DESIGN OF A CYBER PHYSICAL FRAMEWORK FOR THE ASSEMBLY OF MICRO DEVICES

By

RAVITEJA GUNDA

Bachelor of Technology in Computer Science and

Information Technology

Jawaharlal Nehru Technological University

Hyderabad, AP, India

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Thesis Approved:

Dr. J. Cecil

Thesis Adviser

Dr. Subhash Kak

Dr. Johnson P Thomas

Dr. Sheryl A. Tucker

Dean of the Graduate College

PREFACE

The main objective of this study was to develop a Cyber Physical Framework to support a collaborative approach using software and physical resources for the rapid assembly of micro devices in a distributed environment.

I wish to dedicate this thesis to my parents, Mr. Gunda Venkanna and Mr. Gunda Seetha Maha Laxmi for their love, encouragement, and support towards me especially during my MS program at OSU.

I wish to express my sincere appreciation to my thesis adviser, Dr. J Cecil, for his guidance and support throughout this thesis research. I would also like to express my appreciation to my committee members, Dr. Subhash Kak and Dr. Johnson P Thomas, for their interest and guidance during this period.

I want to specially thank Dr. A. Prasad Calyam (Ohio State University) for his guidance in helping with the cloud computing part of this research. I also want to thank Arun Selvadurai (graduate student at Ohio State University) for helping me to complete the various GENI related demonstrations.

I also wish to thank the Computer Science Department to help me fulfill my educational and research goals.

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INTRODUCTION

1.1 Overview of Micro Devices Assembly

Micro Devices Assembly (MDA) can be defined as the assembly of micron-sized parts. Microelectromechanical Systems (MEMS) is a popular technology used to manufacture the micron-sized parts with reduced human involvement and cost. The size of the micro devices varies from 1 micron to several millimeters. MEMS technology cannot manufacture certain micro designs which have complex shapes and varying material properties. In such situations, these micro designs have to be manufactured individually and then assembled. MDA refers to the assembly of the micron sized parts using manual, semi automated or automated techniques. MDA refers to assembly of micron-sized parts of size 1 µm to less than 1 mm. At this scale, adhesive forces come into picture and play a dominant role.

1.2 Problem Statement

Micro Devices Assembly is an emerging domain with a significant economic potential. This technology has the potential to be used to develop biomedical devices, sophisticated miniaturized electronic sensors and surveillance devices. Existing methods for assembly of micro devices are tedious and costly. Computer controlled techniques need to be developed for micro assembly. In the domain of MDA no single organization has the distributed resources to respond to changing user requests. For this reason, it is important to develop collaborative framework for the field of MDA. There is a need to develop Information Centric frameworks to support rapid assembly of micro devices using cyber physical resources.

1.3. Research Objective

The overall goal is to demonstrate innovative Information Centric frameworks to support rapid assembly of micro devices. In order to achieve this goal the following objectives are identified:

1. Develop a cyber physical approach which involves collaborative use of software and physical resources at two university sites.
2. Facilitate innovative use of Virtual Environments for planning and analysis of micro assembly activities.
3. Demonstrate the feasibility of cloud computing techniques to support the cyber physical approach developed.

One of the long-term goals at the Center for Information Centric Engineering (CICE) at Oklahoma State University (OSU) is to develop an Information Centric framework for Micro Assembly. A Virtual environment is created for the physical micro assembly work cell where the user can test their assembly plans, which can then be assembled using physical work cells.

1.4 Organization of Thesis

In Chapter 2, the detailed review of different papers is presented. In Chapter 3, the design of the Information Centric framework is addressed. In Chapter 4, feasibility of cloud computing techniques are discussed. In Chapter 5, implementation and simulation results of the proposed approach is outlined. In Chapter 6, conclusion of the work and the scope of the proposed approach for future research are outlined.

CHAPTER II

REVIEW OF RELEVANT LITERATURE

2.1 Introduction

A detailed review of relevant literature is broadly classified into four sections:

- Micro Gripper designs
- VR based Simulations for MDA
- Force Related Modeling
- Design of Automated work cells and related topics

2.2.1 Micro Gripper Designs

In [1], creation of autonomous robotic systems capable of pick and place of micro objects is discussed. This robotic system provides high accuracy, reliability, and speed (6 s/sphere). Three-Pronged micro gripper is used to overcome the adhesive forces when releasing the micro sphere. Three-pronged micro gripper comprises of left and right gripping arms to hold the micro sphere and a center arm called plunger. Plunger collide the micro sphere that sticks to the gripper arm with a speed that overcomes the adhesive forces. Electrostatic micro actuators are used to open and close the gripper arms.

Increase in the actuation voltage increases the speed of plunger movement. The accuracy of the micro sphere placing on the substrate depends on the height of the release (best results for height < 2 µm). Microsphere contact with the substrate is detected by vision based contact-detection algorithm. 3D assembly of microspheres is used to minimize the collisions.

In [2], Scott et al. outlined the development of a collaborative framework using Virtual Reality technology and information modeling approaches for assembly of micro devices. The information model used in this approach is enterprise Engineering Modeling Language (eEML). A virtual reality based advanced work cell was built with Coin 3D and ProE models. Using eEML, users can provide assembly plans to the virtual work cell or it can be generated automatically. The Virtual environment allows users to study and simulate assembly alternatives in Virtual Reality.

In [3], assembly of micro components to a single substrate is outlined. Electric connections are applied for the assembled components by incorporating electroplating to the microns. A two-batch assembly of square parts with electrical connections is proposed in this approach. Capillary force drives the assembly and hydrophobic sites on the substrates are used for the connections. A simulation tool is used to design the binding site that helps to identify the collisions in the assembly of micro components.

In [4] the author discuss about MEMS gripper and an ultrasonic manipulator. The gripper movement is accomplished with the help of electrostatic actuator. Real-time force feedback is provided during manipulation. The dice-free methodology is used to avoid damages of the fragile structures. Ultrasonic device is used to align the spheres in the water and micro gripper picks sphere on at a time and places it on the side by glass plate. Ultrasonic is also used to release the microns that stick to the gripper arms. Manipulation of HeLa cells is more difficult compared to the gripper of glass spheres.

In [5], Kanty et al. outlined a 3D micro-assembly station for reconfigurable free space micro-optical benches (RFS-MOB) of MOEMS type assembly. Micro assembly sequences, general assembly sequence and detailed assembly sequence are the test inputs to the system. AP2M (based on Borland C++) is the software used to control the micro-assembly station.

In [6], assembly for 3 legged spatial platforms is performed by vision guided multi-probe assembly process. Tele-operated contact management and vision feedback without force sensors are implemented to accomplish the assembly. The work cell setup is of two 3DOF probes, one stationary probe and the die (micro object) is placed in between the two movable probes. Two steps of assembly process in the approach are: (1) 3 legs placement on the substrate vertically, (2) 1 top platform placed on the 3 legs. This approach is very time consuming as it takes 3 hours to complete the assembly process. Sometimes the part rotates if both the gripping arms are not in the same horizontal axis. Vision feedback is obtained by using two cameras, one mounted on the top of the probes to provide top view and other one place at an angle to give side view.

In [7], Mayyas et al. outlined a active joining mechanism which is a System on Chip (SoC) type of actuator for micro structures. SoC allows insertion of micro part with zero force that provides security for the micro object and socket (gripper arms). This approach improves the performance of assembly due to frictionless grasp and release of micro object. Single sided and double sided electro thermal bent beam actuators are used for opening and closing of the socket. End effectors produce high mechanical forces on micro parts to enforce insertion. This micro assembly work cell has 19 DOF manipulation to assemble micro objects using active locking mechanism. In this design damaged micro objects can be replaced. Conductive solder alloy is used to improve the mechanical and electrical joining.

2.2.2 VR based Simulations for MDA

In [8], Cecil et al. a review of Virtual Prototyping techniques in various engineering domains, including design and manufacturing is provided. Virtual Prototyping (VP) is defined as the creation and using of 3D Virtual Reality based models that mimic the real physical world. The VPs possess appearance characteristics, simulation characteristics, representation characteristics, and interface criteria that differ from other models. Exhaustive literature review on Virtual Prototyping was discussed in three categories. (1) Virtual Manufacturing, (2) Virtual Product Design, and (3) Related technologies.

In [9], Joseph et al. outlined a teleoperated micro assembly work cell that integrates VRML-based virtual reality with visual servoing micro manipulation strategies. With the help of closed loop precision they were able to show that visual servoing techniques with high resolution optical systems performs required submicron precision. VRML (Virtual Reality Modeling Language) was used to create the virtual reality micro world. The interface between VRML based virtual micro world and physical micro world was created using Java. A supervisor can operate the virtual world from a remote location. The changes in this virtual environment are transmitted to the real micro world with the help of VRML. Physical world micro manipulations are executed from the output generated by VRML. A modified perceptual cycle of Neisser's for visually servoed manipulators is used in [9]. Despite Internet delays, successful demonstration of teleoperation on micro assembly with submicron precision is discussed. Teleoperation and visual servoing strategies are the key aspects of this paper.

In [10], Zhong et al. discussed modeling of solid objects in virtual environment with constraint based manipulations. This environment allows engineers to create precise solid models in the virtual environments by incorporating constraints. A hierarchal constraint based manipulations for solid modeling is used to object definition, object creation, and object rendering. It includes the following constraints: (1) Representation of allowable motions, (2) Constraint solving for deriving allowable motions, and (3) Rule-based constraint recognition. Creation of parts, its feature primitives and assembly creation of the parts were implemented and an experiment results were discussed in this paper.

In [11], Interactive virtual assembling in augmented reality is discussed. Augmented reality is achieved by using a head mounted display and hand gloves with sensors. Head mounted display collects the images from the real world and user can view the images in the virtual world and interact with the real world with the help of hand gloves. Problems involved using hand gloves equipped with sensors are discussed: correlating the real hand to virtual hand, interpretation of the user's intent and the constraints for grasping and moving objects. Virtual assembly of a cylindrical component into a hole is presented. User's intent can be captured by geometrical reference frames (OAFs) attached to the body. Many cyber-physical improvements are possible in the micro assembly world with the help of augment reality.

In [12,13], a virtual environment for micro assembly was built to interface with a physical Micro Assembly Work Cell (MAWC) (Fig 1). The Physical micro assembly work cell comprises of micro-gripper, micro-positioners, and a camera. Virtual environment of this physical MAWC was created to provide the user to interact with the work cell and generate assembly plans. A genetic algorithm was proposed for the assembly plans which work in coordination with a 3D path planning approach [12]. In [13], the 3 long term goals were outlined: (1) creation of a virtual environment using VR technology, (2) development of physical environments to assemble micron objects and (3) development of information oriented enterprise models to propel various activities. The architecture of the integrated VR work cell was outlined in this paper. The Physical work cell designed of three categories of components: motion related components, part handling resources, and visual sensing resources.

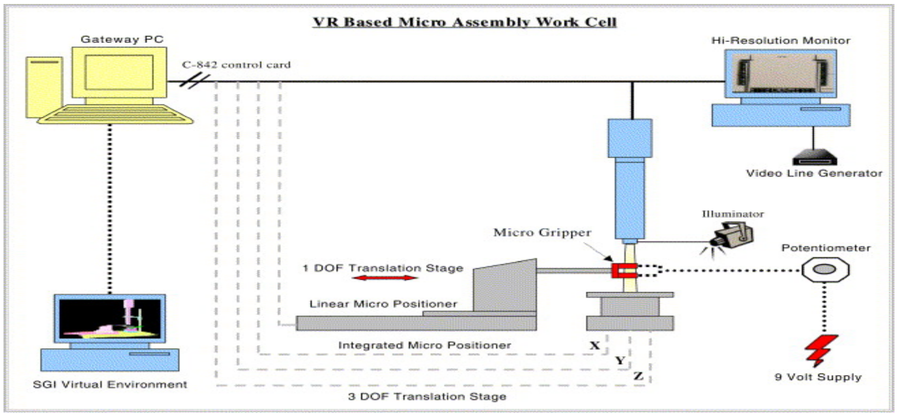

Figure.1 Integrated VR work cell [12]

In [14], a VR based framework for micromanipulation robot is proposed. Currently vision feedback obtained from physical world in 2D has vision fatigue and high precision, small working place leads to the failure of entire system. The importance of implementing VR integration with vision feedback and force feedback in this approach is outlined. User has the option to interact with the VR in offline/online mode using a software switch. WorldToolKit (WTK) was the tool used to build the 3D simulations in VR and ProE was used to build the CAD models. Visual feedback and VR helps to enhance the success rate and reduce the failure of the system.

In assembly of micro devices, sophisticated machines with high precision and manipulations are not sufficient because of lack of skilled persons to run these machines. In the original setup proposed by authors, the micro assembly work cell had 3 cameras but was not able to capture the distances in certain conditions. The authors describe the addition of a VR interface to this system. Virtual reality provides the user a graphical user interface (GUI) to interact with micro assembly in an easy way. Users can view the micro assembly from all directions and can assess the distances. This system was used for collision detection and model based computer vision algorithms. The models used in VR were built using OPENSG [15]. The major challenge of this approach was synchronization of virtual environment with the real world.

In [16], the use of VR in the engineering education sector is highlighted; it brings a new way of learning for the students. Using VR enables the students to get a feel of working in a real time industrial environment. Students can apply and validate their theoretical ideas in the virtual environment. This type of interactive education environment setup is being used at the University of Warwick. Autodesk and Aurora showcase plug-in are used to build for the 3D simulations. This approach helps to perform the verification of product at the concept stage before starting the production in real time.

Bimetallic thermally actuated micro pump design is outlined in [17]. Top-down and bottom-up hybrid design is proposed in this approach. Intellectual Property (IP) library supports the hybrid design and its main advantage is we can reuse the resource and information stored in IP library. In addition, Virtual fabrication based on Voxel-based visualization technique is used that produces better simulation of the real world system. Finally, virtual operation for micro fluidic device exhibits realistic 3D dynamic animation. Finite element method is used to construct accurate models for MEMS.

Bio-Microrobotics can be defined as the application of micro robotics in the field of biomedical systems [18]. Pillcam is bio-microrobotic when swallowed travels through the body to capture the images. The difficulties in assessing the distances can be overcome by creating virtual environments where the user can view the assembly operations from any point. This also avoids the damages of microns in the real world because the collisions are detected in the VR before bringing the assembly operations in the real world. COLLDET is the library used to avoid the collisions.

2.2.3 Force Related Modeling

Adhesive forces come into play during the release of the micron size objects with gripper. It dominates the gravitational force and the micron objects tend to stick to the gripper. Adhesive forces have three components: (1) Vander Waal forces, (2) Surface tension, and (3) Electrostatic forces [19].

In [20], Cassier et al. proposed a combination of computed control with limited human interaction to assembly micro devices. Visual servoing techniques are used for efficient and reliable force feedback during micro assembly tasks. This approach would be cost effective but predictions of forces create errors in the locations, which leads to the damage of the components and failure of assembly. Multiple view microscopes allow the computer to locate and track various components and parts of the assembling robot. Improving the vision system and virtual environment of micro assembly is the major goal of this approach. The VR system can be used to modify the inputs generated by the user to provide collision free paths and users have the option to combine feasible path planning solution into the virtual environment.

