembly module and will put the first line info into the following variables:

```
public static double gripperX[]={0};

public static double gripperY[]={0};

public static double gripperZ[]={0};
```

Second, third, and fourth lines represent parallel feeder coordinates for X, Y, Z axis respectively. The lines will be read by the Assembly Module and fed to these variables:

```
public static double [] feederX={4.0,    6.78};

public static double [] feederY={9.40    ,5.28};

public static double [] feederZ={0.2,    0.4};
```

Fifth, sixth, and seventh lines represent the X axis of the 20 parts given by the customer which will be read and fed into these variables:

```
public static double X[]={3.01,    6.06 ,1.36, 1.43, 5.70, 2.02, 3.54, 6.31 ,4.85 ,3.56};
```

```
public static  double Y[]={4.28 ,1.65 ,3.83 ,2.41 ,4.19 ,1.10 ,2.76 ,2.91 ,1.82 ,0.82};

public static  double Z[]={0.3, 0.2 ,0.4 ,0.6, 0.7 ,0.8 ,0.9, 0.6 ,0.5, 0.3, 0.2};
```

The eighth line represents the association of the parts and their feeders. The line will be read and fed into this variable:

```
public static int F []={0, 0, 0 ,0, 0, 0 ,1 ,1 ,1 ,1};
```

Upon receiving the file, the IoT based framework has an assembly module consisting of two algorithms. IA and GA are utilized to provide near optimal paths. IA and GA are explained in the following section.

3.3 Generation of Assembly Sequences

The Virtual Enterprise (VE) based scenario is examined using two assembly sequences obtained by two different sequence algorithms. The first is obtained using IA based approach and the second is obtained using a modified GA based approach.

3.3.1 Modified Insertion Algorithm (IA) based approach

IA [125-128] is considered one of the leading approximation algorithms that provide near optimal answers at minimal cost. Analysis of the algorithm evaluates its outcome to be less than 2 times of the optimal sequence plan. In the MDA case, 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, In addition, any insertion of an object into the sub sequence must be preceded by an insertion of its feeder. These conditions dictates modification of the IA. We propose a modification to IA to satisfy these conditions.

The proposed IA constructs a subsequence that begins with a home position (Gripper position) as starting point; the same home position is used as an end point as well. The second step of Insertion is to insert any part (e.g. P3) (which needs to be assembled) preceded by its feeder location between the two positions already in the sub sequence. The inserted part is considered the minimal part insertion that yields the least increase in the travel distance. The assembly subsequence will then appear as [Gripper - [Feeder, Part P3]-Gripper]. The next step is to insert a new part between the positions in the sub sequence (this is selected by trial and error for all parts remaining in sequence so that the sequence with the least travel distance is selected). This process is repeated until all parts have been 'inserted' in the assembly sequence**.** The flowchart of the IA is provided in Figure 11.

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

1. Begin with an empty assembly sequence from robot home position back to its home position
2. Insert any one part (e.g. Part 3) into the sub sequence [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 sub sequence and insert the part with the least cost of increase in the subsequence.
5. Subsequence 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.

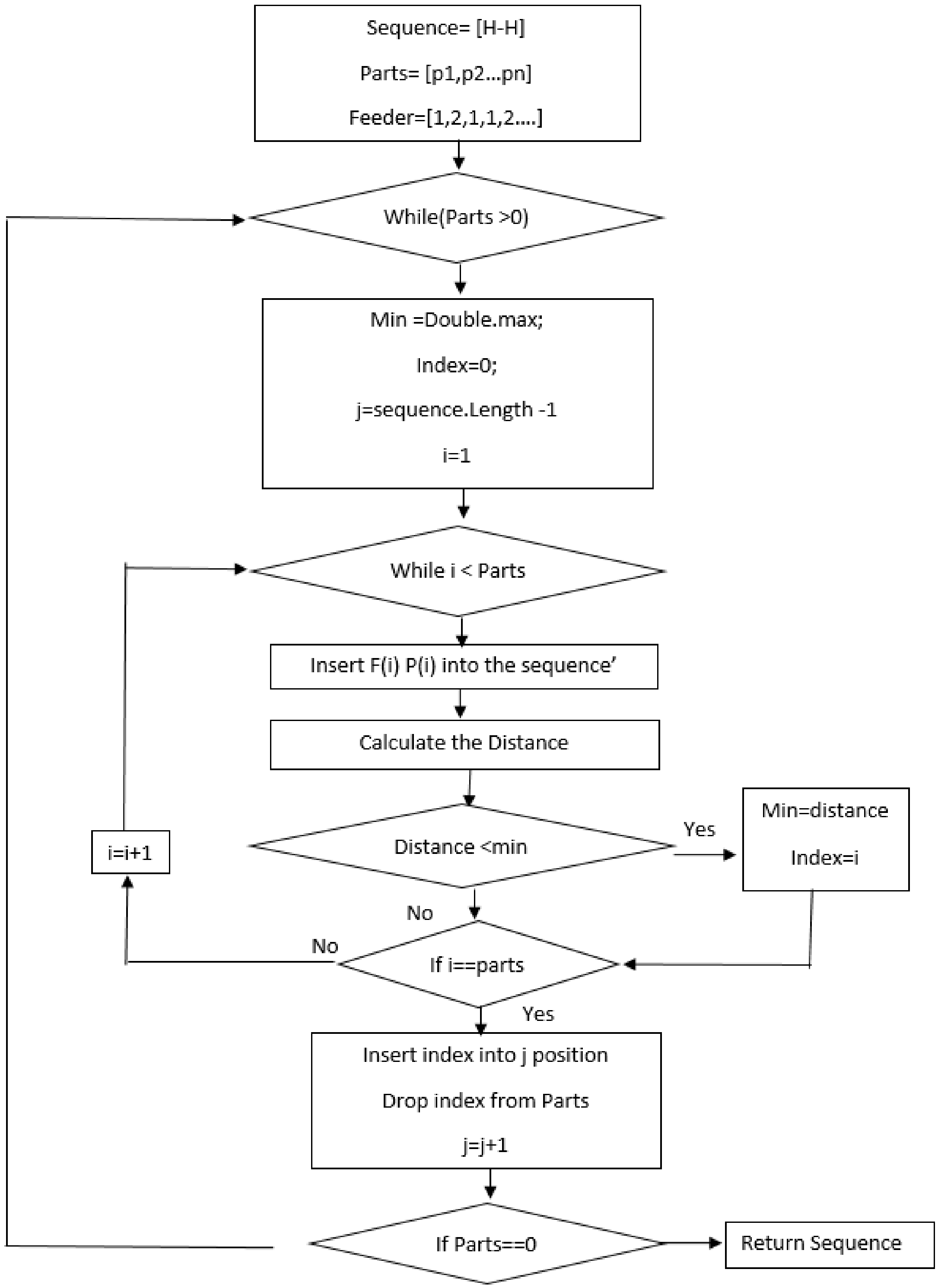


Figure 11: Flowchart for IA

Worst case behavior of IA:

$$\frac{length\ of\ IA}{length\ of\ Optimal\ Tour} \leq 2$$

Number of IA's computations:

$$O\ (n^2 \log_2 (n))$$

3.3.2 Genetic Algorithm (GA) based assembly sequencing

GA [129-131] is considered a heuristic search algorithm that harnesses the idea of the evolution of the fittest chromosome. It follows the natural selection of the best chromosome based on genetic operations performed on parents to generate better children who can survive harsh tests. The GA approach exploits a randomized search which tries to narrow down the search space by directing the search to better regions within the search space. GA is designed to mimic the natural survival of chromosomes in a critical environment where the fittest dominates the weak. The GA produces its result using two biology approaches known as: Crossover and Mutation. It keeps on improving the result based on these approaches until a better result is reached. The fitness score represents the travel distance of traversing all the points in the sequence. The GA will take MDA settings including origin locations of parts in the feeders and their designated destinations in the assembly plate. The GA will get several randomized results that provide different assembly sequences for MDA. Random parents will be selected to perform genetic operations of Crossover and Mutation. Crossover represents mating between two parents in order to create better children as shown in Figure 12. Mutation represents a small random modification which aims to provide a diversity to the generation as shown in Figure 13.

After these operations are performed, the fittest children will dominate weaker children and become the next generation of parents. This resembles directing the search space to a better search region which will eventually evolve the search to a better result. The flowchart of the GA is shown in Figure 14.

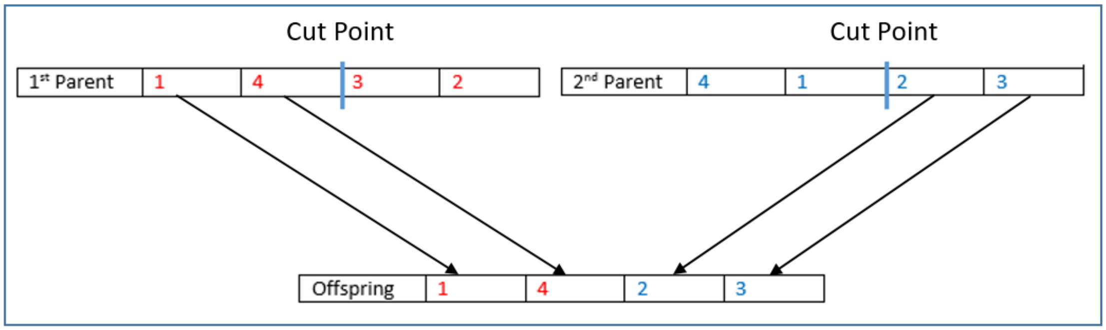


Figure 12: Crossover Operation for the GA

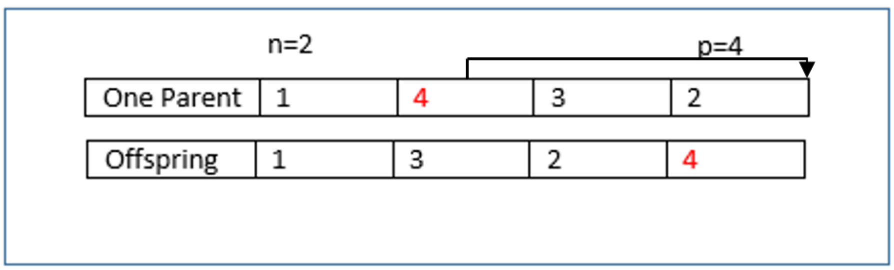


Figure 13: Mutation Operation for the GA

The following is a summary of the main steps of the proposed GA for MDA:

1. Generate random population for one iteration
2. Measure the fitness of the population
3. Perform the following process
    1. Select two parents from the population
    2. Perform crossover on selected parents and generate new child sequences
    3. Perform mutation on one parent; generate new child sequence
    4. Perform this in each iteration until all children are better than their parents; select these children sequences from both cross over and mutation outcomes as the new

parents. The GA heuristic generates 70% of new children using a cross over operation and 30 % of new children using mutation operation.

4. Go back to step1 if there is significant decrease in the fitness score.

When the fitness value does not change significantly between iterations, the GA can come to an end. Prior researches [129-131] have favored the use of 70% crossover along with 30% mutation over other combinations.

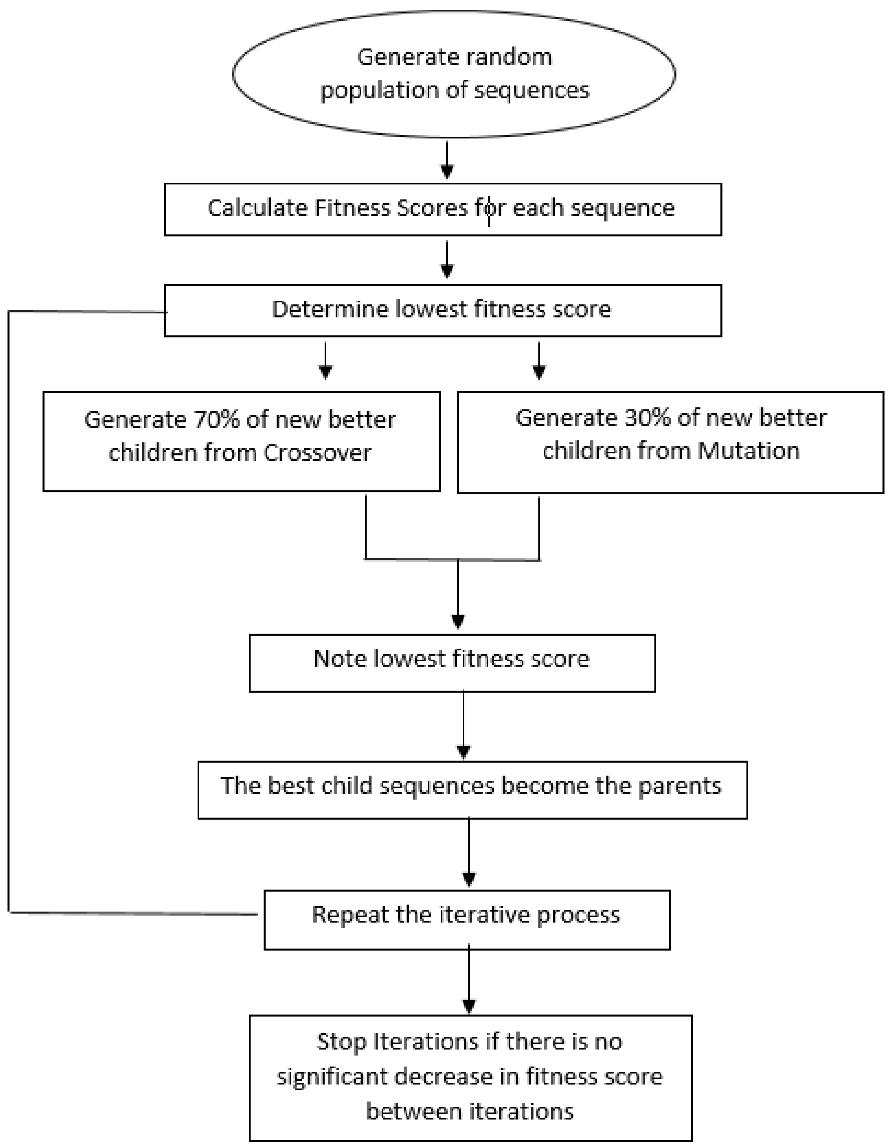


Figure 14: Flowchart for GA

3.4 Path Planning Module

There is a need for a collision free path between the assembly sequence points obtained by GA or IA, due to the possibility of obstacles between two points. A path planning module is developed to provide a collision free path. The emphasis in path planning is to obtain a collision free path plan between two points in the sequence provided by GA or IA. A collision free path using the A Star (A*) algorithm is utilized. The approach of the path planning takes into consideration collision detection of parts in the VR simulation. This approach is implemented and utilized within Unity3D to highlight the collision free path. Collisions detection is identified by changing colors of the collided objects.

A* algorithm is one of the path finding algorithms widely used due to its performance and accuracy [110-112]. The A* path planner is best used for providing shortest collision free path. A* provides an answer based on grid system. Consequently, MDA assembly plate is divided into a 10 X 10 grid consisting of 100 cells. A* requires mapping the parts' coordinates to cells in the grid, which is achieved by rounding a coordinate point to the nearest cell. Moreover, the algorithm takes an input of the originating and destination cells to return a sequence of cells that contains no obstacles leading to the destination cell.