In [21], an analytical model for guiding tasks in Micro assembly is discussed. Two fingers for gripping micro parts - stability is tested, strategies during guiding are discussed. When moving the micro object contact side detection and contact force are detailed in this paper. In this approach after the micro gripper grasps the micro object the substrate moves down instead of gripper moving up as in other approaches. Then, the movement to the destination point is performed and substrate moves upward direction towards the gripper arm. Hybrid Force/position control of the object is established to control the guiding task in automated mode. The deviation of the micro object on collision or contact with the substrate is corrected by the Contact Force (F_y) control. Incremental control approach is implemented here to make sure the grasp force doesn’t get degraded.

In [22], Tan et al. proposed a Virtual reality based framework for micro manipulation robot. Successful experiments on peg-in-hole micro assembly that handles collision detection. User sends input to the virtual environment using 6 DOF spacemouse. Simultaneously these inputs are sent to the physical micro assembly system and force feedback information is sent back to proportional-integral-derivative (PID) controller using vision sensor and force sensor feedback. FDH (Fixed Direction Hulls) is a special convex hull, based on that bounding box algorithm is used to detect the collisions in virtual environment.

In [23], the creation of general framework for micromanipulation robot based on Virtual environment is discussed. Micromanipulation robot has 6DOF that is made of micro and macro motion parts. Geometry models in the virtual environment with physical properties resemble the real physical world models. A collision detection approach (Fixed Direction Hull) based bounding box method is proposed for the virtual environment collisions. Master hand is designed by decoupling pantograph structure; it is used to obtain the virtual force feedback. Collision response with respect to the collisions detected leads to micro needle deformation (Bending deformation and Pressing deformation). Finite element method (FEM) is used to construct the micro needle.

2.2.4 Design of Automated Work Cells and Related Topics

In [24], Subramaniyam et al. outlined two layouts, Layout A (existing) and Layout B (proposed). A micro factory type of production system is discussed which has high precision, high throughput, and low-cost. Using digital manufacturing techniques, this micro-pump-producing micro factory is designed in VR. Layouts A and B are constructed using digital manufacturing. Change in the system configuration improves the productivity and efficiency. The experiment results of Layout A are tabulated in this paper. The bottleneck in this layout is waiting time of the robot arm, which is minimized by adding a micro-milling machine to Layout A and forming a new Layout B. This layout results shows improvement in the waiting time of the robot arm and completion of the micro pump production in less time.

In [25], Cecil et al. discussed the need to create an information-based framework for micro assembly. They also discuss in detail the path planning and virtual assembly modules developed in virtual environment. Two path planning approaches, Genetic algorithms and BFS, Dijkstra's algorithms are implemented here. C++ and open inventor are used to build the 3D simulations in the VR.

In [26], Visual-servo system for peg-in-hole micro assembly is proposed in this paper. Dynamic position-based servo provides accuracy, efficiency, and robustness. Image calibration (DPBS-IC) controls the gripper carrier stage, Regional scanning with edge fitting (RSEF) tracks the position of the micro object, and Shadow aided positioning algorithm (SAP) completes the final operation of placing the micro pin in the hole. The design parameters are micro needle manipulator, micro gripper system, object platform, working stages, and Illuminator & visual system. Using needle tip micro peg is positioned properly on the substrate with the help of SAP algorithm. Human Machine Interface to see the assembly operations are operated by LABVIEW. Finite state machine in automation is implemented here, where states representing micro part alignment and positioning, gripping activities, and assembly of micro parts.

In [27], Cecil et al. proposed a Cyber Physical Test Bed (CTB) for micro devices assembly based on Virtual Enterprise (VE) approach. Micro assembly resources are distributed among VE partners at different locations; there is a need for collaborative architecture to meet customer requirements for the distributed resources. A web based collaborative framework is proposed in this paper that emphasizes on software and equipment components. An Abstract Agent programming language (3APL) is used to create software agents. Agent communication is provided by Foundation for Intelligent Physical Agents (FIPA). Life cycle of CTB is (1) Enterprise planning, (2) Assembly Planning, (3) Path Planning, (4) Gripping and strategy identification, (5) Analysis and Simulation, and (6) Physical Assembly. If the services requested by the user are provided by more than one service provider then select the provider based on cost, prior performance on meeting customer needs.

In [28], the design for automated micro assembly control and planning is discussed. Precision-based robot path planning approach for micro assembly is elaborated. Novel precision-adjusted path planning algorithm is detailed which consists of prediction or planning, execution or control, adaption or event handling. Path precision is used at primary cost metric in this algorithm. Precise Path Searching Algorithm (PPSA) ensures the accuracy for the collision precisions in the robot manipulation. Assembly sequence, choice of motion path, precision metrics for robotic system, and choice of sensor leads to the errors in robot positioning. Measure or predict the errors during micromanipulation, this information is used to precise path planning. Experiment results shows improvement for precise path planning but not for shortest path planning.

In [29] Robotic assembly system is introduced for the assembly of micro devices. Precision is important in the micro assembly and it is addressed by “multiscale approach.” A three-pronged approach: Multiscale manipulation, Parallel manipulation, and Modularity are used to reduce the cost at the micro scale robotic level. To assemble 1*N fiber arrays, 5 subsystems are included: A coarse positioning system, a fine positioning system, a gripper and fixturing system, a high-resolution vision system, and an adhesive dispensing and curing system.

Novel micro-scale coordinate measuring machine (CMM) probe capable of high accuracy measuring system in the micro-scale is considered in [30]. The micro-CMM probe consists of PZT actuators, Flexure, PZT sensors, and micro-stylus. The sphere tipped stylus is subjected to high-energy electro-discharge pulse to shape the diameter according to the requirement that is manufactured from tungsten. The sphere-tipped stylus approach is produced using wire-electro-discharge-grinding (WEDG) and one-pulse-electro-discharge (OPED).

Multi-scale assembly and packaging system (MAPS) is presented in [31]. This system is flexible in configuration that extends to 20 degrees of freedom depending on the task. Four high resolution cameras are used for the vision. "Design for Micromanufacturibility" is a software application used for process yield, cycle time, production cost, and device performance. Netpune 4.0 software (Lab view + visual studio .NET) is used to control the micro assembly operation. Virtual 3D simulation, Microsim 1.0 is used to mimic the real world micro assembly work cell.

In [33], Prasad et al. Proposed OnTimeMeasure a reference implementation of Future Internet Performance Architecture (FIPA). Current Internet provides best effort model for data rich and multimedia applications, but user Quality of Experience (QoE) is not guaranteed. If the users request are more than the limit it degrades the quality of video shared by all the users. Using Performance Intelligence OnTimeMeasure increases the cloud scalability while assuring the Quality of Experience to the maximum possible for users. OnTimeMeasure interoperability with other GENI components is discussed in this approach.

2.3 Conclusion

Numerous researchers have researched in the field of assembly of micro devices. A few of them have used VR based approaches to facilitate physical assembly. However, no other work has reported the use of immersive VR technology for MDA. This thesis addresses this void directly. In this chapter, a review of relevant literature was provided under four areas:

- Micro Gripper designs
- VR based Simulations for MDA
- Force Related Modeling
- Design of Automated work cells and related topics

CHAPTER III

PROPOSED ARCHITECTURE

3.1 Introduction to Cyber Physical Framework

The use of Cyber Physical Framework in general lies in its potential ability to allow engineers (from different backgrounds) and resources (software and equipment) in geographically distributed locations to collaborate globally. In this thesis, a framework is developed and demonstrated for the domain of MDA. Various algorithms and software modules have been developed to demonstrate this approach.

This chapter outlines the cyber physical framework development for micro devices assembly contexts. *Section 3.1* discusses the distributed context for the domain of Micro Devices Assembly. *Section 3.2* gives an overview of Cyber Physical Test Bed (CPTB). *Section 3.3* outlines the user interface. *Section 3.4* describes the functional capabilities of VIRAM-2.

3.1.1 Developing a cyber physical approach

The cyber physical approach will be demonstrated for the following context. Consider a scenario with two or more computers located at distributed sites in Oklahoma State University and on Global Environment for Network Innovations (GENI).

The geographically distributed resources linked via the internet part of cyber physical framework are the following

- VR based virtual environment (VIRAM-2) (section 3.4)
- Assembly Sequence Module (ASM) (section 3.4.1)
- Path Planning Module (PPM) (section 3.4.2)
- Physical work cells (MAWC) (section 3.5)
- Camera Monitoring Module (CMM)
- Cyber Physical Interface Module (IM) (section 3.6)
- Cloud Computing Module (CMM) (section 3.7)

The physical work cells and the CMM are at Oklahoma State University (OSU). VIRAM-2 virtual environment modules, PPM, and ASM are distributed at different sites on GENI. When the user input is obtained, ASM generates the near optimal assembly sequences and sends them to PPM. Once the final path avoiding collisions is generated then the outputs are sent back to Oklahoma State University for the final VR based Simulation. Once the simulation is executed and visualized, the physical details for the micro assembly are sent to the physical work cell to complete the assembly of the target design.

The micro assembly life cycle process for this collaboration includes:

1) Obtain user input
2) Generate an assembly plan
3) Generate 3D path plan,
4) Perform feasibility analysis using VR simulation of target assembly/path plans
5) Complete physical assembly of target part designs.

If there are any collisions in the path plan given by the user, the VIRAM-2 environment detects these collisions and necessary modifications can be made to the path planning output to avoid collisions. After the analysis is completed, the output from this virtual environment is sent to the physical micro assembly work cell. Sharing the physical assembly videos using Camera monitoring module (CMM), where distributed users can view the assembly tasks simultaneously in real time.

3.2 Overview of Cyber Physical Test Bed (CPTB)

A Cyber Physical Test Bed (CPTB) has been developed to demonstrate the feasibility of the proposed approach in this thesis including the simulation (lower level software algorithms) physical assembly and cloud computing principles.

3.2.1 Overview of the various components or resources in the CPTB

1. User Interface Module (UIM): User can input the assembly sequence through an external file or they can select an automated assembly sequence that is generated by assembly plan generation module.
2. The virtual environment (VIRAM-2): A virtual reality environment has been created to simulate the micro assembly operations. This has several modules:
    - 2.1 Assembly sequence generation module (ASM): Once the user selection is completed, the assembly sequence is sent to the assembly plan generation module. Here a Genetic Algorithm based approach is used to find the near optimal assembly sequence to assemble microns. The assembly sequences are sent to the path planning module to find a path that avoids collisions.
    - 2.2 Path planning module (PPM): To avoid collisions in the path generated by the assembly sequence, a modified breadth first search (BFS) is implemented. Using this

approach the final path is determined to assemble the micro devices and sent to the virtual environment.

2.3 Visualization engine: The user input or automated assembly sequence sent to the virtual environment for the assembly of micro devices. After the simulation is completed, the data is transferred to the physical environment for the final assembly.

3. Physical Micro Devices Resources: The final micro assembly tasks are implemented using work cell resources.

3.1 Camera monitoring module (CMM): The physical assembly of the micro devices is recorded using a microscopic video mounted on the top of the work cell. These videos are also shared among the distributed users using the cloud. CMM is resided at OSU

3.2 The cyber physical interface module: This cyber physical interface module transfers the data from the Virtual environment to the Physical cell.

4. Cloud computing module: Distributed engineers or users can share the virtual simulations and physical videos very efficiently using a measurement service, OnTimeMeasure developed at Ohio State University. Even the resources such as assembly sequence module, path planning modules, virtual simulations and physical work cells are distributed at different locations. Cloud computing brings distributed engineers and resources together to accomplish the tasks efficiently.

3.3 The User Interface

The user interface allows the user to interact with the virtual environment to visualize the work cell simulation. The cyber elements involved in the user interface are an assembly plan generator module, path planning module, and a visualization module. On interaction with the interface, a welcome screen appears wherein the users have an option to select the types of parts used in the assembly of microns. On selection of a part, an assembly plan is either generated or obtained from the user. If the assembly plan is to be generated, then the ASM is executed to find the near optimal solution for it. This displays the assembly distance for the selected plan on the screen. The program is then exited in order to start the simulation of work cell in virtual environment. The systematic interaction with the user interface is detailed in chapter 5.

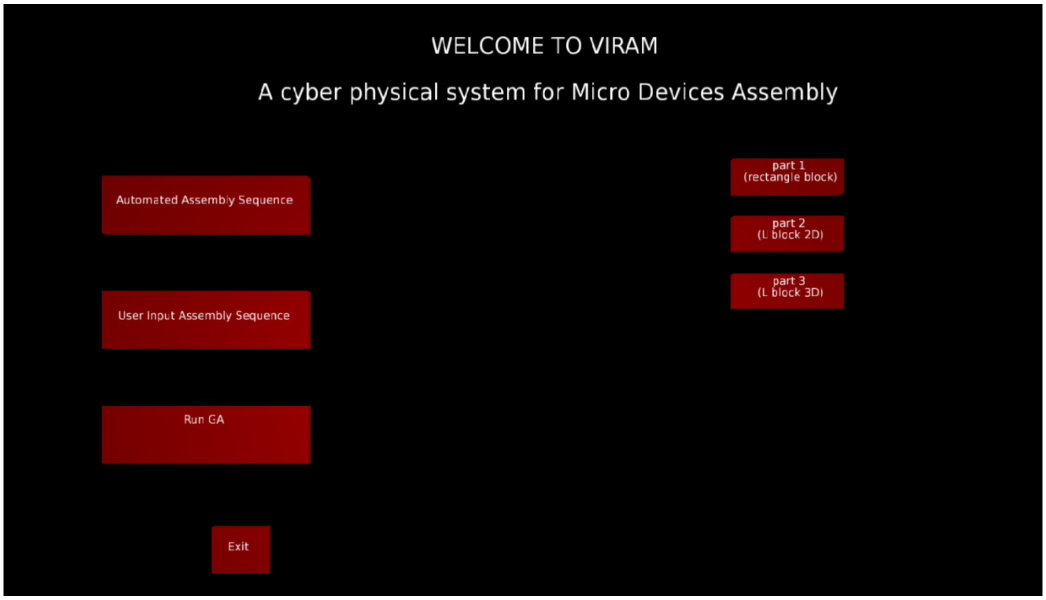

Figure.2 Welcome screen for the user interface

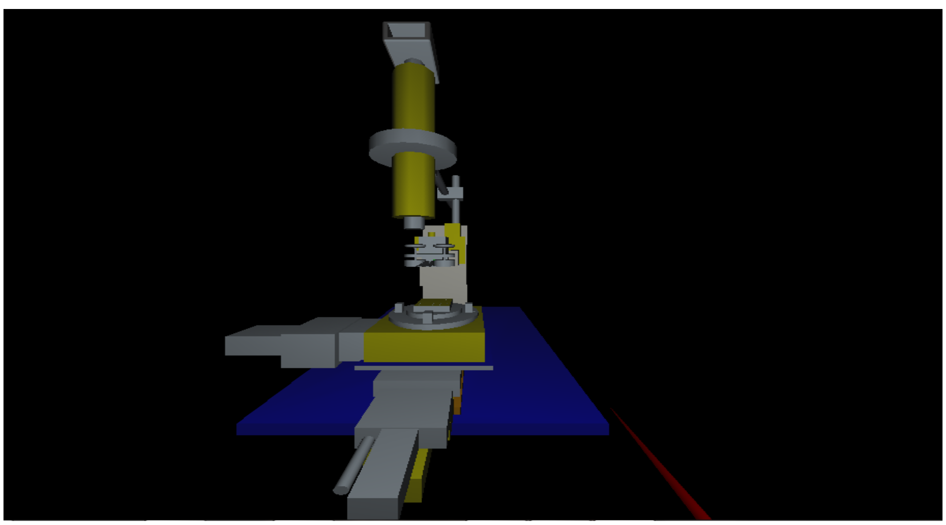

Figure.3 Virtual Reality Environment for Micro Assembly (VIRAM-2)

3.4 Virtual Reality Environment for Assembly of Micro Devices (VIRAM-2)

Introduction

The VIRAM-2 extends the earlier VIRAM system that was implemented using coin 3D on a semi-immersive system where a large computer screen was the VR screen [37]. The new VIRAM-2 implemented using VRScape (3D tool kit based on python 3.0.1).

The modules in the VIRAM-2 are:

3.4.1. Assembly planning / sequence generator module

3.4.2. Path planning module

3.4.3. Visualization/ virtual reality module

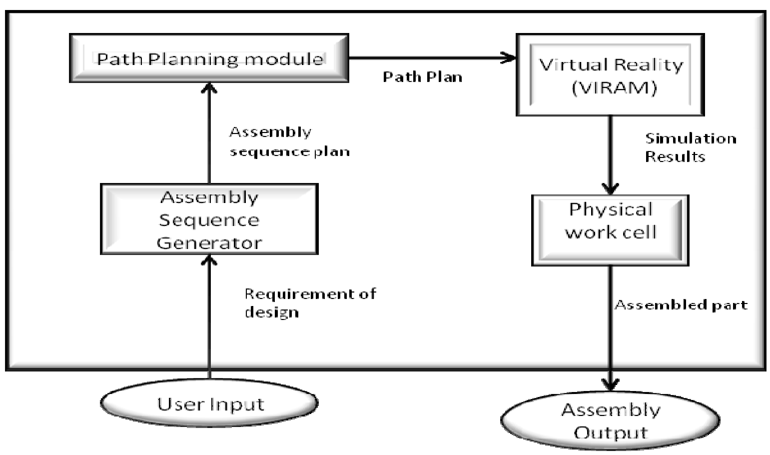

Figure.4 Data exchange between the modules

3.4.1 Assembly planning Module

Genetic algorithms are used for solving the assembly sequencing and planning problem, which is modeled as Travelling Sales problem (TSP). The assembly of microns for a given assembly sequence consists of different sources and destinations can be considered as a variant of the TSP problem. Genetic algorithms generate child sequences based on the combinations of the parent sequences to find the nearly optimal assembly sequence.

3.4.1.1 Overview of Genetic Algorithms (GAs)

Every organism is made up of tiny building blocks termed genes that are connected together to form chromosomes. The user input assembly sequence is considered as a chromosome. Genetic algorithm uses combinations of the parent sequences to generate the offspring sequences. The processes involved in the generation of offspring sequences are reproduction, recombination (crossover), mutation, and inversion. The GA based approach is chosen because of its simplicity, robustness and ability to determine the optimal solution where there is a large search space.

3.4.1.2 The TSP Problem

The Genetic Algorithm produces the nearly optimal solution from a set of feasible solutions. If there are n cities to travel for a sales man, he should visit all the cities only once. There are n! ways for a person to travel all the cities. This is called as Travelling sales man problem. In a Travelling Sales Man (TSP) problem, there will be many options to travel all the cities but finding the best solution is NP-hard problem. The set of feasible solutions is called as *Search Space.* The search space or state space is shown in the Fig 8 is between the two orange lines. Each point in the state space can be represented as one feasible solution. The red line points to the best solution but there is no assurance that GA reaches to this solution in every run. In each run it gets a value from the search space. If the process of generating child sequences is not properly planned, then there is probability of falling into local optimum where the parent sequences could not generate better child sequences after a point. Hill climbing, Tabu search, simulated annealing, and genetic algorithms are some of the methods to find the search space for a given problem. These methods may not be giving the best solution for a given problem, but finds a feasible solution from the set of points in the search space.

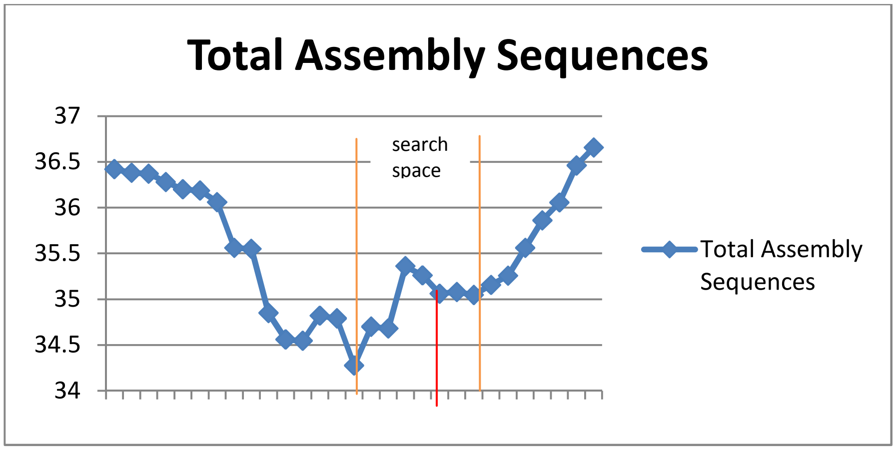

Figure.5 Search Space

3.4.1.3 Details of GA approach

In this MDA context, the operation of pick and place of microns from feeders to the destination can be considered as a variant of Travelling Sales Problem. The aim is to find the near optimal possible sequence of path so the placement robot can assemble all the pins in a sequence that consumes less time.

Assembly precedence constraints: There should not be any repetition of source or destination locations in the path given. Assembly precedence constraints need to be programmed and compared with regular GA. User have the option of specifying the constraints of certain pins to be assembled in specific sequence. This type of user constraints are programmed and compared with the regular GA. The working of GA in the assembly sequence environment can be seen in the figure 10.

Overview of the assembly planning main steps

1) Get input from the user
2) Get feeder locations and final destinations
3) Generate new parents

4) Calculate the assembly distances of the parent sequences

5) Generate new children (based on GA operators) and store assembly distances

Generation of new sequences

- **Crossover** is used for 60%. This operator selects two random parent sequences from the list of n sequences and chooses a cut. The values from the first parent before the cut is copied into the child sequence and the values after the cut are copied from the second parent. It ensures that there is no repetition in the values in the child sequence.

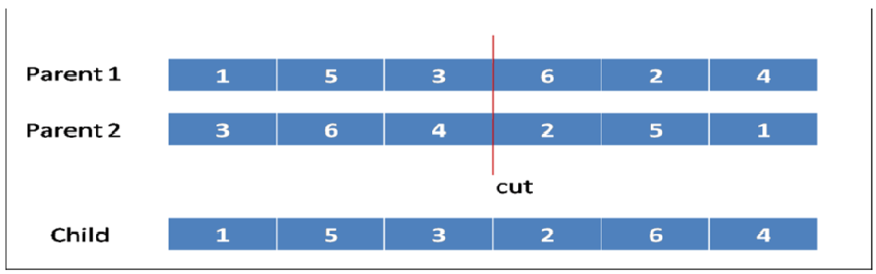

Figure.6 Crossover operator

- **Mutation** is used for 40%. This operator selects a random parent sequence from the list of n parents and chooses a random n and k values. n is the node and k is position where the node is to be shifted. The nodes between n and k are moved to the left.

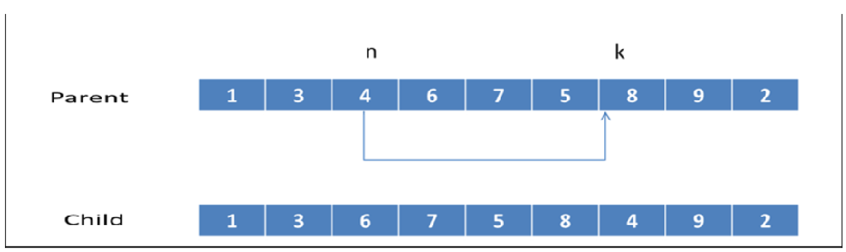

Figure.7 Mutation operator

- **Inversion:** If the mutation or crossover reaches, threshold values of finding the new child sequences whose distance is less than the maximum distance of parent sequence then apply an ***inversion*** technique on a random parent sequence.

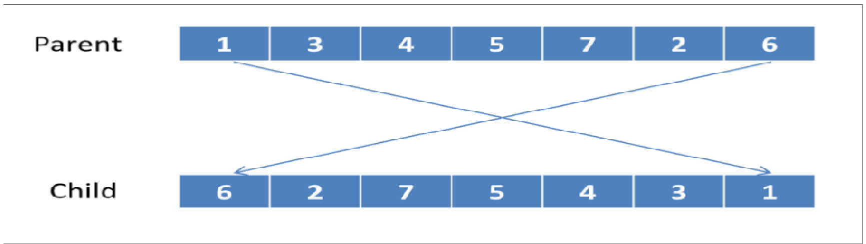

Figure.8 Inversion operator

Details of GA steps

1) The input is obtained from an external file as shown in figure 9. The source and final positions are provided in the input file. Each line indicates one pin movement from source (start) to destination. The information provided in the figure 9 refers to the 3 pins each from source to destination.

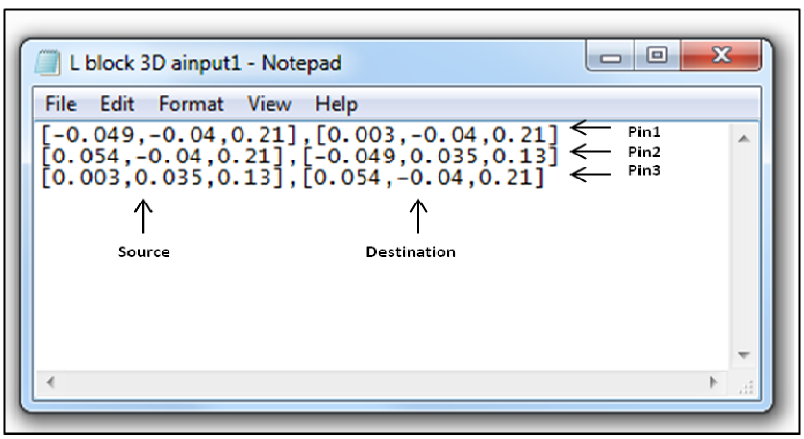

Figure.9 Input file for the Assembly plan generation module

2) Consider a sequence of placing n pins from feeders to the destination block.

3) Generate n-1 random sequences using the first sequence. In this way you have n parent sequences for n pins placement.

4) Calculate the assembly distance of each sequence and store the sequences and it's corresponding assembly distances in a 2*2 array

5) Generate child sequences from these n parent sequences using Genetic operators

6) After the generation of each child sequence using crossover or mutation or inversion, the sequence is sent to the ***path planning*** module for the test of collisions. The precedence constraints are taken into consideration when selecting the child sequences. Then the distance is calculated with the updated path avoiding collisions

7) If the distance of newly created child sequence is less than the maximum assembly distance of the parent sequence then it is treated as child sequence and added to the list.

8) The next method is finding out the n best sequences from the mix of parent and child sequences and these best sequences are considered as the new parent sequences for the next iteration.

9) Repeat the steps from 5 to 8 over 1 Million iterations (assuming 'n' value is more than 12). The final best sequences have the near optimal solution for the given assembly sequence. This assembly sequence with minimal distance avoid collisions is stored in a file and sent as an input to Virtual Environment.

An example of the assembly sequence generated by the assembly plan module : (a -> 5), (e-> 12), (g -> 15), (h -> 21), (d->3) .

The alphabets represent the source (feeder) locations and the numbers represents the destination locations. A more detailed description of output file of GA is described in chapter 5.

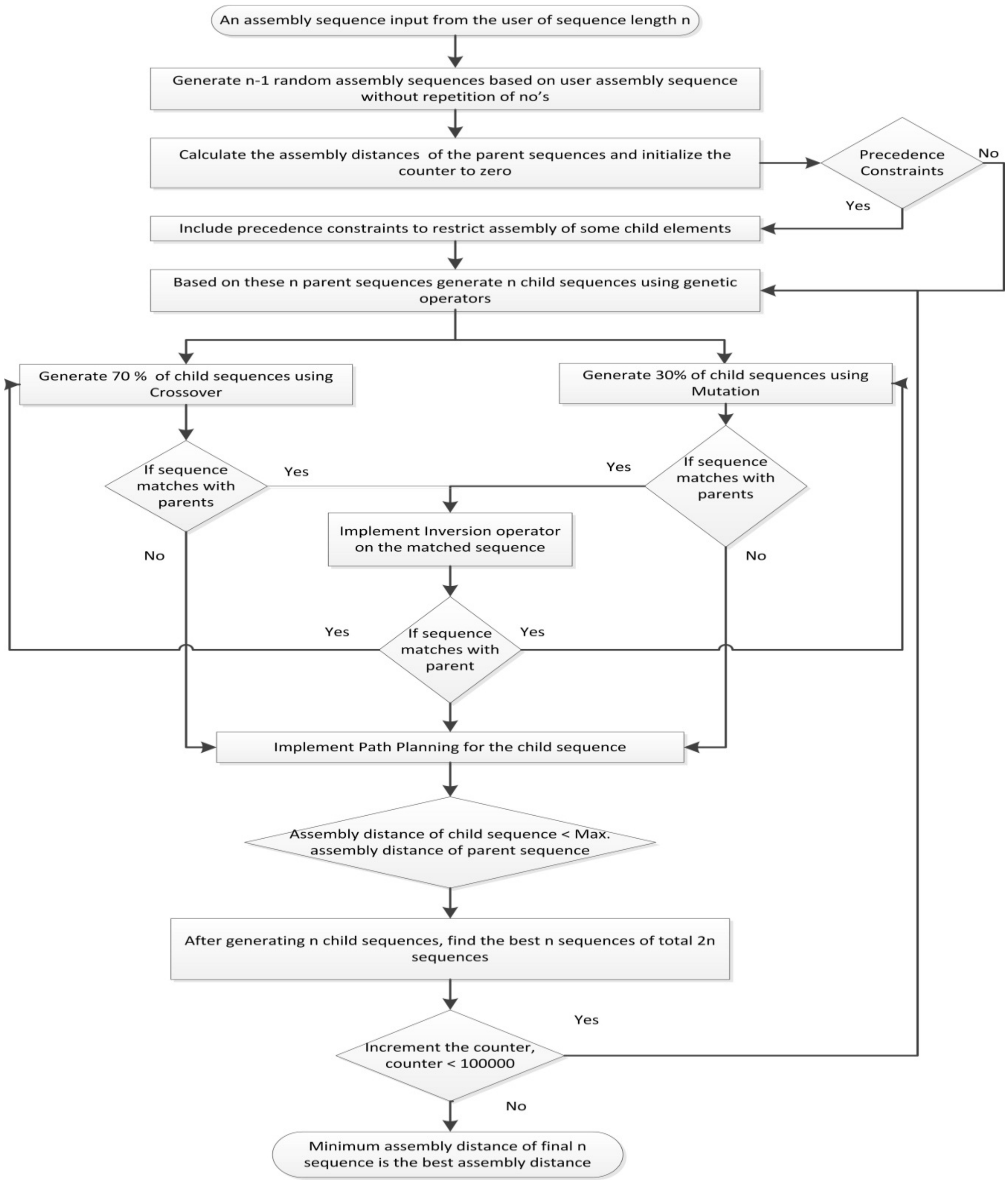

Figure.10 Flow Chart representing the working of Genetic Algorithm in the micro assembly

3.4.2 The Path Planning Module

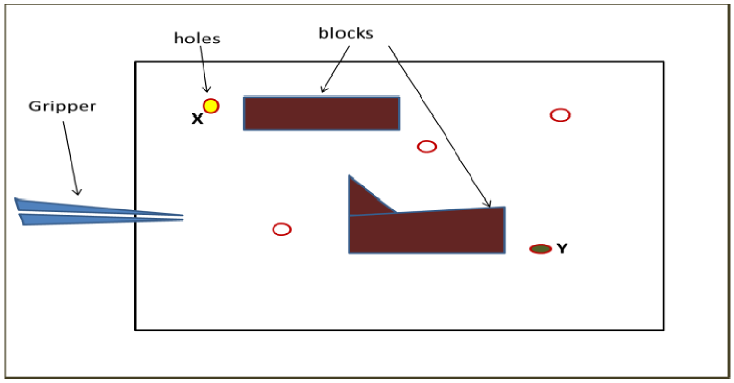

Figure.11 Assembly Area Layout

3.4.2.1 Introduction

The path planning module is used to find the collisions in the path sequence generated by the assembly plan module. Path planning algorithms are implemented to avoid these collisions and provide a feasible path to reach the destination.