A* algorithm uses the following set of variables to calculate the collision free path.

g cost: the cost of movement from the starting point to a given cell on the grid

h cost: the estimated cost from the given cell to the destination cell

f cost: is the sum of g and h ; $f = g+h$

The variables are used to calculate and track a trace leading to the destination with the least cost possible. The following is a basic example illustrating how the A* works: assume a grid system of 5 x 5 cells (as shown in Figure 15). The originating cell is colored blue with an index of 3 and the destination colored red with an index of 17. The black cells in the grid represent the obstacles. The goal is to start at the blue cell and find a path that is the lowest cost to the red cell in the meantime avoiding the black cells. In an MDA case, the orthogonal distance between two cells is set to 10 and the diagonal distance is not allowed.

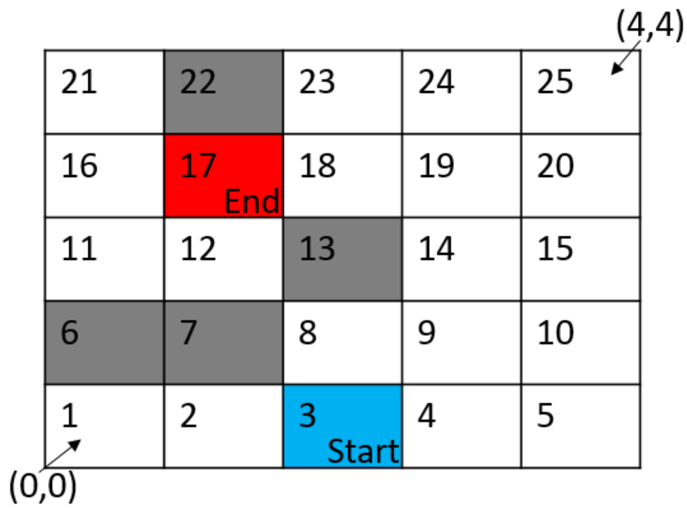


Figure 15: Grid showing the start point, destination and obstacles

Figure 16 represents the calculation that the A* outputs to reach its answer. Calculations are shown for g cost, h cost and f cost for neighboring cells of origin cell.

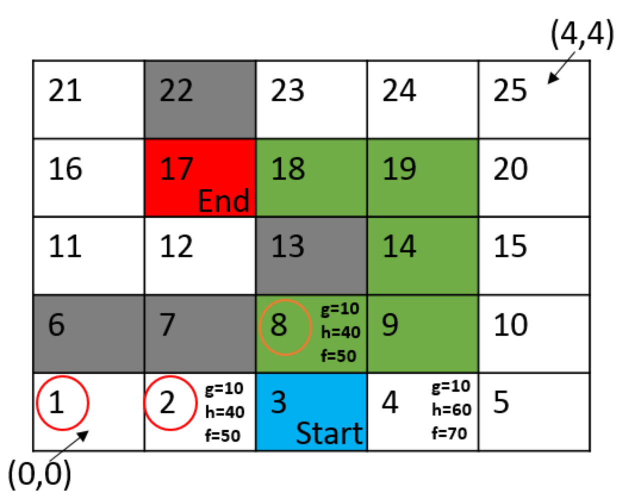


Figure 16: Calculations for g, h and f costs

Comparing the f costs, the least is found in cell 2 and 8. A* algorithm can pick any of these two choices. If A* picked cell 2, then it will pick cell 1 from which it cannot proceed any further. In that case, A* algorithm backtracks to the origin cell and picks the second choice (cell 8) and proceeds from it to the destination. The calculation of f costs for the surrounding of cell 8 is carried out to determine the next cell to be traversed until the destination cell is reached. Figure 16 shows one step calculation of the shortest collision free path. In MDA case, diagonal movement is not allowed due to limitation in the physical work cell. Therefore, the movements in the A* are modified to prevent diagonal movement and allow horizontal and vertical traversal only. This mandate is to mimic the physical work cell movements in which diagonal movements cannot be performed. Figure 17 shows the results for the given example in Figure 16.

Coordinates : [0, 2] -> [1, 2] -> [1, 3] -> [2, 3] -> [3, 3] -> [3, 2] -> [3, 1]
Index : 3->8->9 ->14 ->19 ->18 ->17

Figure 17: Collision Free path generated

3.5 Design of the VR based Assembly Simulation Environment (VRASE)

The design of an advanced VR environment that simulates the process of the assembly plan is explored to determine the feasibility of an assembly plan in the physical Work cells. The VR environments are 3D graphics simulation environments built using Unity Game development software, which utilizes two programming languages C# and JavaScript. The VR environment is linked to the physical Work cells in order to download a feasible assembly plan and perform the physical assembly of micron sizes of parts. The creation of a VR environment using two level of immersions is investigated:

1. A semi-immersive environment which is equipped with trackers and sensors. The benefits of semi-immersive include:

a. The ability to 'immerse' the user in the simulated 3D environment

b. Interact more effectively in studying the problems and comparing various alternatives

The Semi-immersive environments was built to be used on the PowerWall™. (The PowerWall™ is from Mechdyne). PowerWall™ is a semi-immersive VR system. It consists of a high performance CPU, back projector, motion tracking cameras, stereoscopic eye-wears and handheld controller. The scene from the back projector is projected onto the screen. The scene displayed in the projector is stereoscopic in nature and provides realistic 3D vision to the users wearing the stereoscopic eye-wear. The screen is attached with a number of motion tracking cameras which track the position of the active user holding the controller and wearing the stereoscopic eye-wear. Navigation through the semi-immersive VR environment is done using the stereo eyewear and controllers. The PowerWall™ is illustrated in Figure 18. Users interacting with the PowerWall™ are shown in Figure 19.

Steps to convert a Unity scene to the semi-immersive PowerWall™ scene includes:

1. Import the *GetReal3D* package into the Unity simulation project.

2. Change the attributes in the Unity scene, such as camera, player movement, wand manger and build the executable file.

3. Open *GetReal3D for Unity* software on the PowerWall™, add the executable file and launch it.

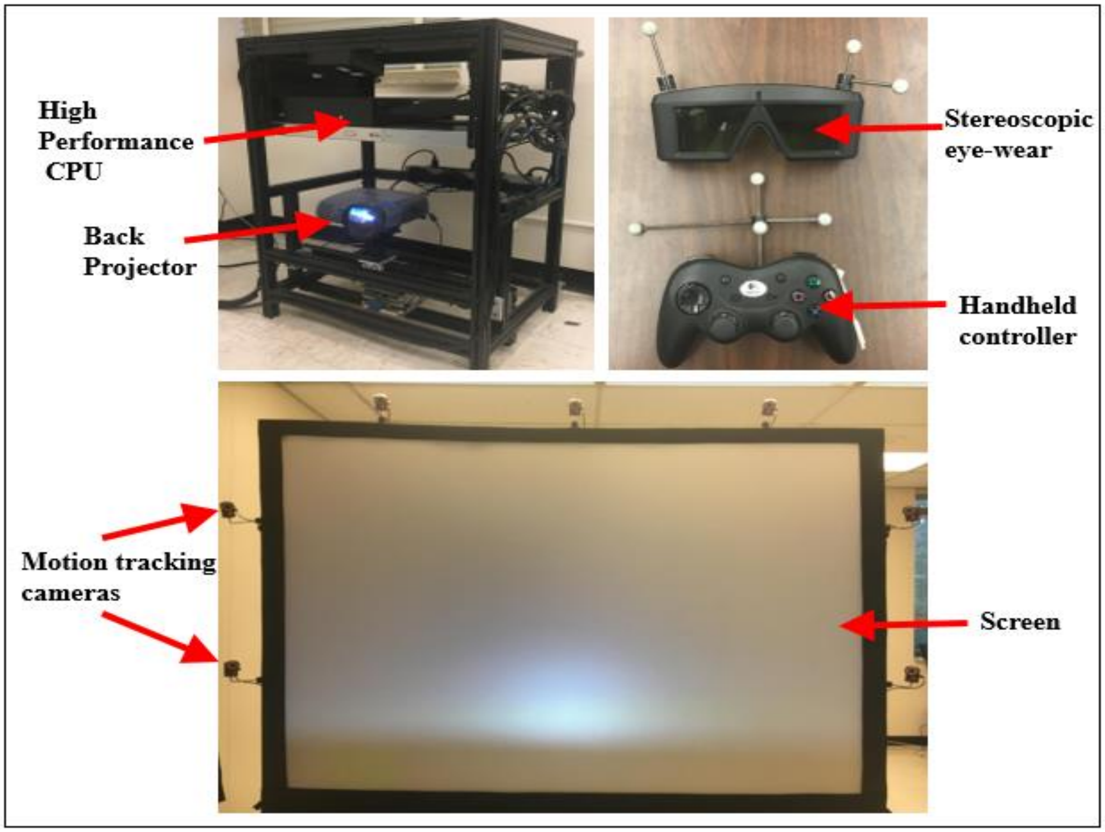


Figure 18: Semi-immersive PowerWall™

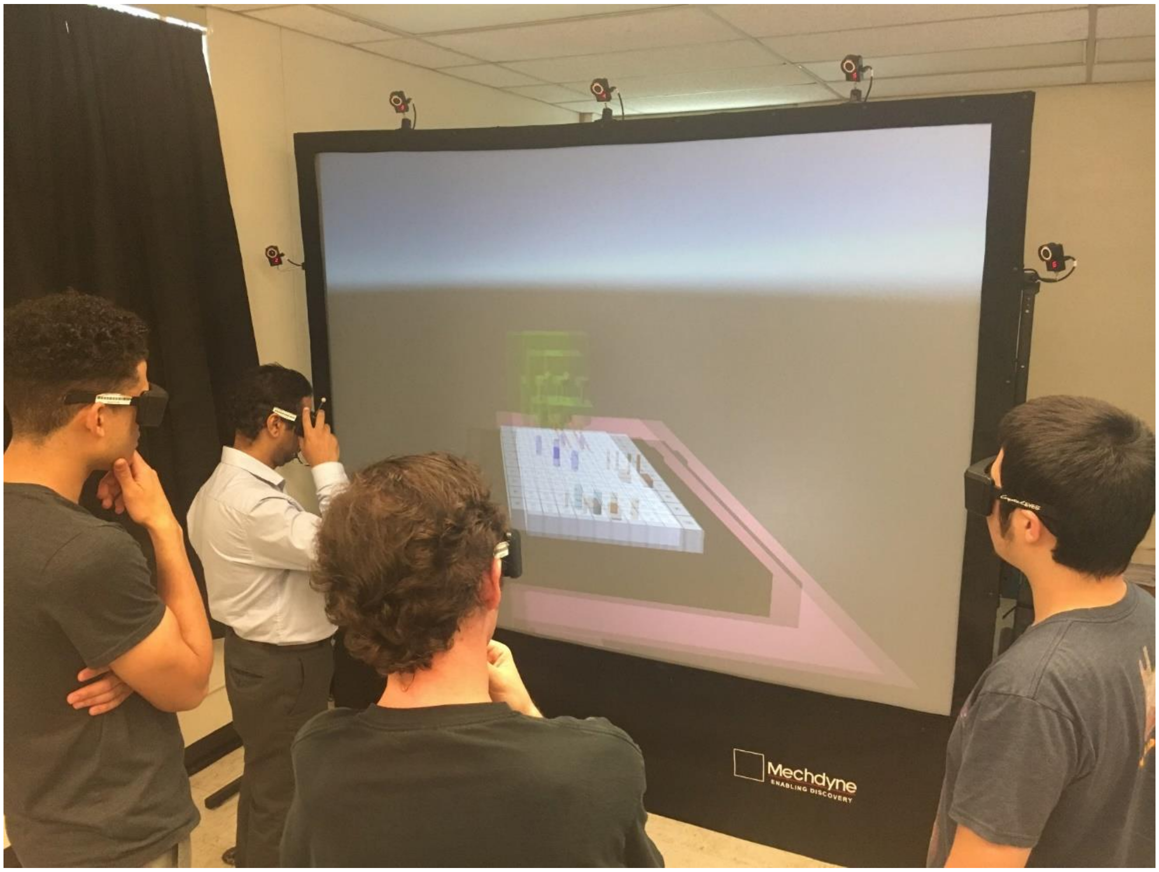


Figure 19: Users interacting with the PowerWall™

2. Non-immersive environment involves a typical computer based 2D environment and can be run on regular PCs.

Non-Immersive environments are low cost in general as they only require PC displays that are readily available in most engineering organizations. A screenshot of non-immersive environment is shown in Figure 20.

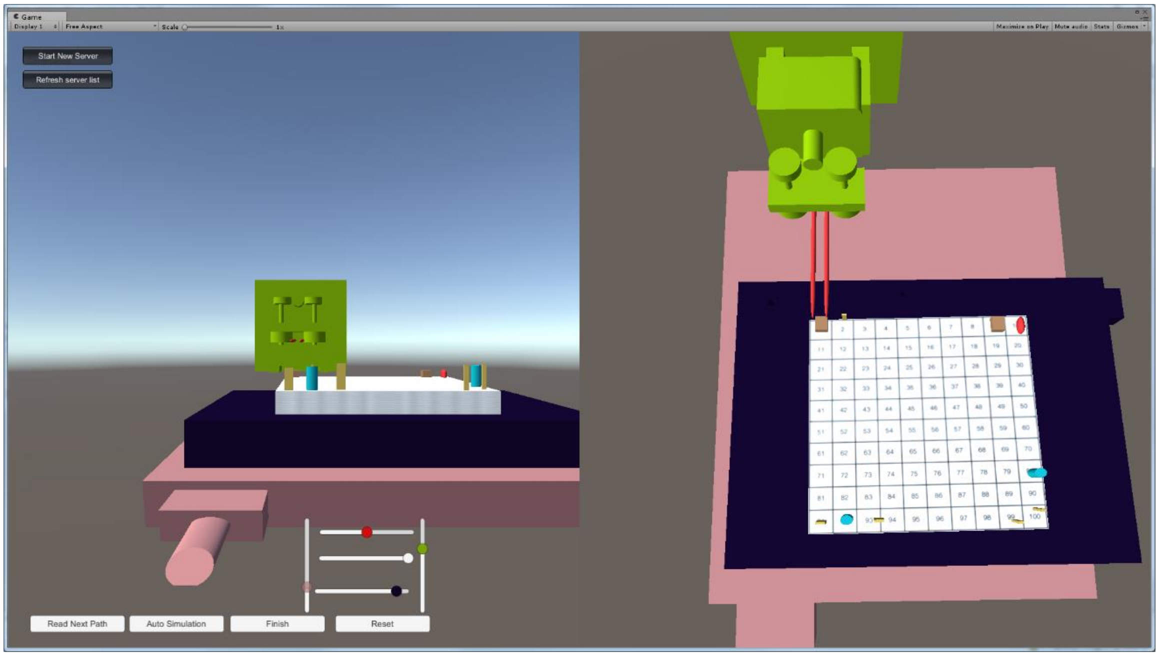


Figure 20: Non-immersive VR environment

The assembly plan can be virtually examined and analyzed using the VR environments. The simulated assembly process is examined and problems such as collisions are identified and modified accordingly. The VR environment takes the candidate assembly sequence as an input for determining its feasibility. It will then furnish the assembly sequence with a collision free path between its points to complete the assembly plan. While an assembly plan is analyzed and examined for feasibility, the VR environment converts the simulation details into physical commands that can be downloaded to a computer linked to the physical Work cells. Through the VR environment, users are able to propose their own assembly plans and compare it with the automatically generated plans and select the most preferable plan. Figure 21 shows the cloud based VR environment. The cloud based VR environment allows participants from geographically distance regions to engage and collaborate in producing feasible assembly plan.