3.4.2.2 Overview of the PP approach

The main steps involved in this approach are

- Input: (1 -> 205), (45 -> 542)
- BFS based path planning algorithm has been implemented
- output from the path plan module: (1 -> 2-> 3-> 4->5->105->205), (45-> 44-> 43 -> 42-> 142-> 242-> 342-> 442-> 542)

The format of input and output are explained in the section 3.4.2.3

Figure 11 describes the layout of the assembly area of the physical assembly work cell for the gripper movements. The Gripper can move up or down along the XY plane consisting of holes and blocks. The blocks/obstacles can be sensors; pins and complex design of the destination block itself. The gripper picks up the pin from the start position represented by X in the figure and ensures the pin at the destination hole represented by Y as shown in figure 11. The path planner makes sure the assembly sequence is collision free while moving from source to destination. This is based on the earlier work of Trivedi [32].

3.4.2.3 Details of PP approach

This approach uses Breadth First Search (BFS) and Dijkstra's algorithm. Breadth First Search is a tree search algorithm begins at the root node and traverses through all the neighboring nodes in the form of waves in the water. Nodes connected directly to the root node have a distance of unit 1, and its neighboring nodes have the distance of unit 2, and so on. When the distance between any two nodes is equal we can opt for BFS which reaches the destination in the minimal time. If the distance between the neighboring nodes is varying, then Dijkstra's algorithm comes into the picture. The algorithm starts with the source node. All the nodes start with an initial distance of infinite. The source node distance is zero. The neighboring nodes of source distance are compared with its own distance. If the distance of a node is more than the distance from its parent node then the distance is updated. In this way the algorithm explores all the neighboring nodes till it reaches the destination node.

The complete assembly area is divided into a floor map depending on the size of the micron as in Fig. 12 Source is node 1 and the destination is 203. All the obstacles are colored in blue (202, 102, 103). Here the distances between the nodes are equal, so the path would be 1->2->3->4->104->204->203.

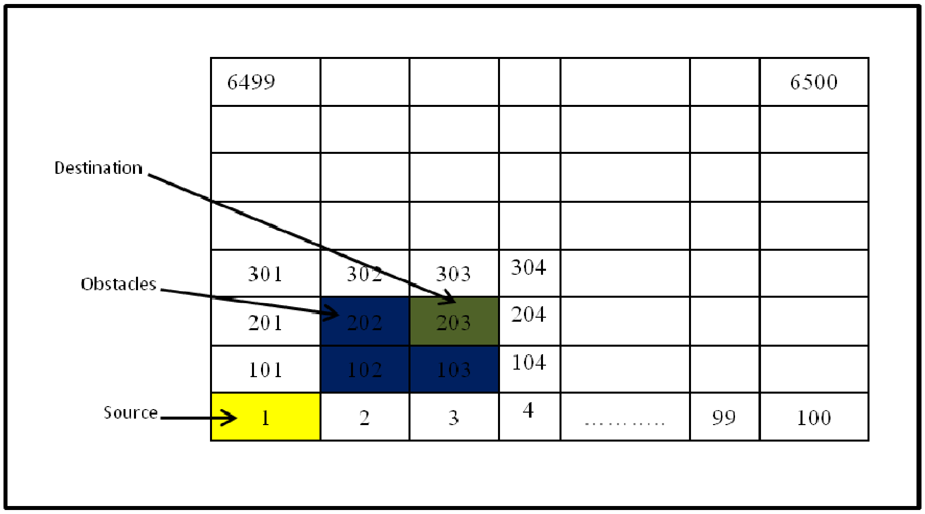

Figure.12 Floor map of Assembly Area

In this thesis research, BFS is implemented as the distances between two nodes are constant. When the distance between two nodes varies then Dijkstra's algorithm is implemented. In chapter 5, a more detailed description of tests performed using BFS and Dijkstra's algorithm is outlined.

3.4.3 Visualization Engine

The virtual environment module is built using VRScript from Mechdyne Corporation. The VRScript engine is based on inheritance concept (parent - child relationship). A node in the in the engine may have several children but often a single parent. The parent properties are inherited to the child nodes. In this virtual environment the base of the work cell is treated as parent and all the other parts are attached to this node as children.

3.4.4 Collision Avoidance

Normally, the gripper is positioned horizontal to the base of the work cell. In some scenarios, the left micron blocks the path of the gripper that must grip the right micron, as shown in fig. 13. This causes the path of the gripper to collide with the other micron. In such a situation, there are two ways of avoiding collision with the micron in between the gripper and right micron: either the gripper is positioned at an angle of 45^0 or the cylindrical positioner is rotated to bring the micron towards the gripper.

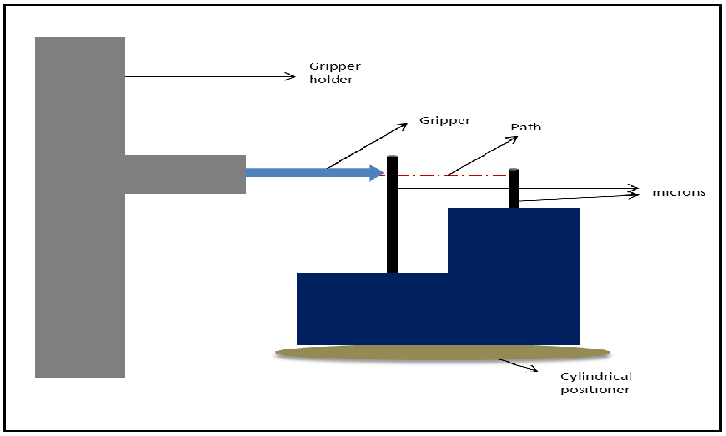

Figure.13 Collision of gripper with an intermediate micron pin

Case I: The gripper is positioned at an angle of 45 degrees so the variation in the height of the microns does not block the gripper. This scenario is implemented in the virtual environment to prove that the positioning of the gripper at such an angle avoids collision between gripper and the micron.

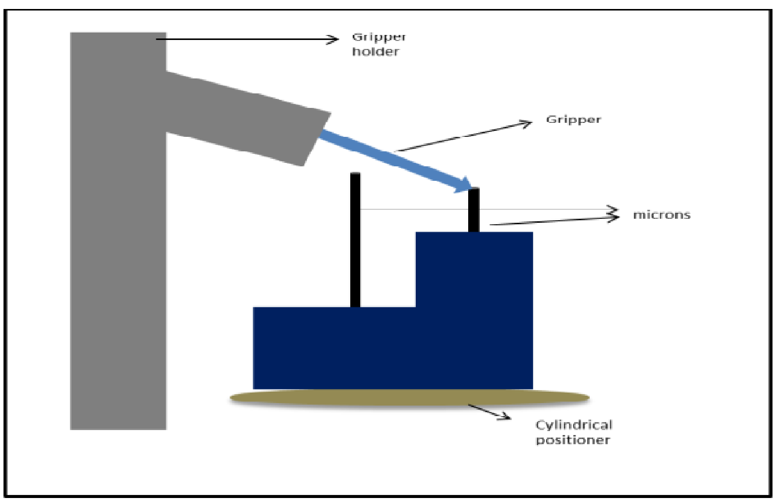

Figure.14 Collision avoidance using gripper angle change

Case II: The gripper is positioned horizontally, parallel to the base of the work cell. The block is placed on the cylinder positioner that can rotate 360 degrees. Using the cylindrical positioner the block is rotated such that the intermediate blocking pin moves out the path between the gripper and right micron. This is shown in figure 15. However, this heuristic has not been implemented as part of the CPTB. (It is easier to rotate the assembly area using rotational positioner and avoid collisions).

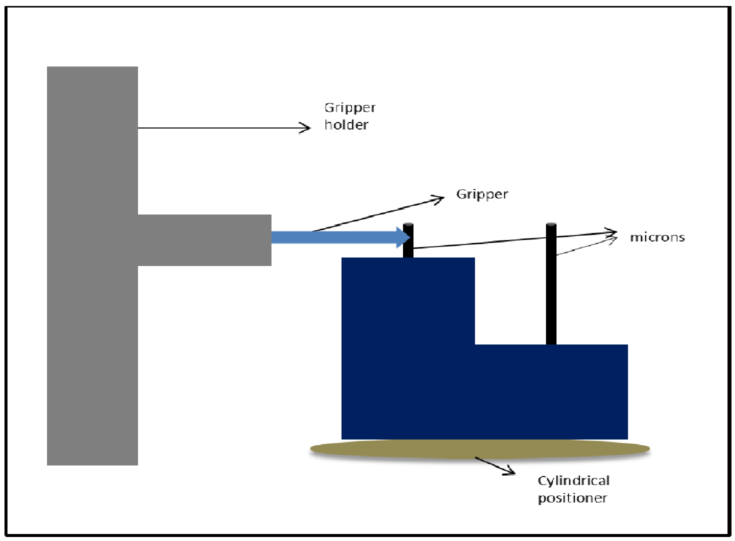

Figure.15 Collision avoidance using rotation

3.5 Physical Micro Devices Resources

3.5.1 Introduction

Manual assembly of micro devices involves humans picking and placing of microns using tweezers, microscopic cameras which is a tedious and time-consuming task. Automation of this process is called as micro devices assembly (MDA). This is accomplished using micro assembly work cells (MAWC) that consists of linear positioners that helps in translating the part containing microns and the gripper to perform the target assembly tasks. In the Cyber Physical Test Bed (CPTB), the work cell comes into play in the final stage after the simulations are completed in the virtual environment and the physical assembly details are transferred to the work cell station/computer.

3.5.2 Description of Work Cell

Work cell 2 is composed of the following components:

- linear positioners
- assembly plate
- a micro Gripper
- Illumination lights
- Computer
- Camera
- Control units and power supply

The camera has an interface to a computer, where the physical tasks and activities can be viewed and recorded. Two focusing lights are used to adjust the lighting on the micro devices to give clear image for the camera. A variety of tweezers function as a gripper to manipulate micron sized objects.

i. Motion: The work cell has 3 linear degrees of freedom (X, Y, and Z axis). Two linear positioners act as the base of the assembly plate that moves front/back (X) and left/right (Y). A gripper is attached to the other linear positioner that moves up/down (Z). All the three micro positioners are from Parker Corporation. Figure 16 shows the linear positioners and rotation positioners that are part of the work cell.

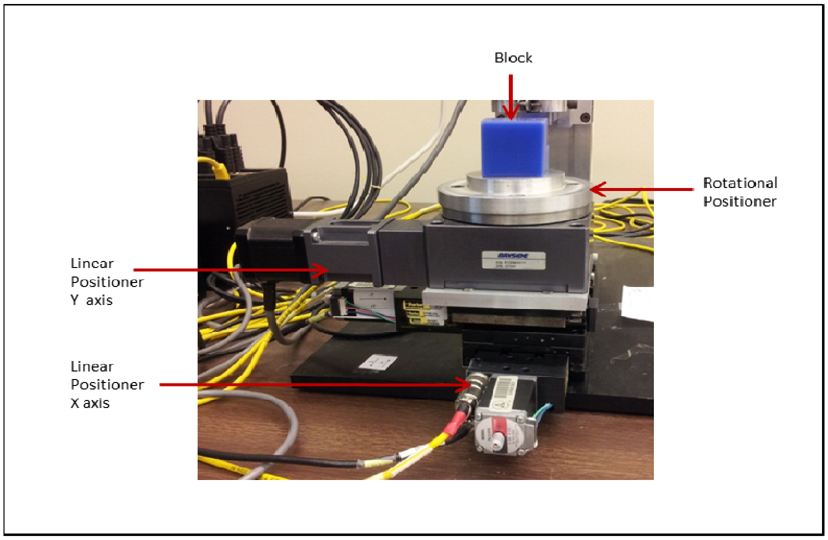

Figure.16 XY Linear Positioners

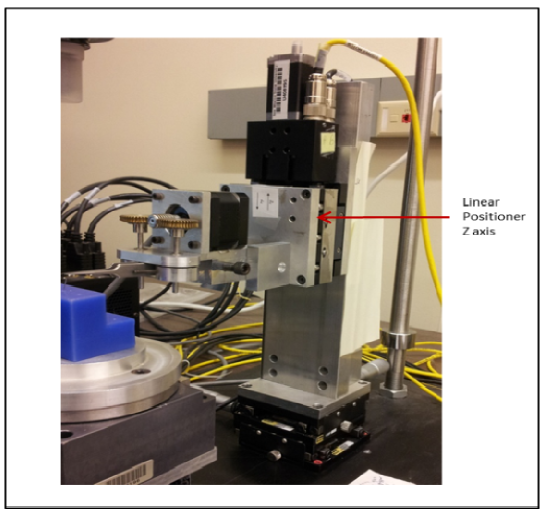

Figure.17 Linear Positioner Z, on which the Gripper is mounted

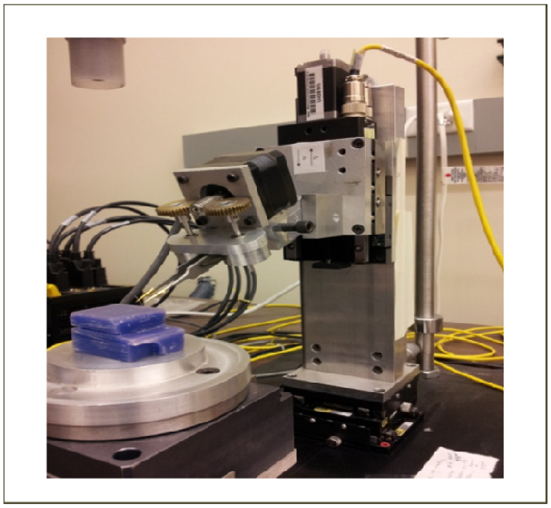

Figure.18 Linear positioner Z holding the gripper at an angle (45^0)

ii. Gripper: The setup comprises of a tweezer, which can be opened or closed by worm gears (fig 19). Gripper is used to pick and place micro devices from the source to destination locations according to the assembly sequence. The gripper can be placed either parallel to the assembly area or upto 45 degrees of angle as shown in fig 17 and 18 respectively. Gripper can move up/down as it is attached to a Z-axis linear positioned (fig 17).

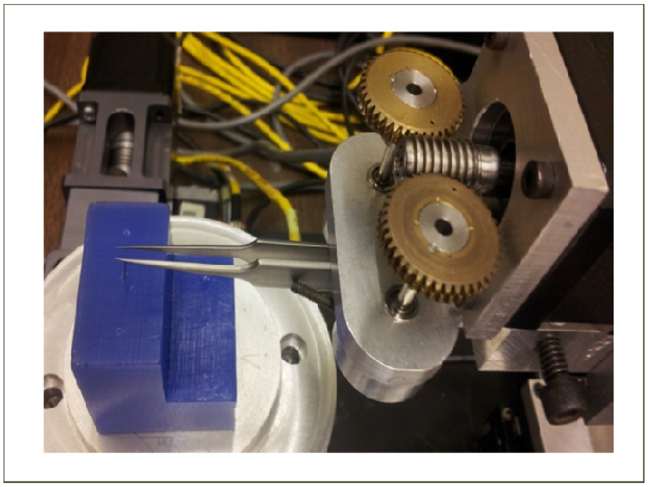

Figure.19 Gripper used to pick and release microns

iii. Camera: A microscope camera is mounted on the top of the work cell to record the physical micro assembly accomplished using the micro assembly work cell (MAWC). The camera is connected to a computer to provide a visualization of assembly for the users.

iv. Illumination: Two focusing lights are used to give a clear image of the assembly area. This helps to record the physical operations on to the system using the camera. Illumination lights and camera are shown in the figure 20.

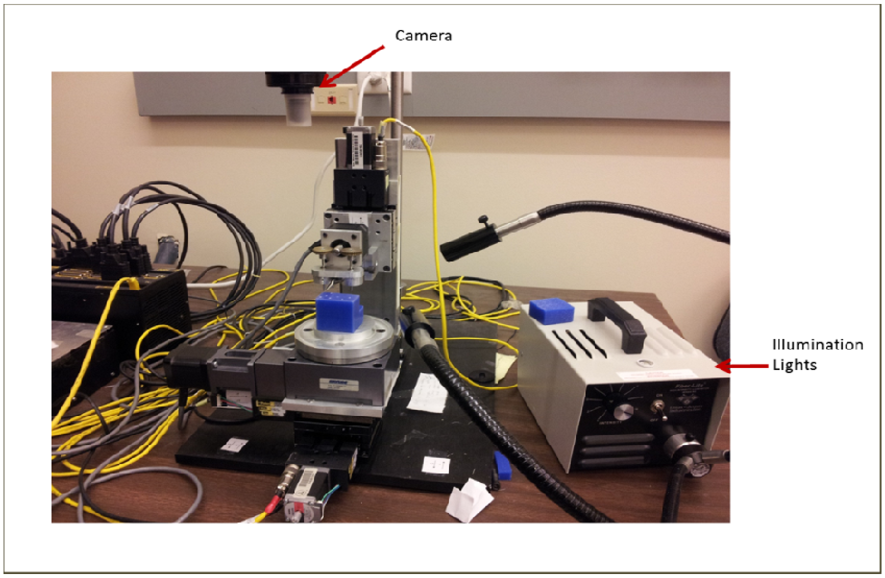

Figure.20 Camera and Illumination lights

v. Control units: The micro positioners movement is controlled using the control units. This is the power controller for the linear positioners enable the motion for them.

vi. Computer: This provides a user interface to control the work cell. User can interact with the micro assembly work cell in two modes. First, a program with step-by-step instruction to guide the pick and place of microns from source to destination can be given as a single file input to the work cell. Second, each movement (x, y, or z) and gripper open/close can be given to the work cell using a GUI interface manually.

3.6 Cyber Physical Interface Module

3.6.1 Introduction

The interface module transfers the output of the virtual environment to the physical work cell. Once the simulation starts executing in the VR, (to assemble the micro devices) the linear positioners move front/back, left/right, and up/down. To pick and place the pins during assembly, the gripper opens and closes corresponding to the target requirements. All of these translations in the virtual environment are calculated using Python 3.0.1 and stored in a text file. In the next section, the details on how the virtual environment assembly are transferred to physical world through text files are illustrated.

3.6.2 Details of the Interface Module

A discussion on how this module function is provided in this section

This interface module is written using Python 3.0.1. This module generate the step by step instructions to control the physical work cell, which is used to complete the target micro assembly.

Figure 21 explains how the user 3D input is mapped to the floor map of the assembly area. The first point, source in the input (-0.20, -0.20, 0.21) maps to the block 1 (B1). Second point, destination in the input (0.20, 0.20, 0.21) maps to the block 160000 (B160000). Similarly, the remaining 3D inputs point to the corresponding block number.

As the user specifies the source and destination points in 3D, these 3D points are converted into their respective block numbers as explained previously. Based upon the block numbers, the distance is calculated and the pin is moved virtually.

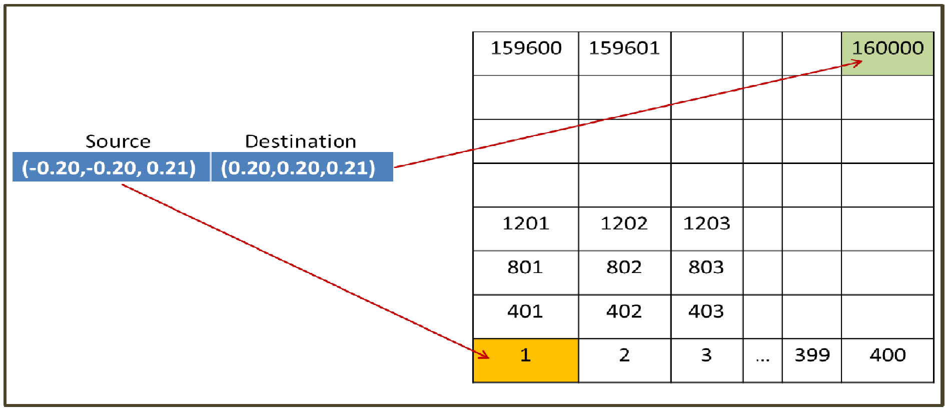

Figure.21 Mapping of 3D input to floor map

The planned path is then tested to see if the desired destination is reached virtually. If the user is satisfied with the results, the distance calculated to virtually assemble the pin is then converted into real time units (in this case inch). The conversion factor to change the virtual units to the real time data is 0.01.

Figure 22 shows the user input and their corresponding block numbers in the floor map. Here source is block 100 (B100) and destination is block 8200 (B8200). First the linear positioner 'Y' moves to the right 100 units and then linear positioner 'X' moves 2 units away from the user. So, the real time units are 1 inch right (100 * 0.01) and 0.02 inches up (2*0.01). This is represented as Y/1 followed by X/0.02.

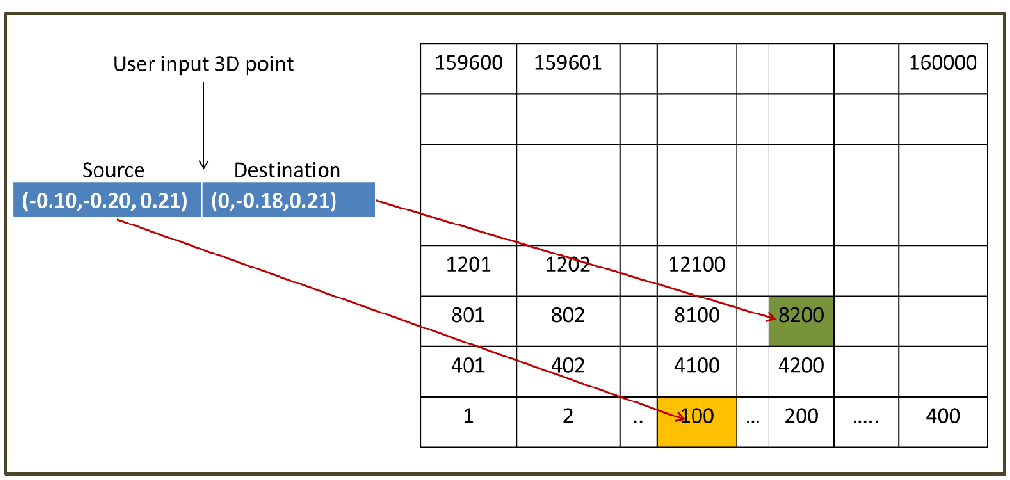

Figure.22 sample 3D user input and converted blocks.

After the conversion is completed from virtual assembly to the real time data, a write command is used to pass the assembly details to a text file. In general, the command ‘f.write(‘P’) writes the data specified within the ‘’ (in this case ‘P’). For example, the command f.write(‘Y/-0.7’) represents ‘Y’ linear positioner is translating 0.7 inches to the left. If the distance is positive then the linear positioner moves to the right. Similarly, the translations of assembly details of the complete simulation in each direction are written to the output file.

The output from the virtual environment is shown below :

```
program
   Y/-0.7
   X/-3.9
   Z/-0.18
   M/-1
   Z/3.0
   Y/4.2
   Z/-3.0
   M/1
   Z/3.0
end
```

Figure.23 Sample output file of physicalprogram.txt

3.6.2.1 Description of the output file

Physical instructions are stored in a file ‘physicalpath.txt’. This file begins with the key word ‘program’ and ends with ‘end’. The following discussion explains in detail, each step in the output file.

Y/-0.7

This command moves the linear positioner 'Y' to the left. '/' operator in the command indicates that it is an incremental movement. If the linear positioner Y is currently at -0.3, Y/-0.7 moves 0.7 inches from -0.3. So, the total distance from origin of Y will be 1 inch. If the command is Y-0.7, then it moves in a direction such that the difference between the origin and current Y position is 0.7. If the Y is currently at -0.3 then it moves only -0.4 inches. In this approach we used incremental command in moving the linear positioners.

X/-3.9

This moves linear positioner 'X' 3.9 inches away from the user from the current X position

Z/-0.18

This moves linear positioner 'Z' 0.18 inches down. Positive value moves 'Z' in the up direction

M/-1

This closes the gripper to pick the micro device. If the value is positive the gripper opens to release the gripper.

The virtual environment calculates the direction of movements for the work cell linear positioners to assemble the microns in the assembly sequence generated by GA. Once the physical work cell commands are generated, the ‘physicalpath.txt’ (containing these commands or instructions) is transferred to the physical work cell by the python program. The content of physical assembly instructions is shown in figure 24.

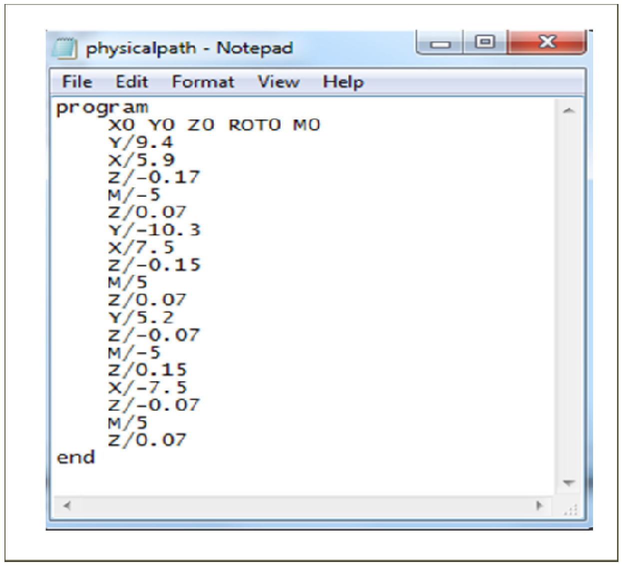

Figure.24 Input file for the physical work cell

3.7 Conclusion

An innovative approach Cyber Physical Framework is proposed in this chapter. An overview of CPTB and user interface is discussed here. A brief description on VIRAM-2 that consists of assembly plan generator module, path planning module, and visualization engine is outlined. Consequently the physical work cell description is detailed followed by the cyber physical interface module description for transferring assembly details from virtual environment to the physical work cell.

CHAPTER IV

CLOUD COMPUTING APPROACH

4.1 Introduction

4.1.1 Cloud Computing

In a typical business application, a user to have access to datacenters, data storage, a complicated software stack, and a team of experts to run them. If the business applications grow in number then the complexity in the maintenance of the application increases. If users have access to the "cloud" they can build their applications in the cloud and need not worry about the maintenance of the business applications. In the context of this thesis, the benefit of using a cloud computing approach is that remote users with limited computing capabilities can use the CPF through a cloud. The advantages of the cloud are infrastructure as a service, software as a service and platform as a service. The similar concept can be related to this thesis research and figure 26 illustrates the same in detail. For the researchers, GENI provides a free access to the cloud resources (Emulab) to test our experiments.

4.1.2 GENI

A brief note on GENI is provided. GENI is being developed by the National Science Foundation (NSF) in collaboration with academia and industry. "The Global Environment for Network Innovations (GENI) is a unique virtual laboratory for at-scale networking experimentation where the brightest minds unite to envision and create new possibilities of future internets. The GENI mission is to:

- open the way for transformative research at the frontiers of network science and engineering; and
- inspire and accelerate the potential for groundbreaking innovations of significant socio-economic impact" [36]

The architecture of the GENI, OnTimeMeasure and micro assembly work cell is shown in Figure 26.

4.1.3 OnTimeMeasure (OTM)

Today's Internet provides low quality video sharing to provide access to all the users, which however compromises the quality of the video. OnTimeMeasure resolves this issue by maintaining measurement services time to time while improving the video quality through RICE based on the response from each user. It achieves this without compromising the quality of the video while providing access to the maximum possible users. [33].

4.2 Overview of approach

In the Cyber Physical Framework, distributed engineers or users can share the virtual simulations and with optimal quality of experience using a measurement service, called OnTimeMeasure Ohio State University [33], whose performance intelligence can be used for suitable encoding selections in the Remote Instrumentation Collaboration Environment (RICE) software, also developed at Ohio State University [34] [35].. Both OnTimeMeasure and RICE software can be delivered to the users in a Software-as-a-Service (SaaS) coupled with Platform-as-a-Service (PaaS) model so that the administrators as well as the users need not install the server software on local systems, but can use cloud platforms such as GENI. At a time, one user can input assembly plan to the system, other users are passive observers can assembly simulations and physical assembly. OnTimeMeasure along with RICE in GENI gives a better performance than the regular desktop sharing software such UltraVNC and Real VNC.

4.3 Using OnTimeMeasure in Cyber Physical Environment

Consider a scenario with two computers located at Oklahoma State University, and the other one is from Emulab (GENI). These geographically distributed resources (across GENI framework) are linked via the Internet.