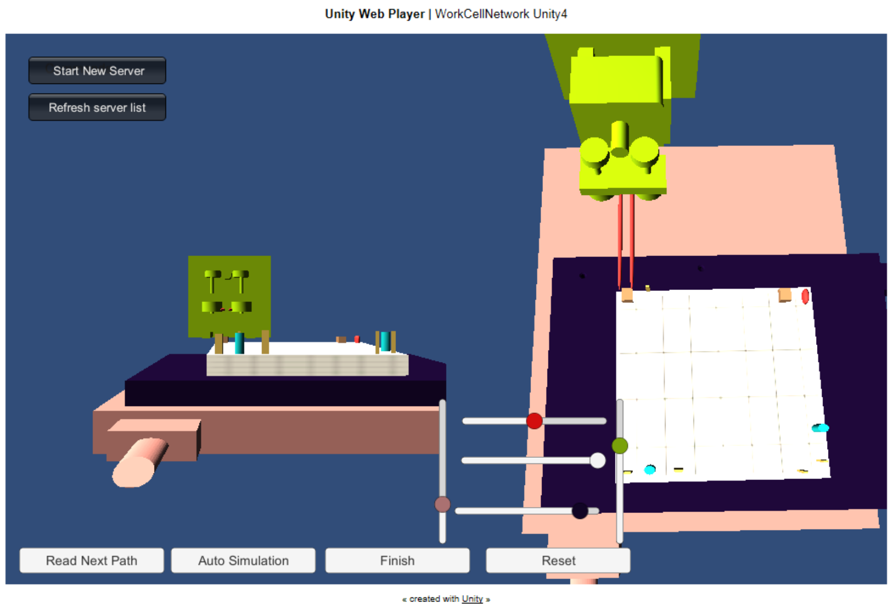


Figure 21: Non-immersive cloud based VR environment

3.6 Physical Assembly Command Generation

The assembly plan obtained using the VR environment is used to generate a physical assembly commands. When an assembly plan is constructed and passed the rigorous analysis. It's marked as a feasible assembly. The assembly plan is fed to the command generation module for converting the VR environment assembly plan to a Work cell physical commands. The physical command generation will work in two modes: (1) manual generation, where a human is involved in examining the steps of the VR simulation and logging in the mechanical movements of different micro-positioners of the work cell using designated control buttons. (2) Semi-automatic generation, where the command generation module will produce an automated physical commands plan without human intervention based on the VR assembly plan.

3.6.1 Manual Generation

Manual interaction with the VR simulation environment is used to extract the correct movements by having the end user to intuitively try moving the micro positioners to allow basic steps like (Pick and place). Once the user determine a certain movement is correct he/she can then save the micro positioners adjustment settings in a log file which should contain the sequence of micro positioner's movements recorded in the syntax of the physical work cell. The VR environment features controlling sliders that represent the actual physical work cell which activate movements. Colored sliders are used to match the micro positioners' colors that they control. Vertical sliders control moving micro positioner up and down or forward and backward. Whereas the horizontal sliders control moving micro positioners left to right or rotate the assembly plate. Figure 21 shows the VR environment with the sliders.

3.6.2 Semi-Automatic Generation

In the semi-automatic mode, the VR environment will exploit the various software modules to follow predetermined steps for assembling micron parts. The semi-automated mode serves educational goals for engineering users seeking learning several objectives of MDA. While the VR assembly is processing the parts, the VR environment instructions are converted to a physical assembly command. The Auto Simulation button in Figure 21 invokes the semi-automated mode.

3.7 Monitoring and Machine Vision Module

In the IoT based approach, a monitoring and machine vision module keeps track of the physical MDA activities in the work cells. This module was developed as part of a different research project in the Center for CPS at OSU; it was built using OpenCV, which is an open source computer vision and cross-platform library [133]. It is used to help identify part positions and gripper movement during assembly as well provide updates on the overall assembly tasks in progress to the Cyber Physical Manager and distributed partners. For instance, when the micro gripper is performing various tasks, the cameras transmit these views to the distributed partners and modules in real time.

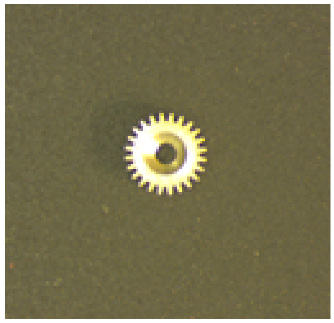


Figure 23: Template Image

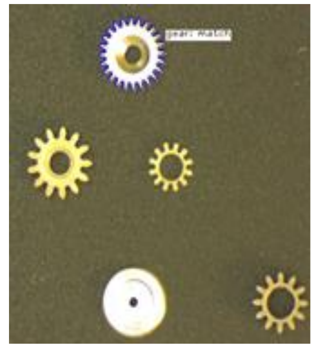


Figure 22: Test Image

The part recognition algorithm is accomplished using a process that can be broken into 3 general sections: preparation, filtering, and matching. First, the image is prepared by converting it to grayscale and thresholding it. Dilating and eroding the binary image removes noise without causing any significant changes to the shape or size of the features. Features are identified through template matching; these methods are used to identify gripper position, WIP of assembly and other task progress. The pairs of contours are filtered by area and moment. Figure 23 is one example showing how this machine vision module works. The Figure 23 is the template and test is successfully matched with gears labeled whose matching contour is traced in blue (Figure 22). This software module was an outcome of a previous project [113] and was used as part of the CPS implementation.

3.8 Cyber Physical Manager (CPM) and Cyber Physical Interactions

Cyber-physical manager has been designed and implemented to facilitate the collaboration between the cyber and physical components. The various modules discussed in the previous sections can be seen on this webpage (Figure 24). This webpage can be used for collaboration and interaction among the various cyber physical components as indicated.

The status of the various cyber physical interactions can be monitored through a CPS status web page; at any instant, the status and progress of the various life cycle activities in the collaborative process can be followed through this web page.

The work cell performing the physical assembly has cameras mounted on it. Two cameras are available to stream the live feed of the assembly process to the CPM. The cameras can act as a monitoring tool in which users can access remotely through the live stream. Figure 25 shows the physical work cell and the cameras mounted on it.

Insertion Algorithm based Assembly Sequence	Genetic Algorithm based Assembly Sequence	Generation of Path Plan	VR based Assembly Analysis	Physical Assembly
Started	Started	Started	Not Started	Not Started

Figure 24: Webpage depicting the status of Cyber Physical Interactions

Four states are used to convey the progress of the Cyber Physical interactions:

Started: triggered the module for execution.

Completed: finished execution.

Not Started: no execution of the module is triggered.

Problem: error occurred during the execution.

3.9 Physical Assembly Work cell

The Physical assembly module receives the feasible assembly commands which is used as the basis to complete the physical assembly tasks. The physical work cells represent the physical component of the IoT based framework. Three physical work cells are available in Oklahoma State University; however, the CPS approach was demonstrated using work cell 2 only. The assembly plan and path plan obtained and analyzed in the VR environment are converted to a physical commands using the Commands Generation Module (which was described earlier). Consequently, the converted physical assembly commands act as an input for the physical work cell to assemble micro devices.

The work cell 2 (Figure 25) comprises of the following components:

1. Gripper; a tweezer instruments used to pick and place micron parts. The gripper has one Degree of Freedom along the Z axis.
2. Assembly plate, it is a platform that the gripper places micron parts into.
3. Micro positioners, mechanical movers that move the assembly plate along X-axis, Y-axis and one with rotational Degree of Freedom.
4. Cameras are used to monitor the physical activities.

The physical Work cell in Figure 25 has 4 DOF, with the assembly plate capable of rotation and the gripper capable of movement along the z axis; it is versatile and is capable of supporting different grippers for assembly. Also, it is capable of assembling 30 to 1 mm. Two cameras are available for assisting in the assembly activities as well as for monitoring the progress of the assembly tasks. Figure 26 shows a live-stream of the progress of the assembly via the mounted cameras.

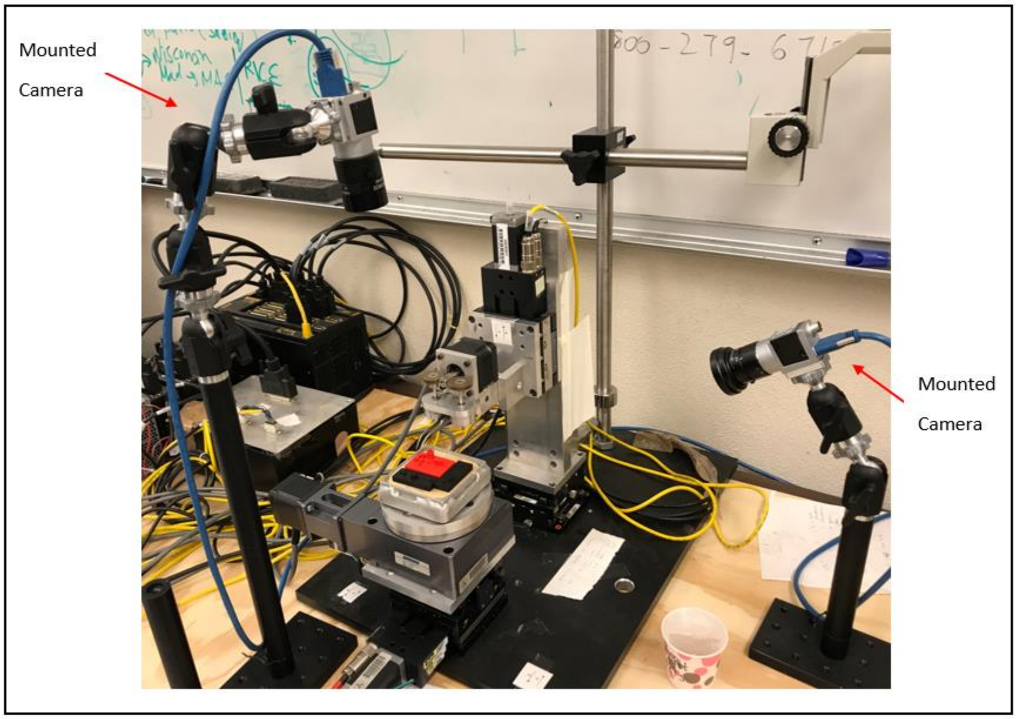


Figure 25: Physical Work Cell 2

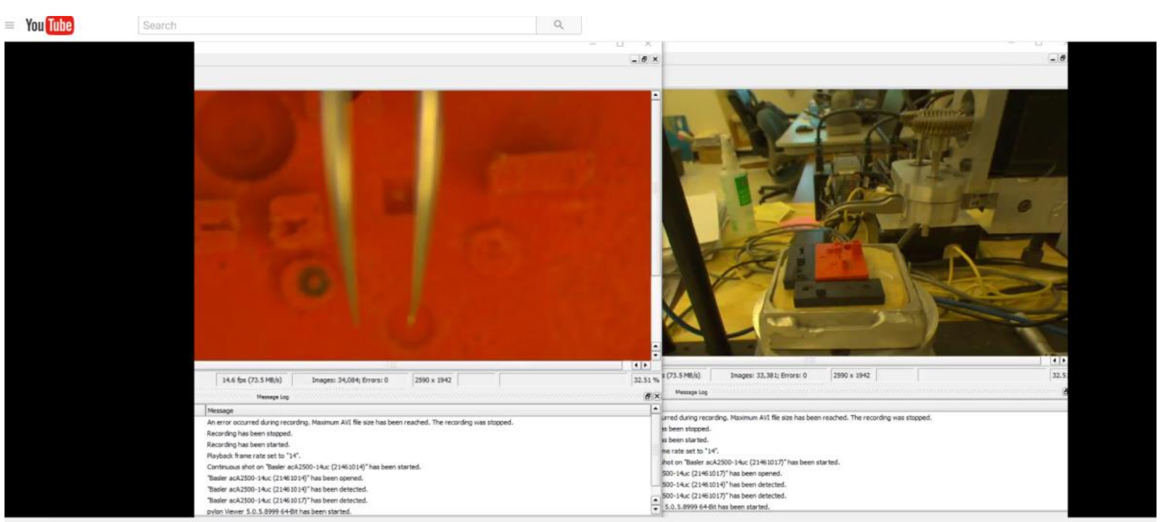


Figure 26: Physical Work Cell live stream

3.10 GENI based Collaborative VR framework

The GENI (www.geni.net) initiative involves the design and deployment of advanced networks and approaches that have several innovative aspects including Software Defined Networking (SDN) and adoption of cloud technologies; these networks will enable seamless exchange of information across heterogeneous platforms among distributed partners. Consequently, improve collaboration between distributed locations to access and share resources especially involving high bandwidth data; using such networking approaches and technologies will enable sharing of VR based environments (involving rich 3D VR data), as well as enabling interacting with distributed work cells.

Exploring GENI and investigating its benefits to support distributed collaborative engineering activities is carried out using the IoT based framework, the result of latency and bandwidth is recorded while routing the VR Simulation incoming data packets and outgoing data traffic to a master server placed on GENI Node. The VR Server and Client are running on non GENI platform but their communication data is channeled through GENI Node.

Figure 27: Location of GENI Racks [121]

A GENI node is a virtual machine which is located on the GENI aggregate (GENI server). GENI servers or GENI racks are set up in various locations all around the United States. Figure 27 [121] provides the details about the locations of GENI racks.

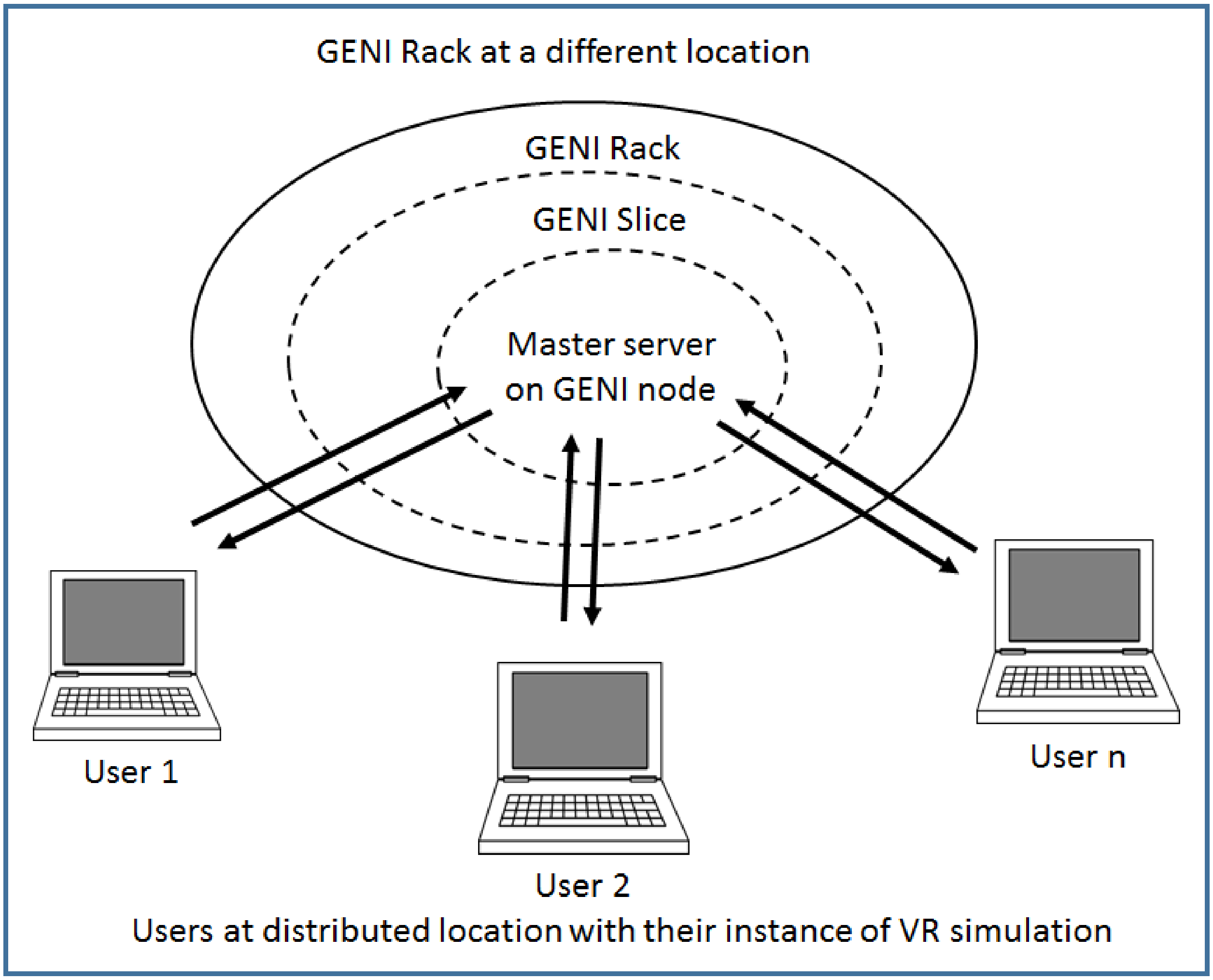


Figure 28: GENI based collaborative framework

A Master Server is created on the GENI node at one of the many GENI racks available as shown in Figure 27. The users situated at distributed locations are provided with their instance of the VRASE. When the users first launch the VRASE, they will be prompted to join as a client. After the users have joined as clients, all the instances of the VRASE will synchronize and they can interact with the VRASE collaboratively. Figure 28 shows the framework of GENI based collaborative interactions.

3.11 Summary

In this chapter, an overview of the overall framework and approach was provided. We discussed the functioning of various cyber and physical modules of this framework for MDA. These modules perform the following tasks: (1) part design input, (2) assembly planning, (3) path planning, (4) VR based simulation (5) command generation, (7) Monitoring, (8) Physical Manager and Cloud based interactions, (9) physical assembly. Further, a discussion on the feasibility of using GENI based networking to support collaborative VR based simulation activities was also provided.

CHAPTER IV

CASE STUDIES AND RESULTS

4.1 Introduction

In the chapter, test cases and examples involving various aspects of the CPS approach and algorithms discussed in chapter 3 are provided. This includes examples of parts inputs, outputs from the GA and IA based approaches, path planning and command generation tasks. Figure 29 represents the cloud based CPS Framework. The cloud based CPS framework is created for the user convenient. Using the website, the user will be able to supply the input file containing parts locations and associated feeders. The user will be able to perform the cyber activities and run VR environments online. Through the website the user will be able to monitor activities through the CPM and access the generated physical commands.

Project By:
Sadiq Albuhamood

For

Doctoral Dissertation

Summer 2017

To submit an input file (coordinates) click on the following link

Submit Part Design File

To obtain the sequence from the Genetic Algorithm GA

Genetic Algorithm based Assembly Sequence

To obtain the sequence from Insertion Algorithm IA

Insertion Algorithm based Assembly Sequence

To obtain a collision free path using (A*) with GA sequence

Generation of Path Plan with GA based assembly sequence

To obtain a collision free path using (A*) with IA sequence

Generation of Path Plan with IA based assembly sequence

To run the VR Assembly Environment

VR based Assembly Analysis

Cyber Physical Manager ,to track progress

Track Progress of Cyber Physical Activities (Status)

To show the Physical Command

Physical Commands Generated for Assembly

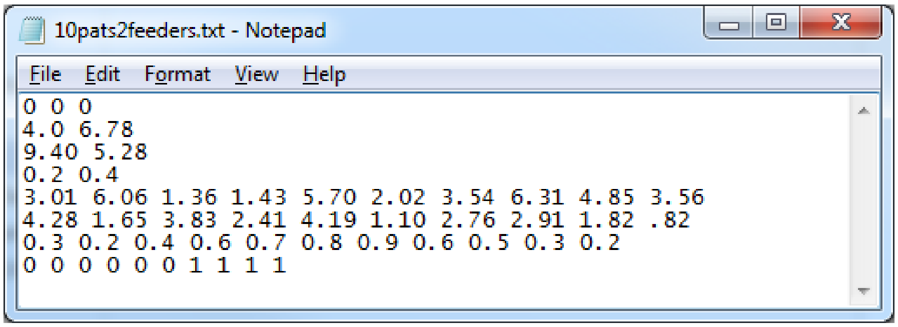
Assembly Video from the Physical workcell

Assembly Video from Work Cell

Figure 29: The Cloud based CPS Framework

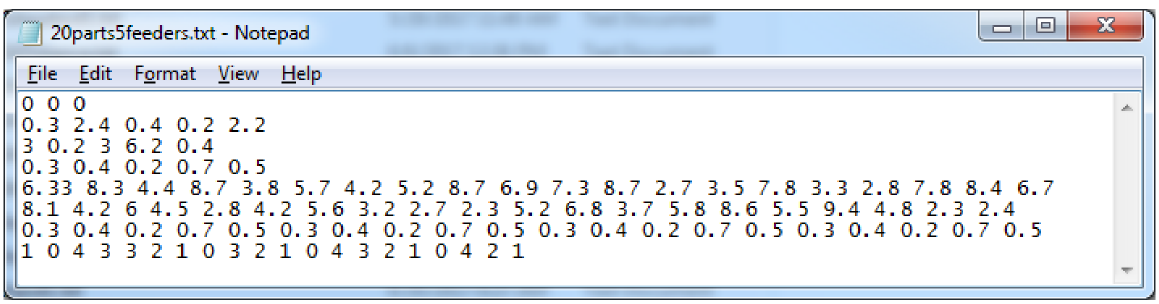
4.1 Test Cases

The IoT based framework is tested out using the two examples. The first consists of 10 parts and 2 feeders. The second example consists of 20 parts and 5 feeders. The input file of the two examples are in Figure 30 and Figure 31, respectively. Figure 32 represents a graph of the first example input file with part locations and feeders.




```
0 0 0
4.0 6.78
9.40 5.28
0.2 0.4
3.01 6.06 1.36 1.43 5.70 2.02 3.54 6.31 4.85 3.56
4.28 1.65 3.83 2.41 4.19 1.10 2.76 2.91 1.82 .82
0.3 0.2 0.4 0.6 0.7 0.8 0.9 0.6 0.5 0.3 0.2
0 0 0 0 0 0 1 1 1 1
```

Figure 30: Input file of 10 parts and 2 feeders




```
0 0 0
0.3 2.4 0.4 0.2 2.2
3 0.2 3 6.2 0.4
0.3 0.4 0.2 0.7 0.5
6.33 8.3 4.4 8.7 3.8 5.7 4.2 5.2 8.7 6.9 7.3 8.7 2.7 3.5 7.8 3.3 2.8 7.8 8.4 6.7
8.1 4.2 6 4.5 2.8 4.2 5.6 3.2 2.7 2.3 5.2 6.8 3.7 5.8 8.6 5.5 9.4 4.8 2.3 2.4
0.3 0.4 0.2 0.7 0.5 0.3 0.4 0.2 0.7 0.5 0.3 0.4 0.2 0.7 0.5 0.3 0.4 0.2 0.7 0.5
1 0 4 3 3 2 1 0 3 2 1 0 4 3 2 1 0 4 2 1
```

Figure 31: Input file of 20 parts and 5 feeders

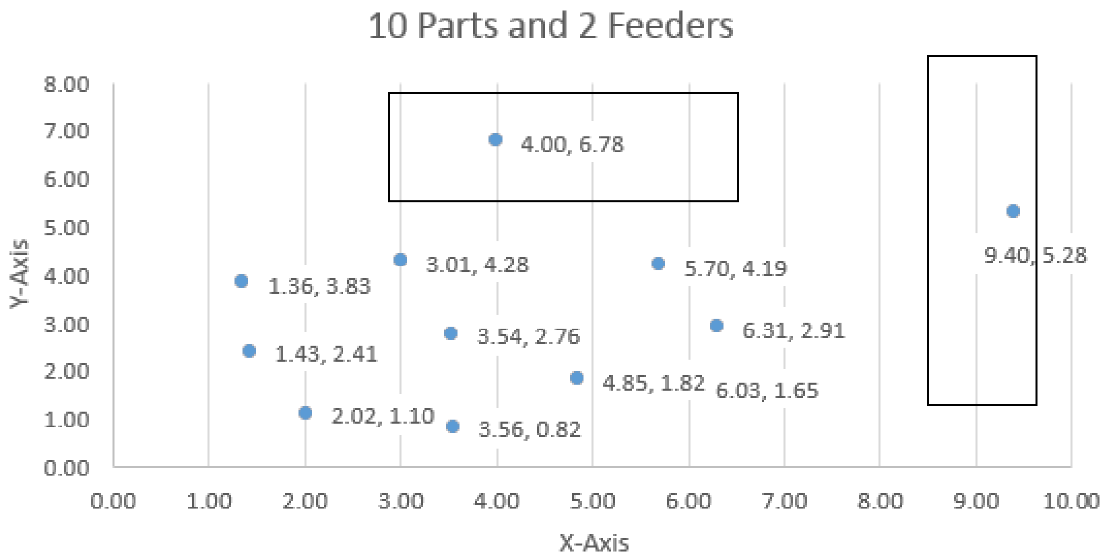


Figure 32: Graph corresponds to the input of 10 parts and 2 feeders.

4.2 Assembly Plan Generation

Upon receiving the input file, the IoT based framework has an assembly module that consists of two sequence algorithms GA and IA. The sequence algorithms are utilized to provide near optimal sequences. Two links are provided in the cloud that will trigger both algorithms and output their results.

4.2.1 Assembly Plan Generation using GA based approach

Figure 33 and Figure 34 represent the output files for the two examples generated by the Assembly Plan Generation using GA based approach.

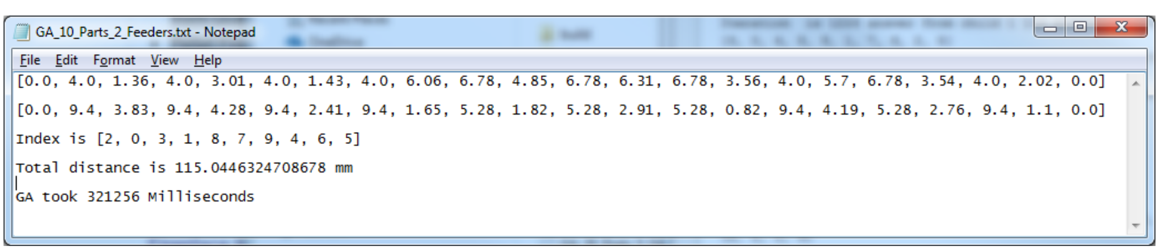
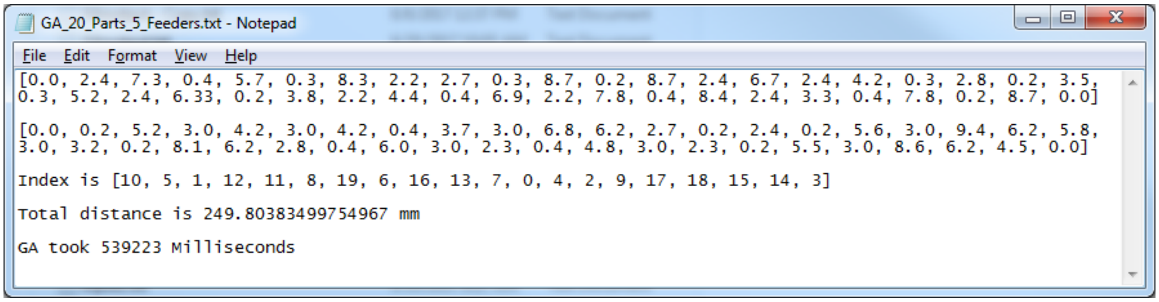


Figure 33: First example GA based assembly sequence

GA based approach convergence for the two examples are shown in Table 3 and Table 4 respectively.

Table 3: Convergence of GA based approach for the first example.