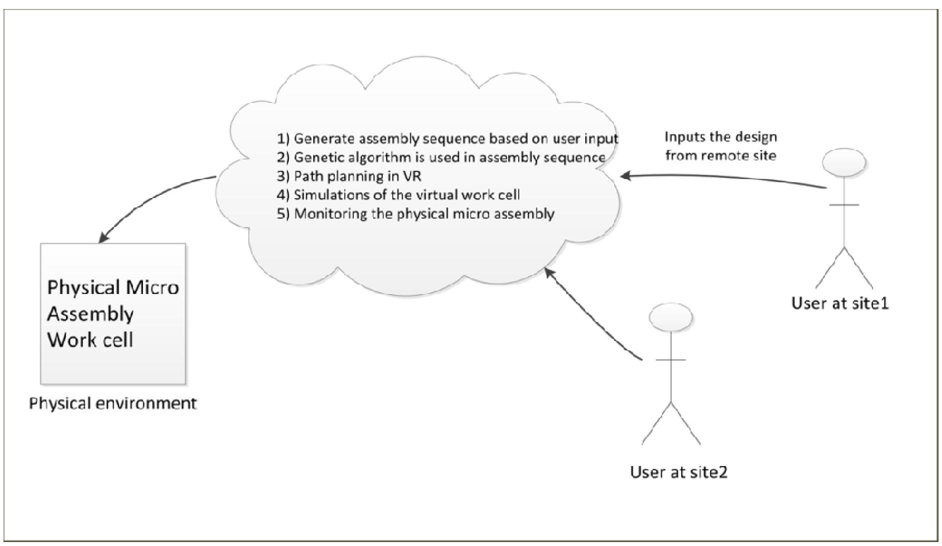

Figure.25 Cloud Architecture of Cyber physical Test Bed

The micro assembly life cycle for this collaboration includes obtaining user input, generating an assembly plan and a 3D path plan, simulation of target assembly/path plans, and physical assembly of target parts.

The simulation of the assembly process was demonstrated using virtual environment in two locations, Oklahoma State University and GENI environment. When a user connected to GENI cloud running the simulation, other users from other locations can simultaneously observe the simulations of work cell 2. Camera video monitoring of final assembly was observed among distributed sites. To make sure the Quality of Experience was guaranteed while viewing the videos across users in different geographical locations, OnTimeMeasure a measurement service was administered by Emulab users in GENI. RICE software is installed on user machines and uses the performance intelligence of OnTimeMeasure measurements.

OnTimeMeasure measurement service in GENI for provides performance intelligence based on instrumented measurement tools that report network Quality of Service (QoS) (e.g., bandwidth, jitter, latency, loss) and application Quality of Experience (QoE) (e.g., frame loss, Objective Mean Opinion Scores) measurements [33]. Users can logon to the OnTimeMeasure website (http://ontime.oar.net) to query the measurement results for the specified IP addresses. OnTimeControl is the other way of retrieving measurement results from command line interface.

Available Bandwidth bk	Encoding
bk > 1 Mbps	Hextile full colors
256 Kbps > bk > 128 Kbps	ZRLE 256 colors
128 Kbps > bk > 19 Kbps	Tight 64 colors
19 Kbps > bk > 5 Kbps	Tight 8 colors

Table1. UltraVNC Encoding techniques [from 35]

OnTimeMeasure improves the performance for the following shared resources:

- Sharing the simulation scenarios across geographically distributed computers
- Sharing the camera monitoring (videos) during the physical micro assembly activities executed at Oklahoma State University

Freewares like UltraVNC and RealVNC are network aware where they consider only end-to-end systems. The online encoding is based on Quality of Service (QoS). The network metrics are taken into consideration but human/end user Quality of Experience is not considered here. From the table 1 it can be seen that there is no encoding selected for the bandwidth between 256 Kbps and 1 Mbps. If the first available bandwidth is 1 Mbps then Hextile full colors is selected. Then the bandwidth decreased to 512 kbps but UltraVNC continues to encode the video in the same Hextile full colors, which degrades the user Quality of Experience. These errors are taken into consideration in RICE software along with the human score for the Quality of video received.

Reliable and Efficient Remote Instrumentation Collaboration Environment (RICE) (human-and-network aware VNC or improved UltraVNC that uses performance intelligence from OnTimeMeasure) was used in this setup. The online encoding is based on Quality of Application (QoA). Users score for the quality of video they perceive at their end and this data is collected and portrayed as Mean Opinion Score (MOS). Geographically distributed computers share the videos/simulations of the work cell using RICE software [34, 35]. The experiment results show that the RICE performs better than the UltraVNC software for sharing the videos. RICE also provides multi user collaboration where the administrator can pass the control to one of the users and the other users can only see the videos without any interaction. Human-and-Network Aware, RICE with OnTimeMeasure and Network Adaption provides better quality than UltraVNC.

In this CPF, we are running a Virtual Enterprise (VE) application within GENI. GENI is used as infrastructure as a service to host the application. The applications correspond to the virtual reality simulations and physicals work cell assembly operations. To ensure the quality of service among these distributed applications we use OnTimeMeasure, platform as a service.

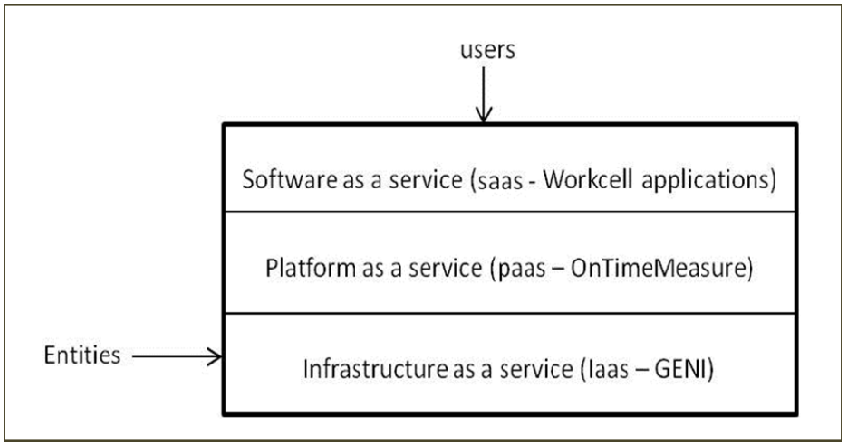

Figure.26 Architecture of micro assembly work cell in cloud

To the users of the application, we are delivering it as software as a service. Work Flow over duration of time is shown in Figure 26, where each step in the workflow is generating the data like simulation in VR or actually physical work cell assembly video. Sharing these videos are accomplished using Virtual Enterprise entities from web services (standard protocols) exchanging the workflow data. Each customer has a user portal, each vendor has vendor portal, and each entity has its instances of OnTimeMeasure. These instances are connected through the web services. User has the access to the webserver through user portal where he can either select automated or manual input assembly sequence to assemble the microns. At the end we are providing to one or many users the completed micro assembly operation in both virtual environment and physical environment.

OnTimeBeacon takes the input, coordinates with the node beacons, and accomplishes the assembly operations (Figure 27). OnTimeBeacon passes the user input to the Node1. Node1 generates different sequences based on Genetic Algorithm and sends each sequence to the Node2 for path avoiding collisions. The Path planning algorithm gives the complete path directing the gripper to pick and place the number of microns on user request. After finding the near optimal assembly sequence, Node1 sends it to the Node3 (physical work cell) for the final physical micro assembly.

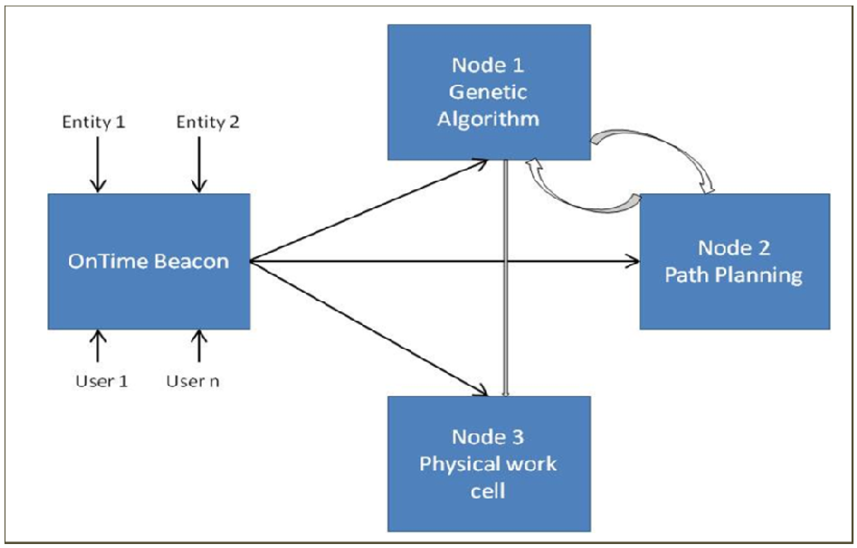

Figure.27 OnTimeBeacon interaction with the Node beacons

The next step is hosting our applications on GENI. We can create one slice for all the entities of organizations, one slice for developing applications. Each of these needs a computer; and one extra computer that act like a web server where all the users have their user portals. Web server will talk to other entities, orchestrate with all the working staff regarding the web services. Another web portal is used for entity collaboration data. To run each portal we need an apache server and we have feasibility to run multiple apache servers. All the systems are available in the GENI cloud. Multiple users can access their user portals to see the videos and operations while one user is active gives input to the system.

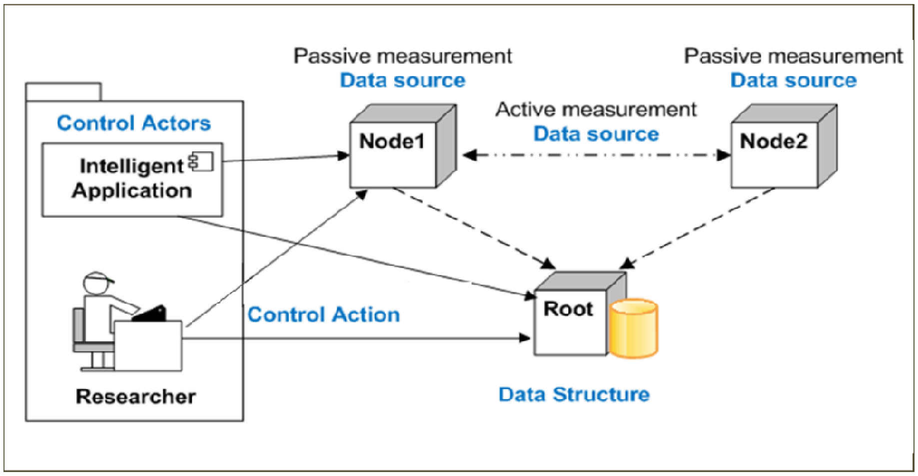

Figure.28 OnTimeMeasure "Custom Metric Integration" Feature Primitives [from 33]

Data Sources: Assembly plan generated by the user. User also has the option to select automatic assembly plan generated by assembly plan generator. Assembly plan details include sequences and 3D path plan includes assembly time.

Data Structure/Types: Different types of grippers (Stainless, Stainless diamond coated, Titanium) were used in this approach to gather the performance results of the gripping techniques of each one. User has the option of interacting with different types of part designs (L block 2D/3D, Square block, Step block).

Control Actors: Engineers at each site access the micro assembly simulation videos or share the videos with other engineers.

Control Actions: They relate to actor controls such as start/stop of the measurement results, querying the measurement results. It also helps in analyzing the performance results and makes necessary modifications to the configuration of the resources that increases the scalability.

- Starts the measurement
- Stops the measurement
- Transfer the video to each location at the specified transfer rate

- Obtain the data from other control actions

Each user slice has the experiment data (life cycle). Multiple runs of the experiment with different assembly plans give the near optimal solutions. OnTimeMeasure provides prototype information to the user and based on the user feedback it make appropriate changes to the number of users allocated with resources. This process will be going on throughout the simulation sharing process till the user requirements are satisfied. OnTimeMeasure optimizes the overall process as it takes the feedback from the user measures, analyze the results, and reconfigure the process without human intervention. This improves the performance of the results and reducing the cost involved in the manufacturing process. We can request and control the service. After the configuration is completed, we can query the results.

At any point of time only one of the user will be active who can interact with the distributed resources, generate assembly plans while the other users can be passive. Users get the slice of the resources, in addition, each user can input an assembly plan and can compare with the other users assembly plan. Genetic Algorithms approach is used in the assembly sequence. The near optimal plan is selected and feedback is obtained from the experiment. In this way, engineers from different backgrounds at different locations can participate in the design phase of the micro devices assembly and evaluate the performance virtually.

4.4 Conclusion

A brief introduction on cloud computing, GENI, OTM is outlined in this chapter. Use of OTM in the cyber physical environment is discussed. RICE was used in this setup that enables the performance of the simulation and physical videos shared across different users. RICE uses OTM measurements and adapts Human Aware Networking principles to improve the performance and scalability.

CHAPTER V

SIMULATION AND RESULTS

5.1 Introduction

The simulation of the virtual environment was implemented using VRScape (3D Graphics Tool kit) based on Python. Implementation of Genetic and Dijkstra's algorithms performed using Python. The simulation of user interface is clearly described in the below section with screenshots. The simulation and results are divided into five sections

1. User Interface
2. Genetic Algorithms
3. BFS and Dijkstra's Algorithm
4. Virtual Environment for work cell
5. OnTimeMeasure

5.2.1 User Interface

The user must give the input in the text file before the VIRAM-2 simulation starts. For each part design (rectangle, L block 2D, L block3D), the user can give up to four assembly sequence inputs using the user input assembly sequence option (see fig 29b). In this way, the user will have more options of selecting the input files when running the simulations. For user input assembly sequences the sample text files have been named as L block 2D input1.txt/input2.txt/input3.txt/input4.txt. Figure 29d shows the representation of the text files as c1, c2, c3, c4. If the user is planning to give his/her input sequence, then the user should manually go to the directory consisting the user input assembly sequences text files and enter the 3D coordinates of the assembly sequences. This step is mandatory before the start of the simulation if users want to test their own assembly sequences. If there is no input received by the user, then simulation will function only for the available automated assembly sequences.

We will be discussing 2 examples which demonstrate the user interface created in VIRAM-2 and the subsequent outputs from the CPF.

Assembly Example 1

In this example, a L block with 3 pins is being assembled. The initial block (before assembly) is shown in figure 29a. The final assembly block in the virtual environment is shown in figure 29l.

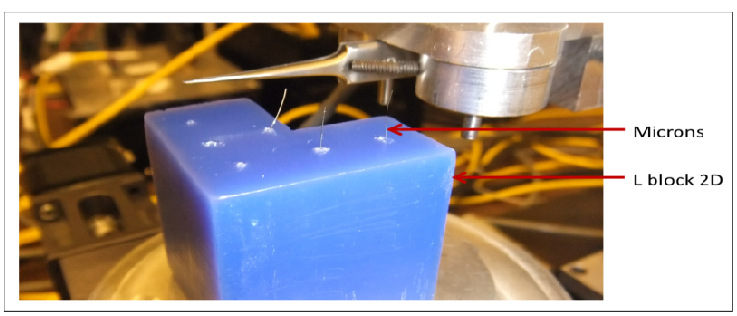

Figure.29a Physical L block 2D before assembly

The following screenshots of the virtual reality environment describe the steps involved in user interface.

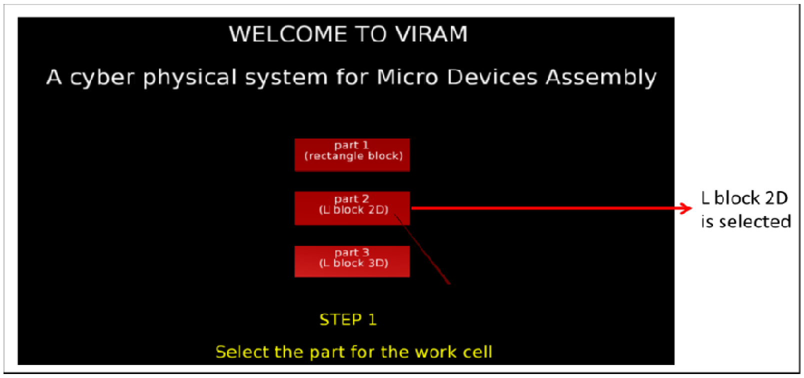

Figure.29b Welcome screen for selection of part design

Step1: Simulation of the assembly pins on three types of part designs can be simulated in VIRAM-2: "Rectangle block, L block 2D and L block 3D."

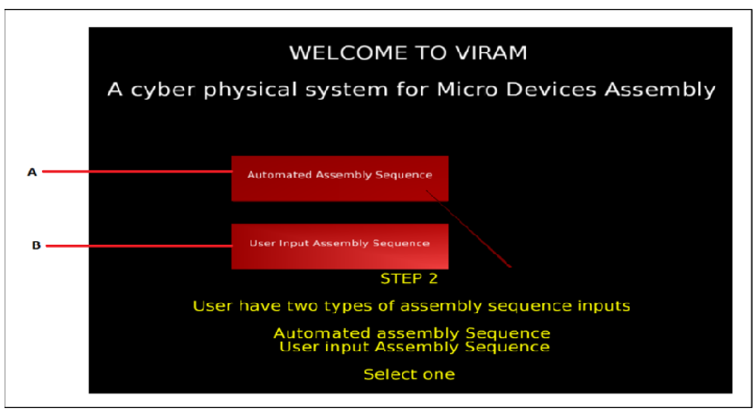

Figure.29c Selection of assembly sequence type

Step 2: Upon selection of the part type, corresponding assembly sequences are displayed. The user can select either "automated assembly sequence" (see A in fig 29c) generated by the assembly plan generation module or an "user input assembly sequence" (see B in fig 29c) can be specified through a text file.

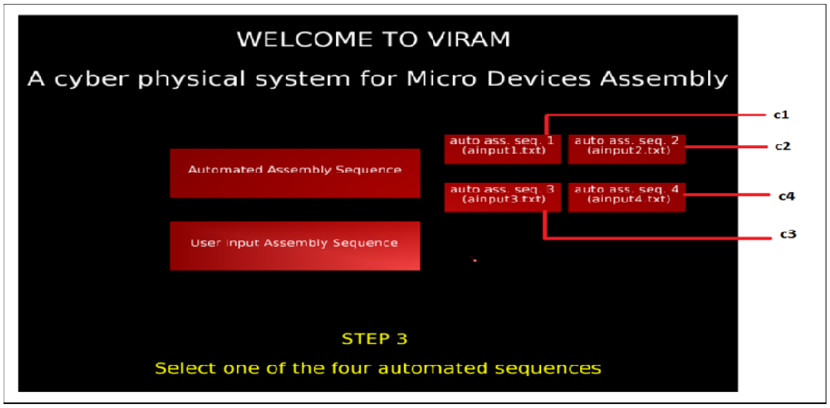

Figure.29d Selection of input text file

Step 3: In step 1, the user can select the part design (rectangle, L block 2D, L block 3D). The input files for these 3 configurations can be modified by selecting the 4 GUI options indicated by "c1, c2, c3, c4" (figure 29d). The user input assembly sequence takes the input through a text file. The user must give the input in the text file before the VIRAM-2 simulation starts. An example for input text file is shown in figure 9.

Figure.29e Interface to run the Genetic Algorithm

Step 4: The user's selection is then displayed. The user can then click on "Run GA" to start the execution of Genetic Algorithm based module. This algorithm finds the near optimal sequence to assemble the pins in the possible shortest path. The assembly plan is also sent to the Path Planning module to determine the final path that avoids the collisions.

```
Original sequence given by the user

[0.0,-0.015,0.21],[-0.037,-0.04,0.21]
[0.040,0.002,0.21],[0.003,-0.04,0.21]
[0.040,0.040,0.21],[0.040, -0.04, 0.21]

A->1
B->2
C->3

Final sequence generated using GA

[[0.040, 0.040, 0.21], [0.040, -0.040, 0.21]]
[[0.040, 0.002, 0.21], [0.003, -0.040, 0.21]]
[[0.0, -0.015, 0.21], [-0.037, -0.040, 0.21]]

C->3
B->2
A->1
```

Figure.29f Output of Assembly Sequence after the execution of GA

The original 3D sequence given by the user is represented using source (alphabets) -> destinations (numbers). The original sequence is shown in the above figure 29f. Once the execution of GA completes, the final micro assembly sequence is shown in 3D coordinates along with source -> destination format (as seen in figure 29f).

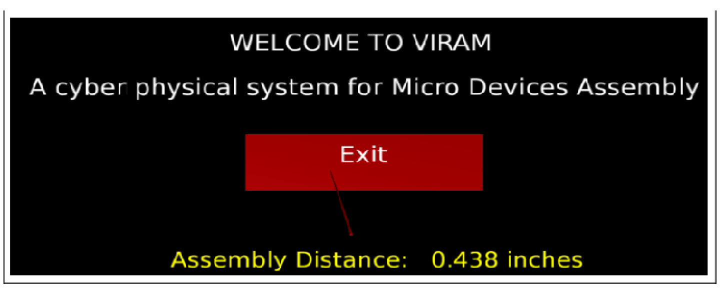

Figure.29g Output of Assembly Distance after the execution of GA

Step 5: Then, the assembly distance of the assembly plan selected is displayed in fig 29g. If the users want to start the simulation again, they can go back to step 1 and repeat the steps to see the performance of the algorithms. Clicking on "exit" will close the user selection window.

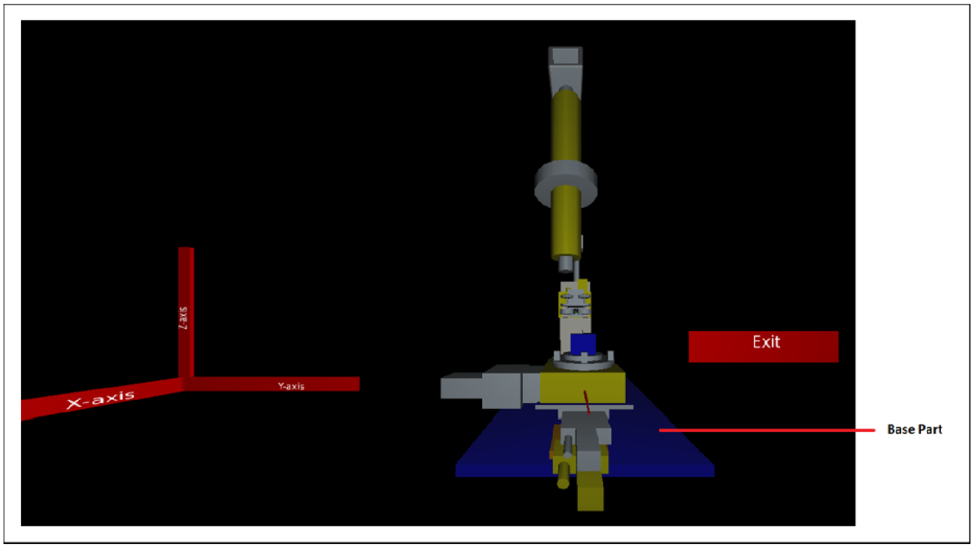

Figure.29h Virtual Environment of the work cell

Step 6: To start the simulation, the user should click on the base part of the work cell (see in fig 29h). User can navigate in the Virtual environment in all the possible directions that cannot be accomplished in the physical world and see the assembly operations in detail. Figure 29i(a) represents the source/start positions of the microns in the assembly area before the start of the simulation. After the simulation executes the target micron devices are placed in the destination locations (as specified by the user). This can be seen in fig 29i(b).

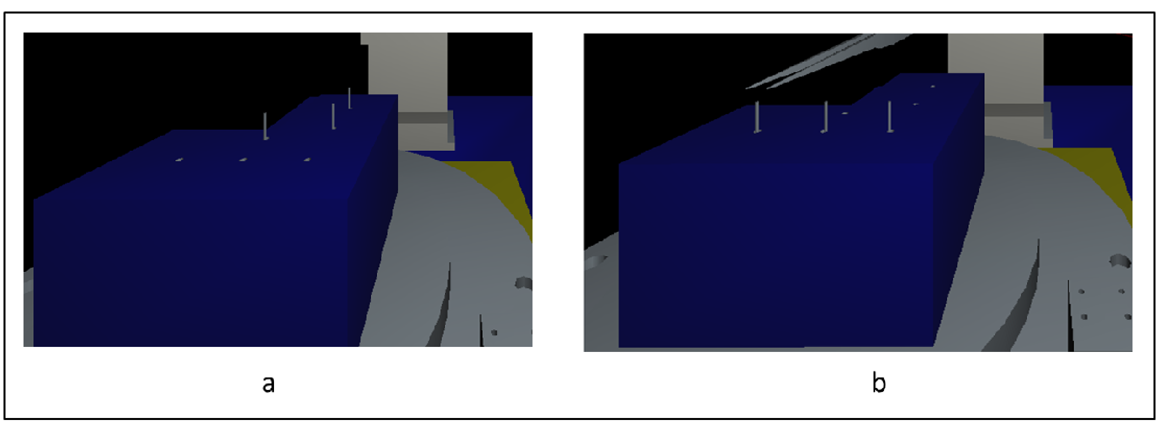

Figure.29i (a) Microns position at start of assembly (b) Microns position after the assembly is completed

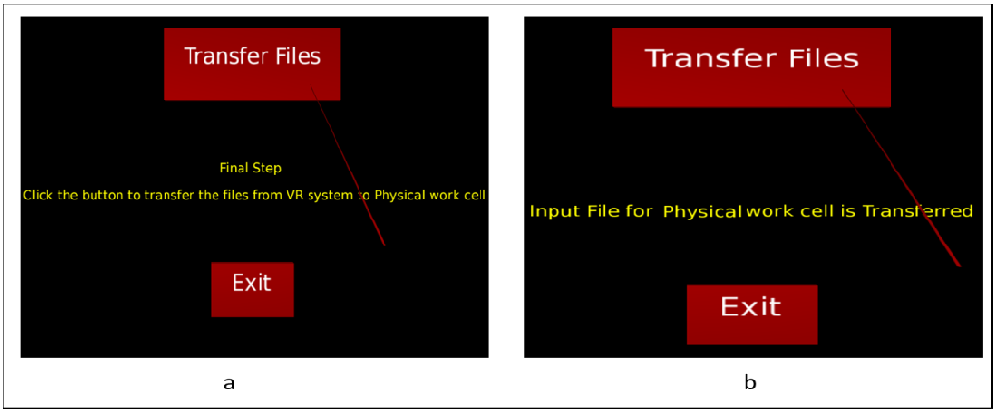

Figure.29j (a) Interface to transfer the files from VIRAM-2 to Physical (b) Success of transferring files

Step 7: After the completion of simulation, if the user is satisfied with the plan, they can click on the "Transfer Files" GUI button to transfer the assembly path from the virtual to the physical environment (Fig 29j (a) & (b)).

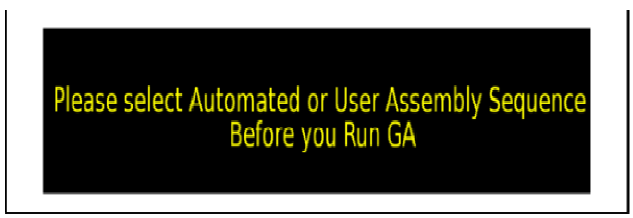

Figure.29k Error message to guide the user

If a wrong GUI box is selected, then the corresponding error messages are displayed to guide the user. The physically assembled micro device is shown in fig 23l.

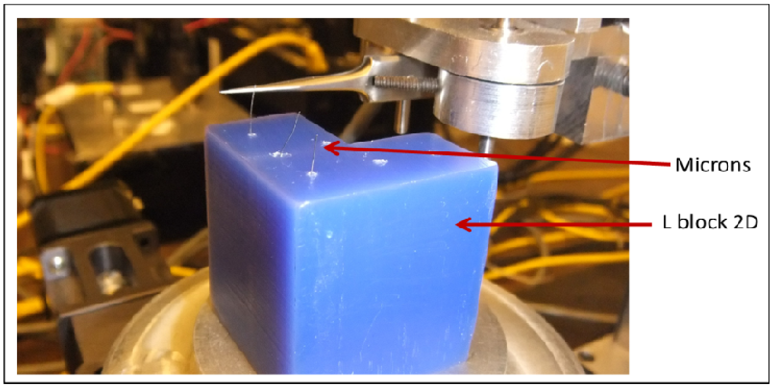

Figure.29l Physical L block 2D after assembly

Assemble Example 2

This second example is for a different target micro assembly design, L block 3D for 5 pin micro assembly sequence. The initial block (before assembly) is shown in figure 30a. The final assembly block in the virtual environment is shown in figure 30j.

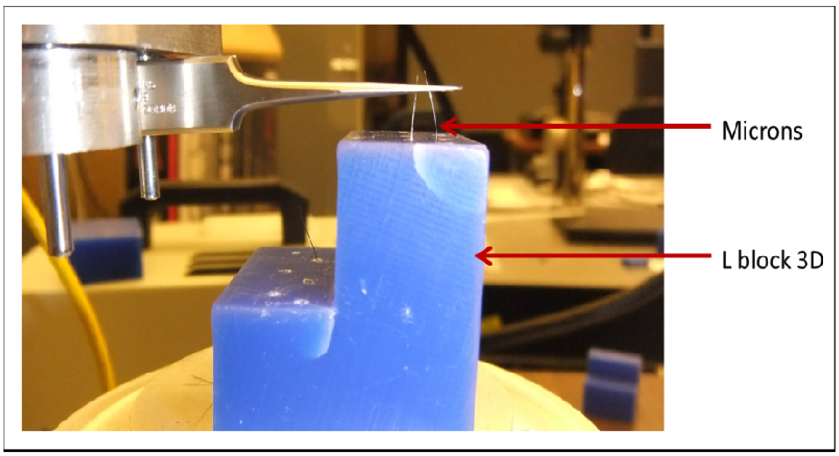

Figure.30a Physical L block 3D before assembly

The following screenshots of the virtual reality environment describe the steps involved in user interface. The main screen shots are shown below.