Iteration	Operation	Sequence	Distance
3	Crossover	[5, 2, 4, 6, 8, 3, 1, 7, 0, 9]	121.18361616466201
4	Crossover	[8, 6, 7, 3, 5, 4, 2, 0, 1, 9]	120.61196434374504
5	Crossover	[8, 7, 6, 3, 5, 2, 4, 0, 1, 9]	120.58444004508684
17	Crossover	[3, 5, 6, 4, 7, 8, 0, 2, 1, 9]	118.66303108903372
60	Mutation	[3, 5, 4, 6, 7, 8, 0, 2, 1, 9]	117.8069415747832
68	Mutation	[1, 7, 3, 2, 0, 4, 8, 6, 9, 5]	117.45373508705721
185	Crossover	[2, 5, 1, 7, 8, 6, 0, 3, 4, 9]	116.96604142692092
217	Crossover	[4, 7, 8, 6, 3, 2, 0, 5, 1, 9]	116.33938966293792
548	Crossover	[2, 0, 1, 6, 8, 3, 4, 7, 9, 5]	116.3393896629379
1101	Crossover	[3, 4, 7, 6, 1, 9, 8, 0, 2, 5]	116.15897789498712
1226	Crossover	[3, 0, 4, 8, 9, 1, 7, 6, 2, 5]	115.61989539983742
2170	Mutation	[2, 0, 3, 1, 8, 7, 9, 4, 6, 5]	115.04463247086781
19839	Crossover	[2, 0, 3, 1, 8, 7, 9, 4, 6, 5]	115.0446324708678



GA_20_Parts_5_Feeders.txt - Notepad

File Edit Format View Help

```
[0.0, 2.4, 7.3, 0.4, 5.7, 0.3, 8.3, 2.2, 2.7, 0.3, 8.7, 0.2, 8.7, 2.4, 6.7, 2.4, 4.2, 0.3, 2.8, 0.2, 3.5,
0.3, 5.2, 2.4, 6.33, 0.2, 3.8, 2.2, 4.4, 0.4, 6.9, 2.2, 7.8, 0.4, 8.4, 2.4, 3.3, 0.4, 7.8, 0.2, 8.7, 0.0]

[0.0, 0.2, 5.2, 3.0, 4.2, 3.0, 4.2, 0.4, 3.7, 3.0, 6.8, 6.2, 2.7, 0.2, 2.4, 0.2, 5.6, 3.0, 9.4, 6.2, 5.8,
3.0, 3.2, 0.2, 8.1, 6.2, 2.8, 0.4, 6.0, 3.0, 2.3, 0.4, 4.8, 3.0, 2.3, 0.2, 5.5, 3.0, 8.6, 6.2, 4.5, 0.0]

Index is [10, 5, 1, 12, 11, 8, 19, 6, 16, 13, 7, 0, 4, 2, 9, 17, 18, 15, 14, 3]

Total distance is 249.80383499754967 mm

GA took 539223 Milliseconds
```

Figure 34: Second example GA based assembly sequence

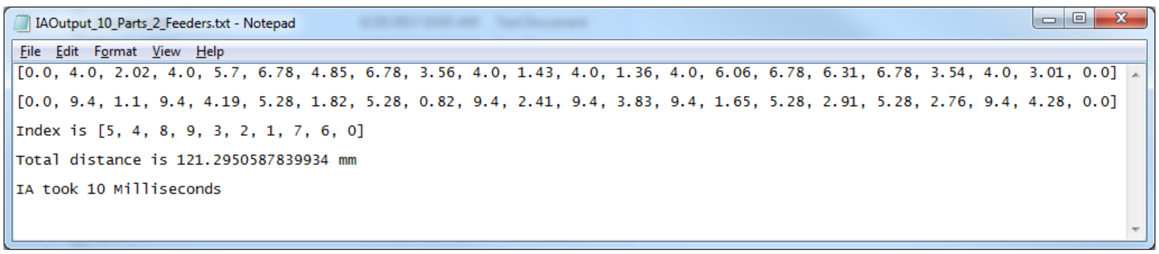
Table 4, Convergence of GA based approach for the second example.

Iteration	Operation	Sequence	Distance
0	Mutation	[16, 7, 11, 14, 4, 2, 1, 12, 18, 6, 3, 19, 10, 9, 15, 8, 17, 0, 13, 5]	253.36011385186504
18	Mutation	[15, 8, 2, 3, 6, 5, 7, 17, 11, 4, 0, 18, 19, 10, 16, 13, 1, 12, 14, 9]	252.05513539273724
3909	Crossover	[6, 5, 4, 14, 8, 15, 11, 7, 0, 3, 17, 18, 2, 16, 13, 1, 12, 9, 10, 19]	251.30746826183517
6494	Mutation	[6, 4, 10, 16, 8, 19, 17, 2, 13, 9, 0, 3, 12, 5, 18, 15, 14, 1, 11, 7]	251.2816984721776
10428	Mutation	[12, 5, 9, 10, 11, 13, 18, 17, 2, 3, 15, 1, 0, 16, 4, 7, 6, 14, 8, 19]	250.64195343320918
41681	Crossover	[0, 13, 9, 10, 5, 11, 16, 8, 17, 2, 14, 4, 12, 7, 1, 6, 18, 19, 15, 3]	250.34891174967692
198381	Crossover	[1, 0, 13, 7, 2, 5, 14, 4, 6, 16, 8, 15, 3, 17, 10, 11, 18, 19, 12, 9]	249.95498618917483

416221	Crossover	[1, 0, 13, 7, 2, 5, 14, 4, 6, 16, 8, 15, 3, 17, 10, 11, 18, 19, 12, 9]	249.94491229306217
607865	Crossover	[10,5,1,12,11,8,19,6,16,13,7,0,4,2,9,17,18,15,14,3]	249.80383499754967

4.2.1 Assembly Plan Generation using IA based approach

Figure 35 and Figure 36 are the output files from the two examples generated by the Assembly Plan Generation using IA.


IAOutput_10_Parts_2_Feeders.txt - Notepad

File Edit Format View Help

[0.0, 4.0, 2.02, 4.0, 5.7, 6.78, 4.85, 6.78, 3.56, 4.0, 1.43, 4.0, 1.36, 4.0, 6.06, 6.78, 6.31, 6.78, 3.54, 4.0, 3.01, 0.0]

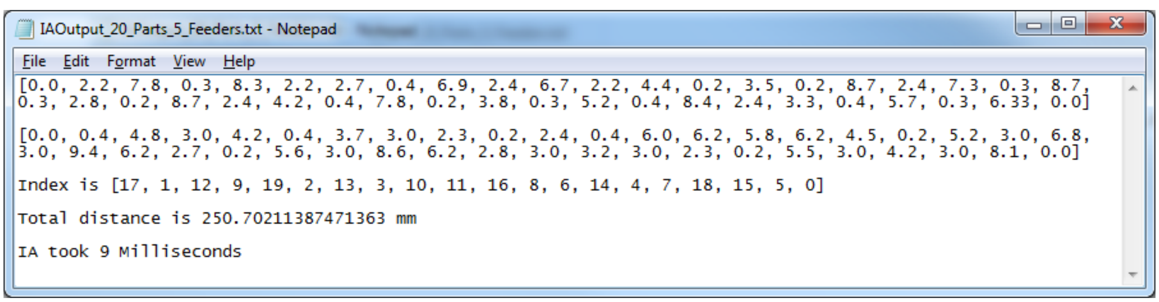
[0.0, 9.4, 1.1, 9.4, 4.19, 5.28, 1.82, 5.28, 0.82, 9.4, 2.41, 9.4, 3.83, 9.4, 1.65, 5.28, 2.91, 5.28, 2.76, 9.4, 4.28, 0.0]

Index is [5, 4, 8, 9, 3, 2, 1, 7, 6, 0]

Total distance is 121.2950587839934 mm

IA took 10 Milliseconds

Figure 35: First example IA based assembly sequence


IAOutput_20_Parts_5_Feeders.txt - Notepad

File Edit Format View Help

[0.0, 2.2, 7.8, 0.3, 8.3, 2.2, 2.7, 0.4, 6.9, 2.4, 6.7, 2.2, 4.4, 0.2, 3.5, 0.2, 8.7, 2.4, 7.3, 0.3, 8.7, 0.3, 2.8, 0.2, 8.7, 2.4, 4.2, 0.4, 7.8, 0.2, 3.8, 0.3, 5.2, 0.4, 8.4, 2.4, 3.3, 0.4, 5.7, 0.3, 6.33, 0.0]

[0.0, 0.4, 4.8, 3.0, 4.2, 0.4, 3.7, 3.0, 2.3, 0.2, 2.4, 0.4, 6.0, 6.2, 5.8, 6.2, 4.5, 0.2, 5.2, 3.0, 6.8, 3.0, 9.4, 6.2, 2.7, 0.2, 5.6, 3.0, 8.6, 6.2, 2.8, 3.0, 3.2, 3.0, 2.3, 0.2, 5.5, 3.0, 4.2, 3.0, 8.1, 0.0]

Index is [17, 1, 12, 9, 19, 2, 13, 3, 10, 11, 16, 8, 6, 14, 4, 7, 18, 15, 5, 0]

Total distance is 250.70211387471363 mm

IA took 9 Milliseconds

Figure 36: Second example IA based assembly sequence

The first example of 10 parts and 2 feeders shown in Figure 30 was calculated using GA and resulted in a total distance of 115.04 mm whereas the IA resulted in ad distance of 121.29 mm.

Time comparison is carried out, the GA finished in 321256 Milliseconds whereas IA finished in 10 milliseconds.

The second example of 20 parts and 5 feeders shown in Figure 31 was calculated using GA and resulted in a total distance of 249.80 mm whereas the IA resulted in ad distance of 121.29 mm. Time comparison is carried out, the GA finished in 539223 Milliseconds whereas IA finished in 9 Milliseconds.

In both examples GA based approach outperformed the IA based approach. Nevertheless, in the time comparison, IA based approach finished earlier.

Other part design examples have been examined for both GA and IA based approaches.

4.3 Cyber Physical Manager (CPM)

The CPM (software) keeps track of the various interactions among the modules of IoT based framework. The CPM receives feedback of the various stages as the process continues through the lifecycle of MDA. Upon successful processing of the input coordinate files by IA and GA, the Assembly module will update the CPM about the progress and the CPM will show the progress in four states. (Not Started, Started, Completed and Problem). The CPM will update the users over the Internet about the progress of the IoT based framework. Figure 37 and Figure 38 show the CPM progress report from start to finish.

Insertion Algorithm based Assembly Sequence	Genetic Algorithm based Assembly Sequence	Generation of Path Plan	VR based Assembly Analysis	Physical Assembly
Started	Started	Started	Not Started	Not Started

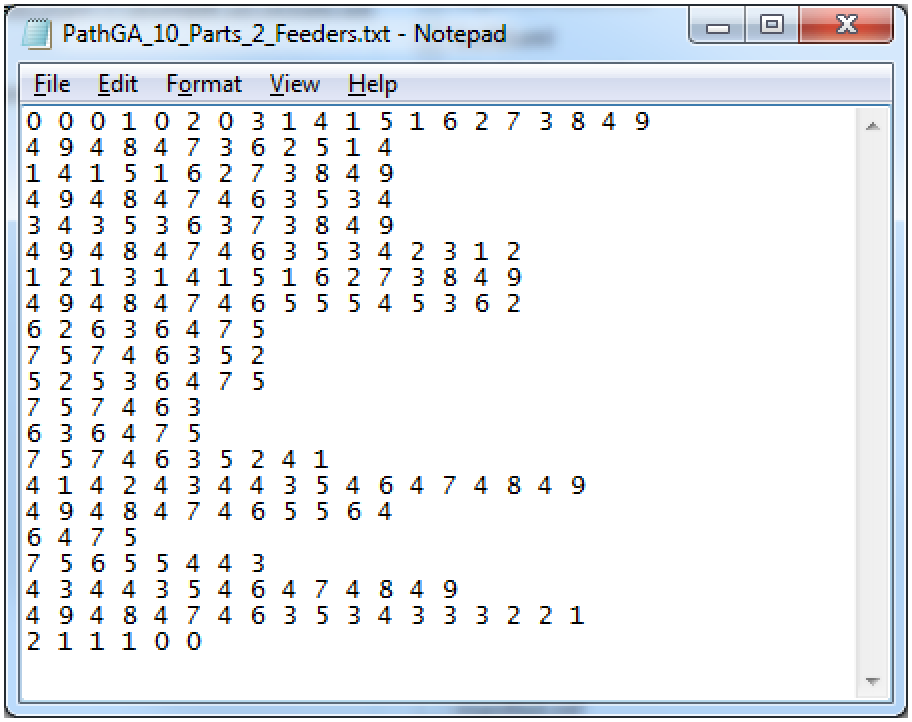
Figure 37: CPM Progress Report

Insertion Algorithm based Assembly Sequence	Genetic Algorithm based Assembly Sequence	Generation of Path Plan	VR based Assembly Analysis	Physical Assembly
Completed	Not Started	Completed	Completed	Completed

Figure 38: CPM Progress Report

4.4 Path Planning Module

Upon receiving output files from the Assembly module, the end users need a collision free path between each two points of the outputted files. To obtain a collision free path , the user is required to execute the A* path planner which will take the IA's output and/or GA's output and provide a collision free path between their points as described in chapter 3. Implementation of A* is taken from [114]. Figure 39 shows an output file for the collision free path processed with GA's output for the first example whereas Each line of the file represents a set of pairs of points. In the first line, the first pair is 0,0 and the last pairs is 4,9 which indicates movement from cell (0,0) to cell(4,9). The pairs of points in between represent the collision free path. Each line represent the path to pick a part or to deliver it to its designated location. Figure 40 shows the GA's output for the second example.

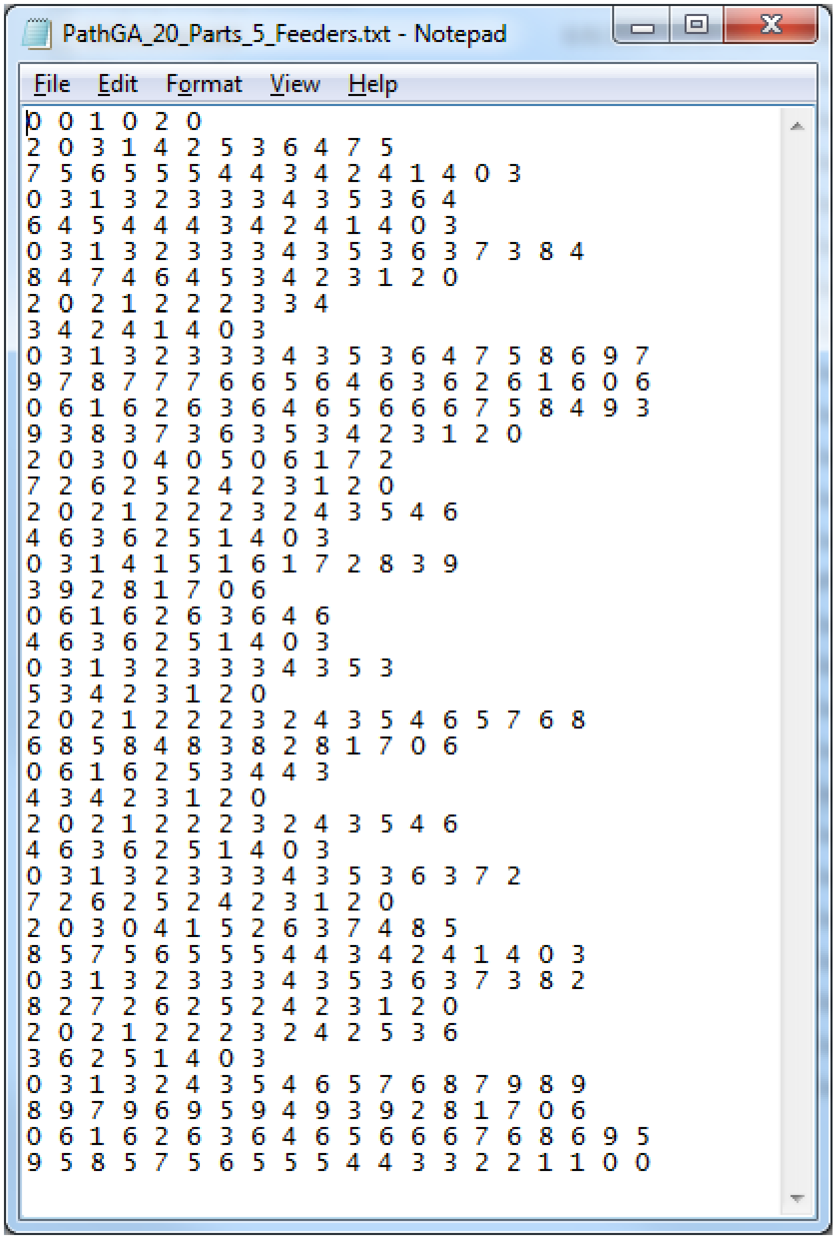


PathGA_10_Parts_2_Feeders.txt - Notepad

File Edit Format View Help

```
0 0 0 1 0 2 0 3 1 4 1 5 1 6 2 7 3 8 4 9
4 9 4 8 4 7 3 6 2 5 1 4
1 4 1 5 1 6 2 7 3 8 4 9
4 9 4 8 4 7 4 6 3 5 3 4
3 4 3 5 3 6 3 7 3 8 4 9
4 9 4 8 4 7 4 6 3 5 3 4 2 3 1 2
1 2 1 3 1 4 1 5 1 6 2 7 3 8 4 9
4 9 4 8 4 7 4 6 5 5 5 4 5 3 6 2
6 2 6 3 6 4 7 5
7 5 7 4 6 3 5 2
5 2 5 3 6 4 7 5
7 5 7 4 6 3
6 3 6 4 7 5
7 5 7 4 6 3 5 2 4 1
4 1 4 2 4 3 4 4 3 5 4 6 4 7 4 8 4 9
4 9 4 8 4 7 4 6 5 5 6 4
6 4 7 5
7 5 6 5 5 4 4 3
4 3 4 4 3 5 4 6 4 7 4 8 4 9
4 9 4 8 4 7 4 6 3 5 3 4 3 3 3 2 2 1
2 1 1 1 0 0
```

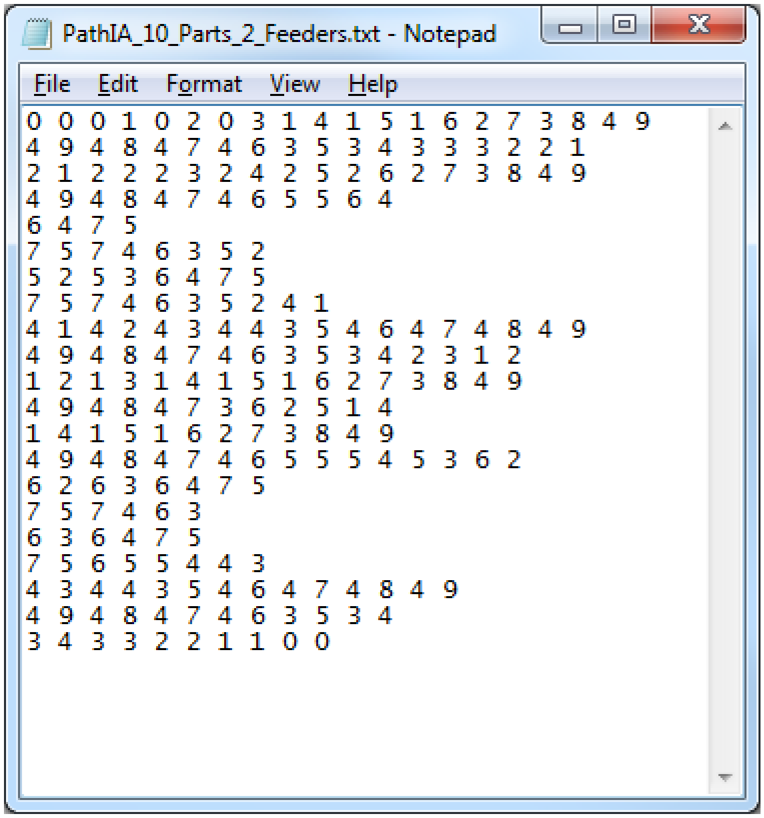
Figure 39: Path plans for GA’s first example with 10 parts and 2 feeders




```
0 0 1 0 2 0
2 0 3 1 4 2 5 3 6 4 7 5
7 5 6 5 5 5 4 4 3 4 2 4 1 4 0 3
0 3 1 3 2 3 3 3 4 3 5 3 6 4
6 4 5 4 4 4 3 4 2 4 1 4 0 3
0 3 1 3 2 3 3 3 4 3 5 3 6 3 7 3 8 4
8 4 7 4 6 4 5 3 4 2 3 1 2 0
2 0 2 1 2 2 2 3 3 4
3 4 2 4 1 4 0 3
0 3 1 3 2 3 3 3 4 3 5 3 6 4 7 5 8 6 9 7
9 7 8 7 7 7 6 6 5 6 4 6 3 6 2 6 1 6 0 6
0 6 1 6 2 6 3 6 4 6 5 6 6 6 7 5 8 4 9 3
9 3 8 3 7 3 6 3 5 3 4 2 3 1 2 0
2 0 3 0 4 0 5 0 6 1 7 2
7 2 6 2 5 2 4 2 3 1 2 0
2 0 2 1 2 2 2 3 2 4 3 5 4 6
4 6 3 6 2 5 1 4 0 3
0 3 1 4 1 5 1 6 1 7 2 8 3 9
3 9 2 8 1 7 0 6
0 6 1 6 2 6 3 6 4 6
4 6 3 6 2 5 1 4 0 3
0 3 1 3 2 3 3 3 4 3 5 3
5 3 4 2 3 1 2 0
2 0 2 1 2 2 2 3 2 4 3 5 4 6 5 7 6 8
6 8 5 8 4 8 3 8 2 8 1 7 0 6
0 6 1 6 2 5 3 4 4 3
4 3 4 2 3 1 2 0
2 0 2 1 2 2 2 3 2 4 3 5 4 6
4 6 3 6 2 5 1 4 0 3
0 3 1 3 2 3 3 3 4 3 5 3 6 3 7 2
7 2 6 2 5 2 4 2 3 1 2 0
2 0 3 0 4 1 5 2 6 3 7 4 8 5
8 5 7 5 6 5 5 5 4 4 3 4 2 4 1 4 0 3
0 3 1 3 2 3 3 3 4 3 5 3 6 3 7 3 8 2
8 2 7 2 6 2 5 2 4 2 3 1 2 0
2 0 2 1 2 2 2 3 2 4 2 5 3 6
3 6 2 5 1 4 0 3
0 3 1 3 2 4 3 5 4 6 5 7 6 8 7 9 8 9
8 9 7 9 6 9 5 9 4 9 3 9 2 8 1 7 0 6
0 6 1 6 2 6 3 6 4 6 5 6 6 6 7 6 8 6 9 5
9 5 8 5 7 5 6 5 5 5 4 4 3 3 2 2 1 1 0 0
```

Figure 40: Path plans for GA's first example with 20 parts and 5 feeders

Figure 41 shows an output file for the collision free path processed with IA's output for the first example, whereas Figure 42 shows the IA's output for the second example.

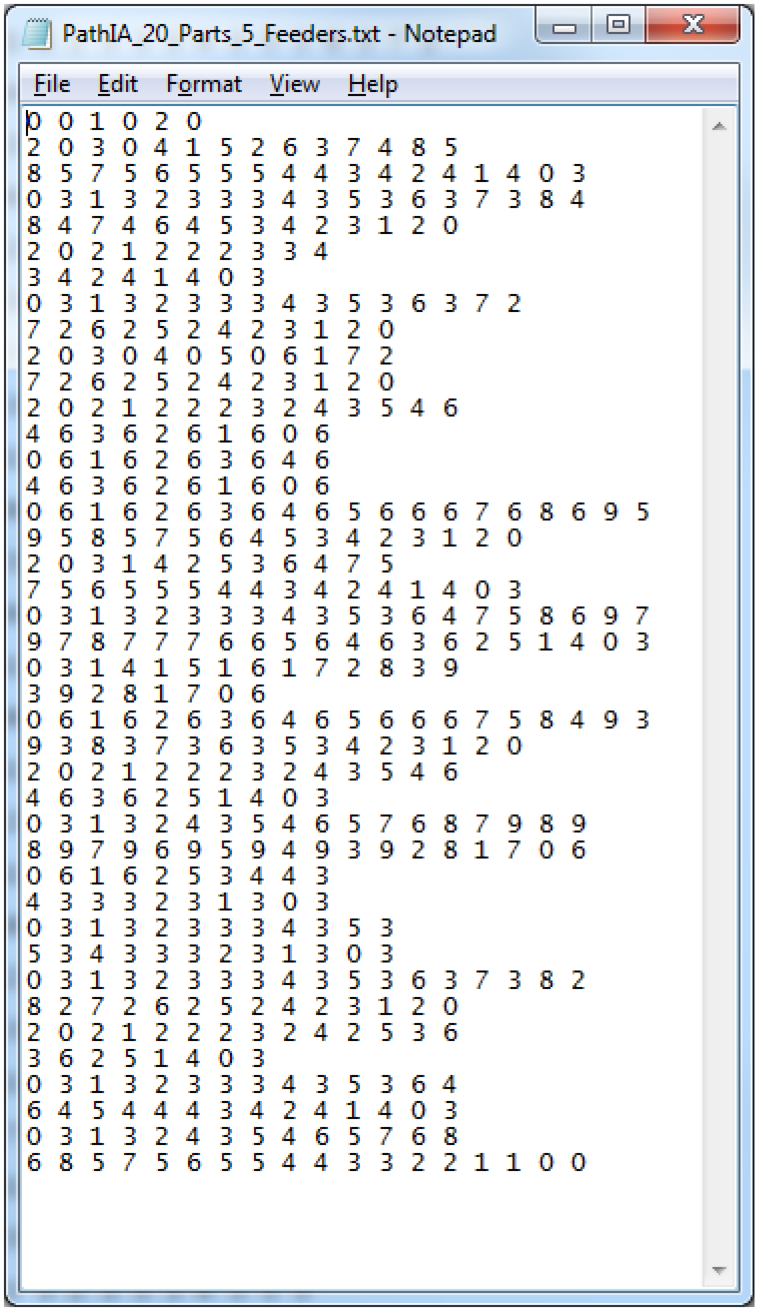


PathIA_10_Parts_2_Feeders.txt - Notepad

File Edit Format View Help

```
0 0 0 1 0 2 0 3 1 4 1 5 1 6 2 7 3 8 4 9
4 9 4 8 4 7 4 6 3 5 3 4 3 3 3 2 2 1
2 1 2 2 2 3 2 4 2 5 2 6 2 7 3 8 4 9
4 9 4 8 4 7 4 6 5 5 6 4
6 4 7 5
7 5 7 4 6 3 5 2
5 2 5 3 6 4 7 5
7 5 7 4 6 3 5 2 4 1
4 1 4 2 4 3 4 4 3 5 4 6 4 7 4 8 4 9
4 9 4 8 4 7 4 6 3 5 3 4 2 3 1 2
1 2 1 3 1 4 1 5 1 6 2 7 3 8 4 9
4 9 4 8 4 7 3 6 2 5 1 4
1 4 1 5 1 6 2 7 3 8 4 9
4 9 4 8 4 7 4 6 5 5 5 4 5 3 6 2
6 2 6 3 6 4 7 5
7 5 7 4 6 3
6 3 6 4 7 5
7 5 6 5 5 4 4 3
4 3 4 4 3 5 4 6 4 7 4 8 4 9
4 9 4 8 4 7 4 6 3 5 3 4
3 4 3 3 2 2 1 1 0 0
```

Figure 41: Path Plan for IA’s first example with 10 parts and 2 feeders


PathIA_20_Parts_5_Feeders.txt - Notepad

File Edit Format View Help

```
0 0 1 0 2 0
2 0 3 0 4 1 5 2 6 3 7 4 8 5
8 5 7 5 6 5 5 5 4 4 3 4 2 4 1 4 0 3
0 3 1 3 2 3 3 3 4 3 5 3 6 3 7 3 8 4
8 4 7 4 6 4 5 3 4 2 3 1 2 0
2 0 2 1 2 2 2 3 3 4
3 4 2 4 1 4 0 3
0 3 1 3 2 3 3 3 4 3 5 3 6 3 7 2
7 2 6 2 5 2 4 2 3 1 2 0
2 0 3 0 4 0 5 0 6 1 7 2
7 2 6 2 5 2 4 2 3 1 2 0
2 0 2 1 2 2 2 3 2 4 3 5 4 6
4 6 3 6 2 6 1 6 0 6
0 6 1 6 2 6 3 6 4 6
4 6 3 6 2 6 1 6 0 6
0 6 1 6 2 6 3 6 4 6 5 6 6 6 7 6 8 6 9 5
9 5 8 5 7 5 6 4 5 3 4 2 3 1 2 0
2 0 3 1 4 2 5 3 6 4 7 5
7 5 6 5 5 5 4 4 3 4 2 4 1 4 0 3
0 3 1 3 2 3 3 3 4 3 5 3 6 4 7 5 8 6 9 7
9 7 8 7 7 7 6 6 5 6 4 6 3 6 2 5 1 4 0 3
0 3 1 4 1 5 1 6 1 7 2 8 3 9
3 9 2 8 1 7 0 6
0 6 1 6 2 6 3 6 4 6 5 6 6 6 7 5 8 4 9 3
9 3 8 3 7 3 6 3 5 3 4 2 3 1 2 0
2 0 2 1 2 2 2 3 2 4 3 5 4 6
4 6 3 6 2 5 1 4 0 3
0 3 1 3 2 4 3 5 4 6 5 7 6 8 7 9 8 9
8 9 7 9 6 9 5 9 4 9 3 9 2 8 1 7 0 6
0 6 1 6 2 5 3 4 4 3
4 3 3 3 2 3 1 3 0 3
0 3 1 3 2 3 3 3 4 3 5 3
5 3 4 3 3 3 2 3 1 3 0 3
0 3 1 3 2 3 3 3 4 3 5 3 6 3 7 3 8 2
8 2 7 2 6 2 5 2 4 2 3 1 2 0
2 0 2 1 2 2 2 3 2 4 2 5 3 6
3 6 2 5 1 4 0 3
0 3 1 3 2 3 3 3 4 3 5 3 6 4
6 4 5 4 4 4 3 4 2 4 1 4 0 3
0 3 1 3 2 4 3 5 4 6 5 7 6 8
6 8 5 7 5 6 5 5 4 4 3 3 2 2 1 1 0 0
```

Figure 42: Path Plan for IA's second example with 20 parts and 5 feeders

4.5 Simulations for Assembly Plans

The VR Simulation takes candidate assembly path as an input for determining its feasibility of the assembly and to generate the corresponding physical commands required by the physical work cell. The VR simulation is mimicking the physical work cell which has several micro positioners that control the work cell. Using the sliders in the VR environment, the users can follow the path generated by the A* to pick the objects and place them in their designated destinations. Figure 43 shows the screenshot of the start of VR simulation, the path to the feeder 1 to pick a part and the feeders are marked with the rectangles. Figure 44 shows the gripper moving toward the destination following the path traced by path planning module. Two parts are placed in their designated locations. Figure 45 shows students interacting with the semi-immersive VR running on the PowerWall™.

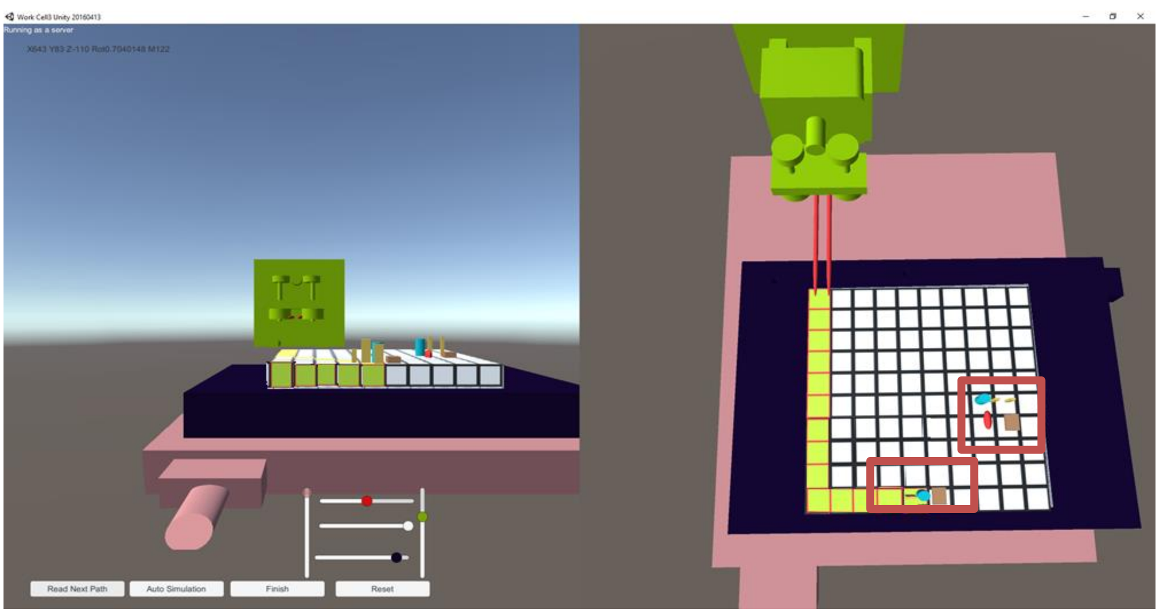


Figure 43: Screenshot of the VR with a path drawn by the Assembly planning module

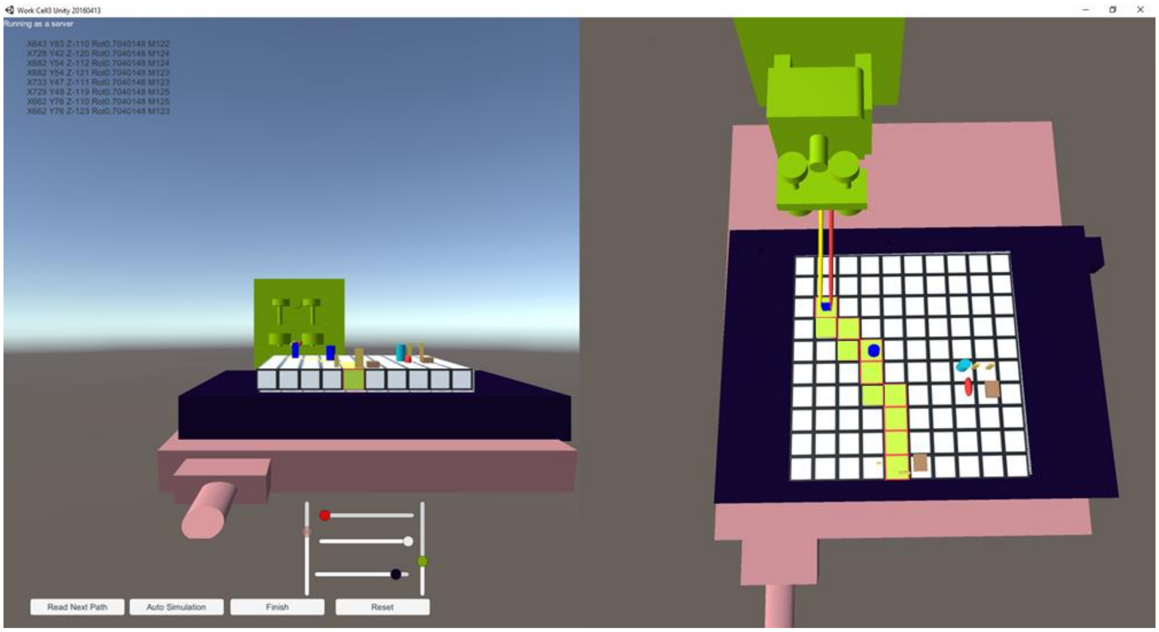


Figure 44: 2 parts assembled using the VR and commands are generated

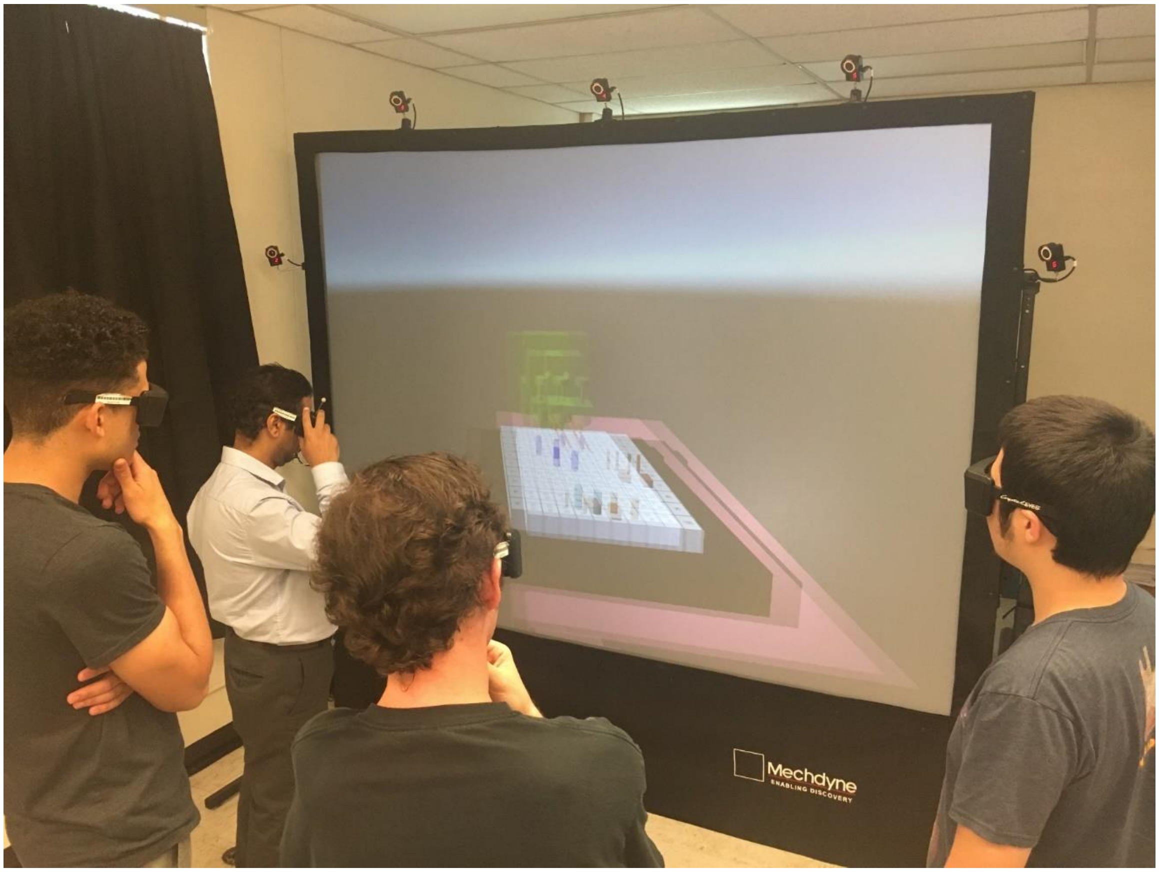


Figure 45: Interacting with the semi-immersive VR

4.6 Command Generation Module

The command generation module converts the VR simulation details into physical work cell syntax commands that can be communicated to the physical work cell to carry out the analyzed VR assembly plans.

A set of Sliders in the VR environment replicate micro positioners' controls in the physical work cell. The sliders are used to extract the exact mechanical movements needed for the physical work cell to perform a set of operations such as pick and place, move in X axis, and rotate the assembly plate. The Sliders benefit in reducing time needed for assembly and help in avoiding near collision cases or van der walls forces. Figure 46 shows the Sliders that control the VR environments. Five sliders are utilized to control the VR environment and extract the exact movements. Colors are used to indicate the part that they control. The sliders are:

1. Forward /Backward Slider (Magenta color): moves the micro positioner in the X axis.
2. Left/Right Slider (Gray Color): moves the micro positioner in the Y axis.
3. Up/Down Slider (Green Color): moves the gripper in the Z axis.
4. Rotational Slider(White Color) : rotates the assembly plate Clockwise(moving the slider to left hand side) , counter clockwise(moving the slider to right hand side)
5. Open/Close Slider (Red color): grip micro parts /release them. Grip (moving the slider the left hand side), Release (moving the slider to right hand side).

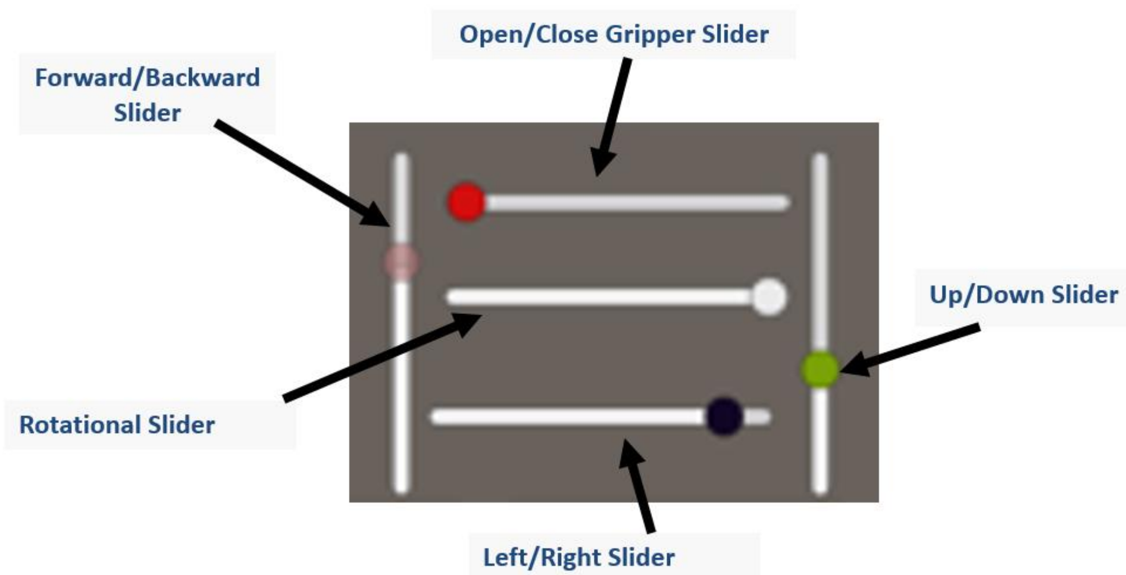


Figure 46 : Sliders to control the VR environment

After analyzing the assembly plan virtually, the Command Generation Module converts the virtually analyzed assembly plan into physical commands. Figure 47 shows a portion of the generated physical commands output file for the parts assembled in Figure 50 and Figure 51. The

Command generation module follows the syntax documented in the physical work cell manual in converting these commands.

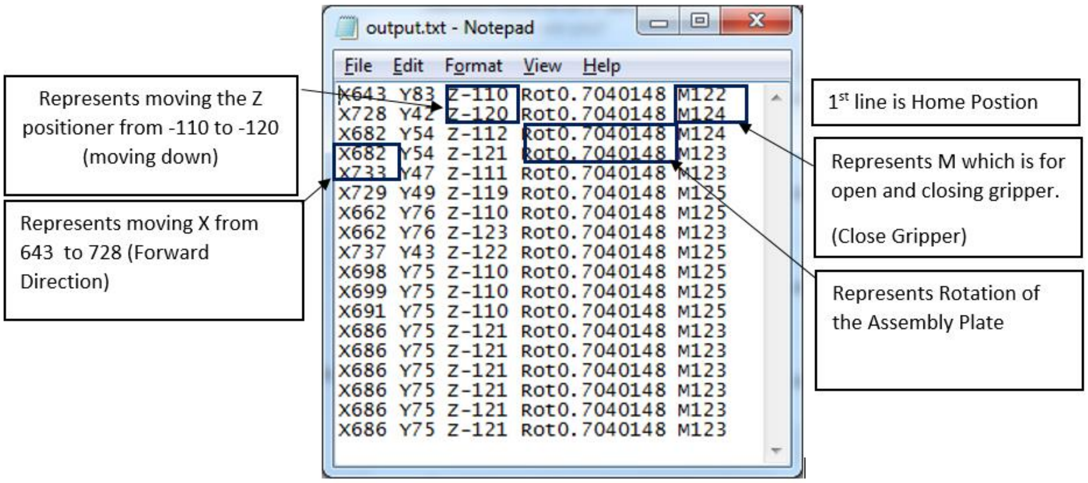


Figure 47: Command generated file

4.7 GENI based framework to support distributed interactions.

As part of this research, the feasibility of GENI based networks in supporting interaction and collaboration involving distributed VR based assembly analysis activities was studied.The performance of the GENI based network in supporting this IoT based framework was studied for multiple scenarios involving distributed locations, Tulsa, Oklahoma, Washington D.C., Stillwater, Oklahoma and Madison, Wisconsin. Performance Measurements of traffic was performed using GENI Desktop which is shown in Figure 48. The network latency between these multiple locations was measured using ICMP ping (Figure 49). As can be seen from Figure 49, the latency is stable at around 46 milliseconds. These experiments indicate the feasibility of the overall GENI based network to support distributed interactions using the IoT framework discussed in this dissertation.

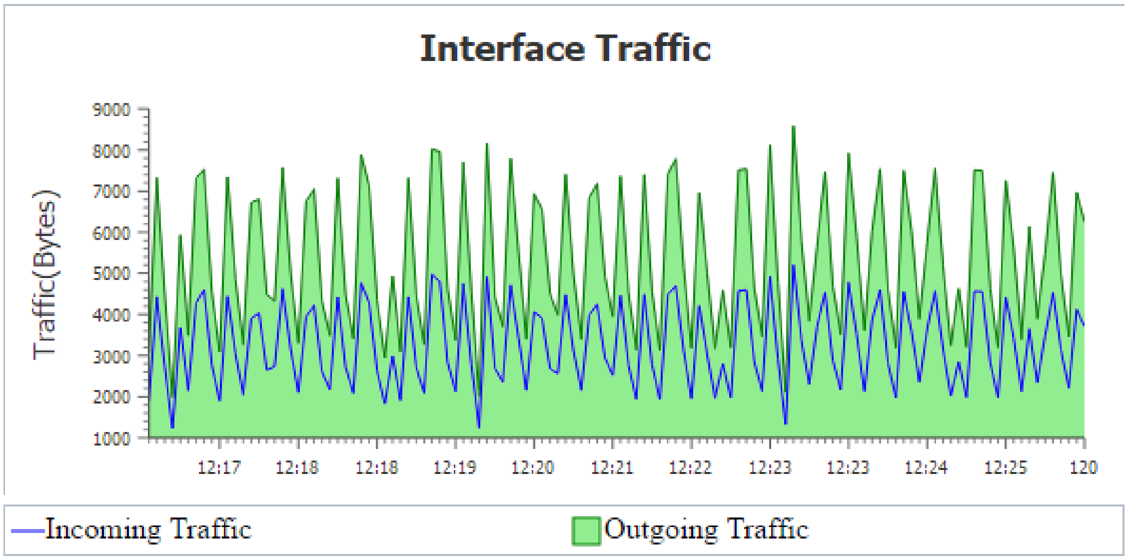


Figure 48: Data Traffic during the IoT interactions

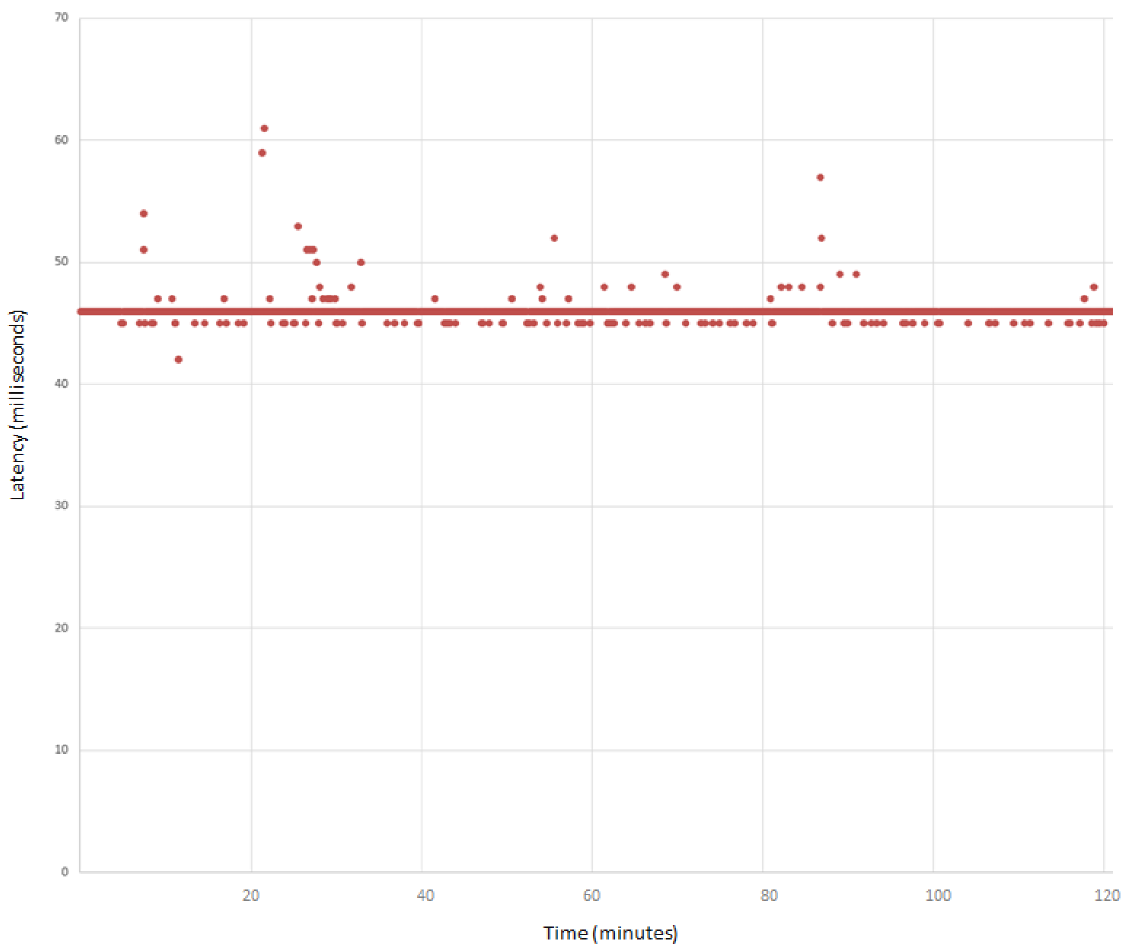


Figure 49: Latency during the IoT interactions (2 hour period)

4.8 Examples

A variety of micro-meso scale parts using the IoT based framework are assembled. The assembly tasks involved manipulation of meso/micro part designs where some of the target parts may be in the meso scale while others are in the micro scale range. Meso scale is defined as including part sizes greater than 1 mm, with accuracies greater than 25 μm. Figure 50 and Figure 51 show assembling 8 parts of first example of (10 parts and 2 feeders) which involve assembling and placing a number of millimeter sized gears and pins. A closeup of the assembly scene is shown where the gripper is placing a target gear in its location.

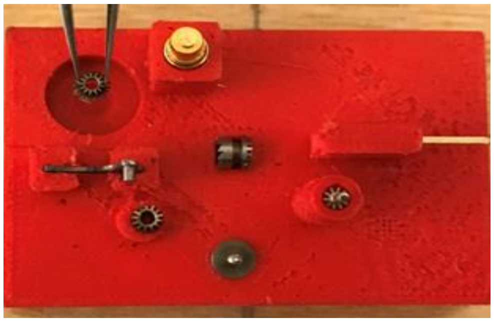


Figure 50: Gripper picking up a millimeter sized gear.

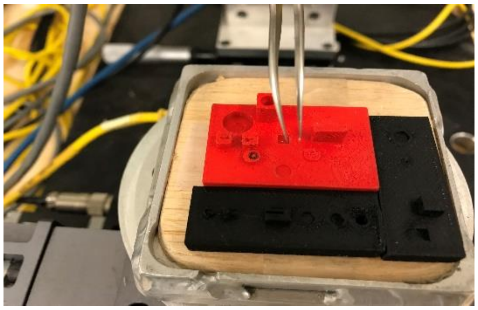


Figure 51: Assembly of micro and meso parts.

Upon completion of the physical assembly , an engineer manually reports back to the CPM the status of the assembly. Figure 52 shows the manual interface used for reporting the status of the physical assembly.

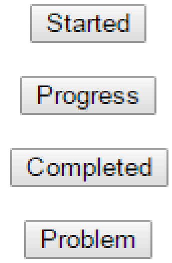


Figure 52: Engineer reports manually to the CPM the progress of the Physical assembly.

4.9 Summary

Two examples of MDA are carried out, steps of the lifecycle of the IoT based framework are detailed and shown the results. First example is for an MDA with 10 parts and 2 feeders. The second example is for an MDA with 20 parts and 5 feeders. Results of the two examples are highlighted to show the feasibility of the IoT based framework to support engineering activities and prove the concept of distributed geographical resources where partners can come together to achieve the lifecycle of MDA.

CHAPTER V

CONCLUSION

5. Introduction

This research outlined a framework for supporting cyber physical interactions for the field of MDA; the approach emphasizes on interactions between cyber technologies and physical resources. Algorithm based planning techniques were used to accomplish assembly sequence generation and path planning. Using a collaborative framework, distributed users were able to communicate and develop an assembly plan; subsequently, the outcomes of this assembly plan was used to generate physical assembly commands which can be used to assemble physical parts. In this chapter, we provide a summary of each chapter in this dissertation document. In addition, an overview of future research directions is provided. A conclusion to this dissertation is provided as well.

5.2 Summary of Dissertation Chapters

5.2.1 Summary of Chapter 1

In this chapter, the background of the research was described which includes definitions and benefits of MDA, CPS, IoT and the use of VR for MDA. Integrating a framework with innovative capabilities using GENI was outlined. A problem statement related to assembly of MDA was identified and set of objectives to address the identified problems were highlighted.

5.2.2 Summary of Chapter 2

This chapter provided an in-depth literature review of MDA along with cross domain technologies which included CPS, IoT and VR environment. A table has been provided discussing MDA literature which have utilized VR. Moreover, a review of literature focusing on CPS and IoT approaches have been outlined. The literature review for Next Generation Internet technologies is also provided in this chapter. Industry 4.0 initiative to support distributed and collaborative manufacturing was discussed. After the completion of the literature review, several research voids were identified.

5.2.3 Summary of Chapter 3

In this chapter, an overview of the overall framework and approach was provided. Components of the framework were detailed. Descriptions of sequencing algorithms such as GA and IA were described. A collision free Path planning approach based on the A* algorithm was described. Description of the VR environment was highlighted and the importance of utilizing semi-immersive VR was identified. A cloud based approach that hosts the cyber components of the cloud was outlined and the use of GENI was explored. A brief description of the CPM that tracks various interactions was defined.

5.2.4 Summary of Chapter 4

Chapter 4 discussed results and outcomes of the various cyber and physical components described in chapter 3. Examples of part data input format as well as outputs from the two assembly sequence planning approaches (including the IA and the GA based approaches) were discussed; further, the generation of the path plan along with the corresponding physical command generation steps were also illustrated. Outputs from using GENI networks to support distributed interaction when using the VR based assembly analysis environment was also discussed in terms of data throughput and latency.

5.3 Significance of Research Contributions

An IoT based Cyber Physical based approach has been successfully developed. The IoT based approach supported collaborations among geographically distributed Cyber and Physical resources. The life cycle of MDA was accomplished through the IoT based Cyber Physical approach. The IoT approach will impact manufacturing fields as it helps forming VEs with a collaborative platform that can sprout out new innovations using the IoT approach.

The use of alternative assembly plan generation methods was investigated by utilizing two assembly plan generation algorithms, GA and IA. The two algorithms were used to show that multiple partners may have different feasible alternatives. This was an important goal that prove that the IoT based approach can support feasible alternatives suggested by different partners in a VE context. Moreover, this demonstrated that manufacturing fields can utilize such approach for different alternatives that suit their need.

A VR environment was developed to support the feasibility analysis of assembly plan methods. This was an important goal to determine that an assembly plan generated by the partners in a VE was feasible using VR environment. Through the VR environment, collisions during the assembly of micro sized part can be identified and therefore a modification of the generated assembly plan becomes necessary. VR environment is capable of providing more insights that help in the feasibility analysis of the assembly plan methods and thus leading to a successful assembly. This will benefit manufacturing domains as it reduces time and cost of production of feasible designs.

A process to generate physical MDA commands was developed to reduce the time needed for best utilization of VR environments. The assembly details of VR environments are generated in the syntax used by the physical resources which helps manufacturing fields apply VR environments details to the physical resources.

The potential of GENI networking to support collaboration was explored. Based on this research, it can be concluded that GENI networking infrastructure has the potential to support distributed manufacturing activities which will benefit from its ability to support higher bandwidth and low latency that require better networking capabilities. Manufacturing domains will benefit of using GENI infrastructure as it supports higher bandwidth and low latency. In the manufacturing fields, geographically distributed clients will be linked using next generation networking infrastructure which will make exchanging of large data possible and communication of information between physical and cyber modules is faster.

The feasibility the IoT based cyber physical approach to support the life cycle of MDA was demonstrated. The life cycle of MDA includes: Assembly Planning, Path Planning, VR analysis, Command Generation and Physical assembly. The life cycle of MDA which involves various cyber physical activities proves that manufacturing fields can adopt such a CPS approach involving IoT principles.

5.4 Future Research and Extensions of Current Research

Several directions of future research based on the completed dissertation research activities are outlined below:

5.4. 1. Studying Collaborative Interactions involving Fully Immersive PowerWall ™ environments as well as between other environments:

One of the future research activities includes exploring collaboration between fully immersive VR environments between distributed users for performing assembly analysis and other tasks within the life-cycle of MDA activities. Interactions of two or more users using immersive environments (such as VR PowerWall ™) from different geographical locations needs to be studied with the help of GENI based networks as well as cloud based platforms.

With the emergence of low cost VR technology such as the HTC Vive [124] (Figure 3) and Microsoft's Hololens [123] (Figure 4) , study of their capabilities to support such CPS based collaborations especially involving collaborative VR based simulation is also another area of future research. Hololens ™ [124] is a mixed reality headset capable of providing interactions between real world and virtual world which can serve is an alternative for the PowerWall™ as well.

5.4. 2. Investigation of other IoT based CPS approaches and frameworks for other fields of manufacturing:

Design of such CPS and IoT based approaches and framework for other manufacturing domains such as manufacturing in the field automobile assembly, assembly of Printed Circuit Boards, and other domains can also be studied. Manufacturing domains will greatly benefit from such CPS and IoT based frameworks as it provides a way for engineers, managers and software tools to effectively interact using smart networks and a combination of cyber physical tools to respond to changing conditions in the work place, predict problems ahead of time as well help data and information exchange in real time for VE oriented partnerships where there is a variety of computing platforms and an assortment of cyber and physical resources which are geographically distributed.

5.4. 3. Information modeling methods to design the collaborative CPS activities

One of the important areas related to this dissertation research is on investigating methods involving information modeling which can be used to design the collaborative activities within a proposed CPS approach and framework linking distributed cyber and physical resources. Information modeling can be used to first study, propose and understand the data and information based interactions among a complex network of cyber and physical components. This has been explored in field such as collaborative training of medical residents using software tools; such approaches hold the potential to provide a strong foundation for designing CPS based approaches in manufacturing

5.4. 4. Creation of 'apps' and app based smart frameworks for IoT based interactions

In this dissertation research, the software modules resided on computers; future research can study the design of smart 'apps' which can be run on smart phones and thin clients such as tablets. Such app based interactions hold the potential to increase the level of user friendliness, conveniences and accessibility along with providing an effective way to respond to changing customer requirements in an agile manner.

5.4.5 Studying the feasibility of GENI to support haptic based interactions for manufacturing and other process level collaborations

In this research, the focus was on studying the feasibility of GENI networking technologies on supporting collaborative interactions involving VR based assembly analysis between distributed users in different locations. Future research can extend these GENI related studies to propose, compare and study the network traffic and bandwidth involving multiple collaborations which involve users interacting with collaborative haptic interface simulation environments; such haptic interfaces will allow modification of manufacturing process layouts (and assessing /comparing different layouts through VR based simulation), training activities to operate manufacturing work cells and machines, controlling machines and physical tools through such interfaces, among others. Some initial work relating to using haptic interfaces through GENI based networking technologies has been reported in the field of medical surgical training and can be extended to manufacturing and other process oriented domains. Figure 53 shows haptic devices.

Figure 53: Geomagic Touch Haptic device

5.5 Summary

In this chapter, the focus was on providing a summary of each chapter along with a discussion of future research. Identifying future research areas is critical in expanding the scope highlighted in this dissertation. Future research included wide varieties of open research areas that need to be fulfilled. In this dissertation, An IoT based Cyber Physical framework has been implemented and detailed. Various technologies have been utilized in making the innovative system which included IoT, CPS, and GENI. Various algorithms have been harnessed to generate assembly plans for MDA which included GA, IA and A*.

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