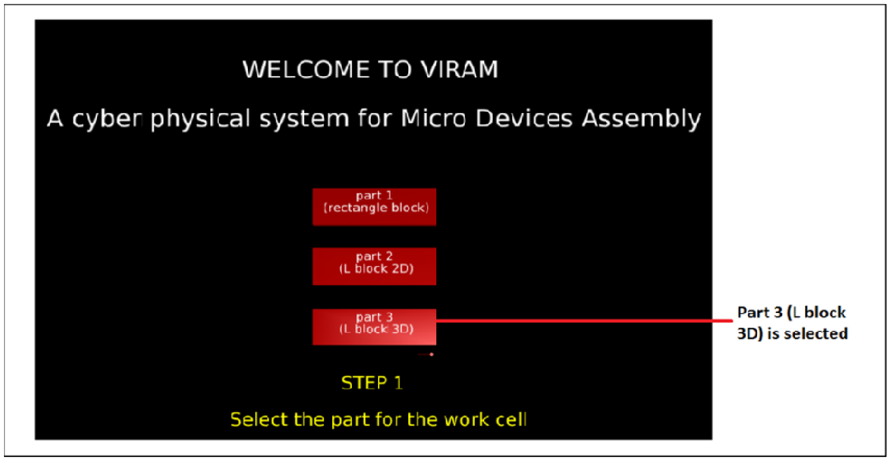

Figure.30b Welcome screen for selection of part design

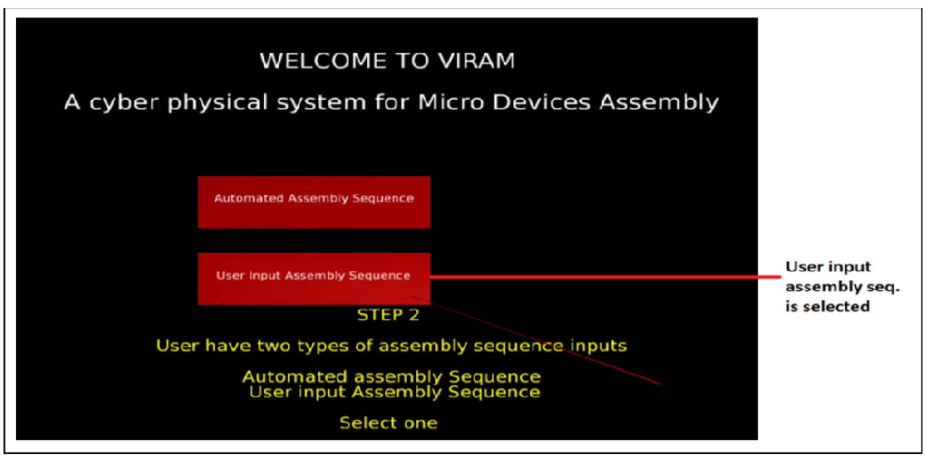

Figure.30c Selection of assembly sequence type

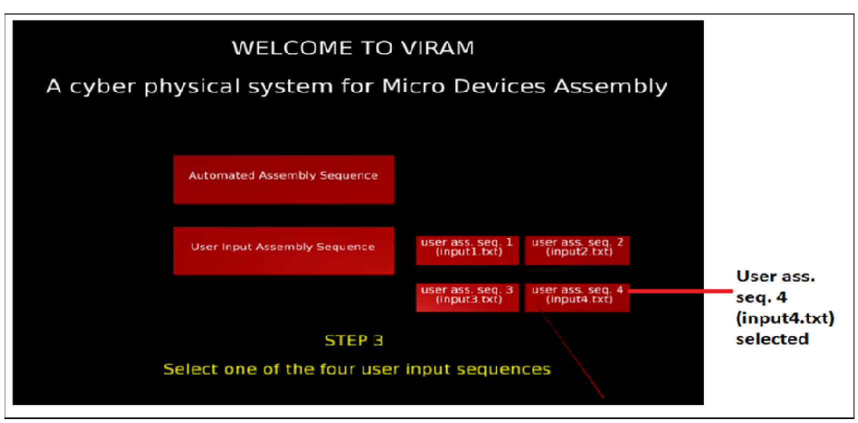

Figure.30d Selection of input text file

Figure.30e Interface to run the Genetic Algorithm

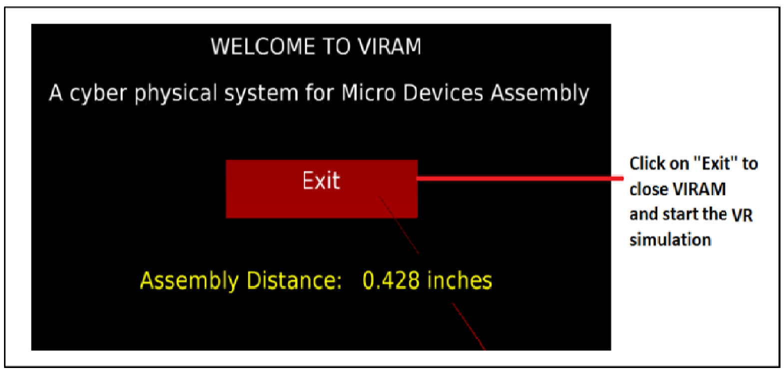

Figure.30f output of Assembly Distance after the execution of GA

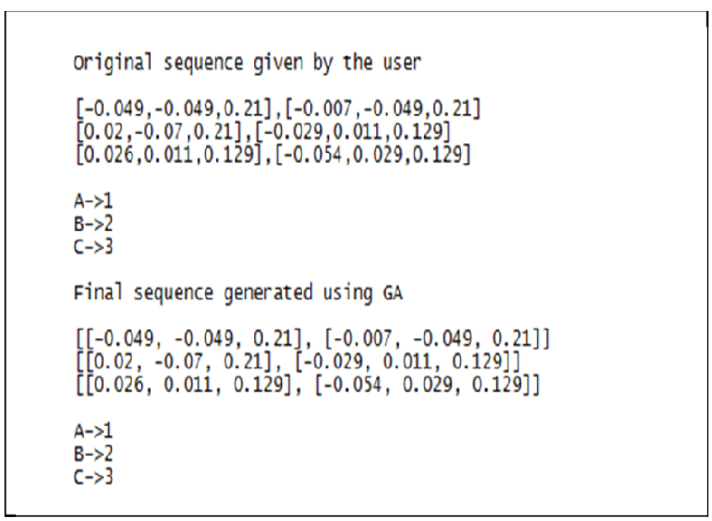

Figure.30g output of Assembly Sequence after the execution of GA

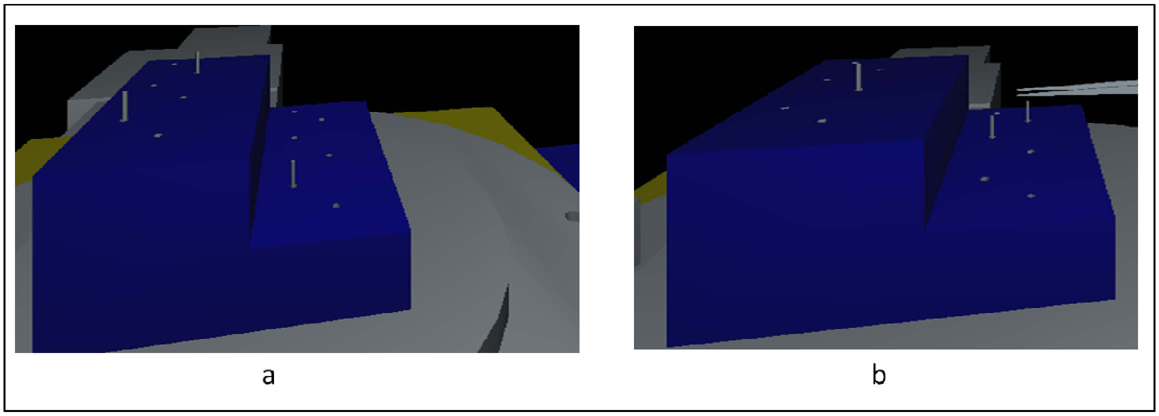

Figure.30h (a) Microns position at start of assembly (b) Microns position after the assembly is completed

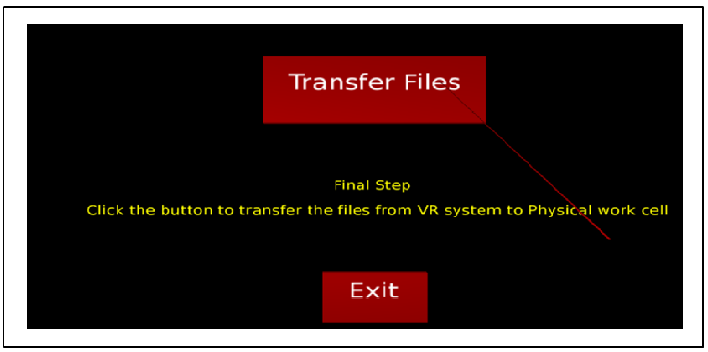

Figure.30i Interface to transfer the files from VIRAM-2 to Physical world

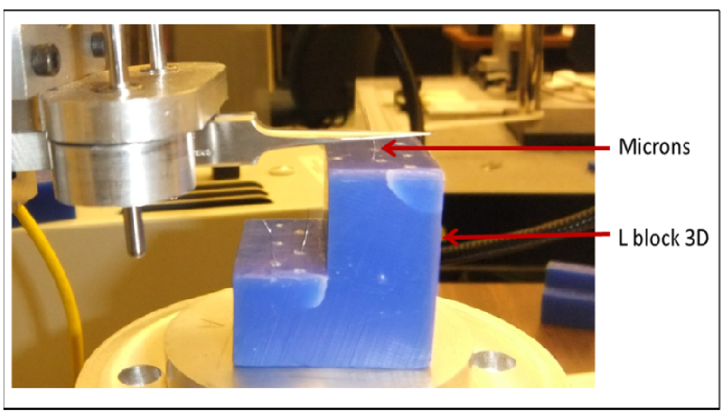

Figure.30j Physical L block 3D after assembly

5.2.2 Genetic Algorithm and Virtual Environment

We will be discussing 2 complex examples to demonstrate the Genetic Algorithm and virtual environment. The simulation outputs and GA's final assembly sequences are discussed here.

Simulation Example 1:

Figure 31a shows the layout of the work cell assembly area before the assembly. Figure 31b shows the completed simulation with the pins in their destination. Here an assembly of 20 pins for a Square block is considered.

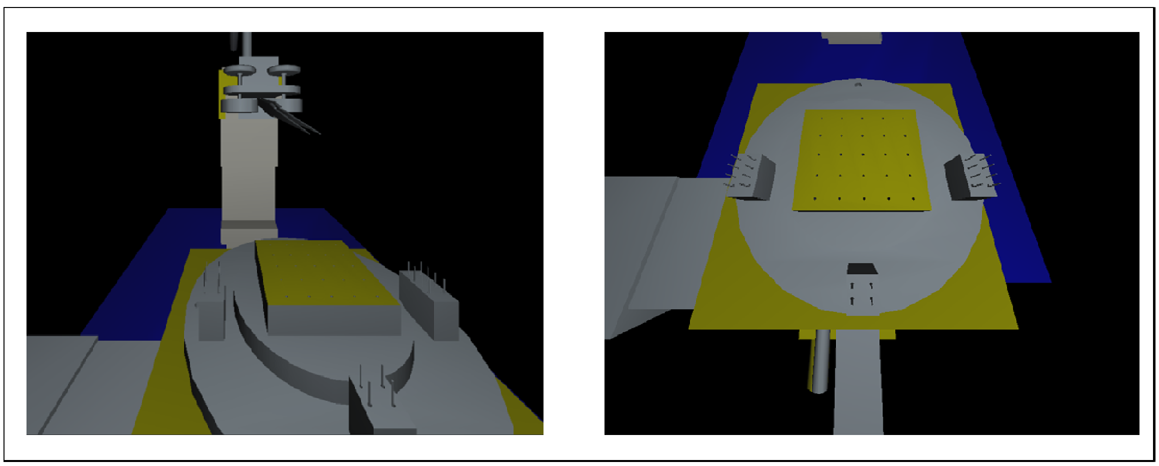

Figure.31a Start of the work cell assembly plan in the Virtual Environment

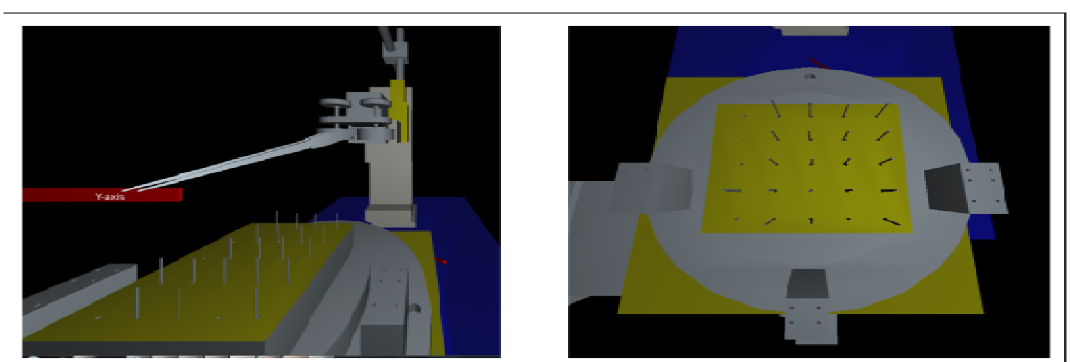

Figure.31b Completion of Work cell Assembly in the virtual environment

The GA output of user selected assembly sequence is shown in figure 31c. Here the user selected assembly sequence (3D coordinates) is represented as A->1 format. ‘A’ represents the source location of the micro device and 1 represents the destination location of the device. After the execution of GA completes, then the final assembly sequence generated by GA is also displayed in the similar format.

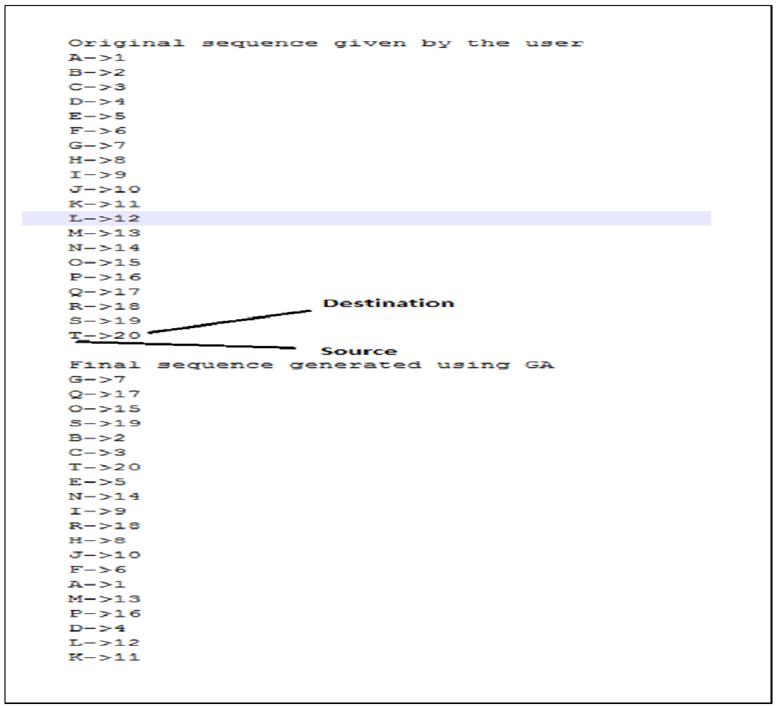

Figure.31c Final assembly sequence generated by GA

Simulation Example 2:

Figure 32a shows the layout of the work cell assembly area before the assembly. Figure 32b shows the completed simulation with the pins in their destination. Here an assembly of 20 pins for a Step block is considered.

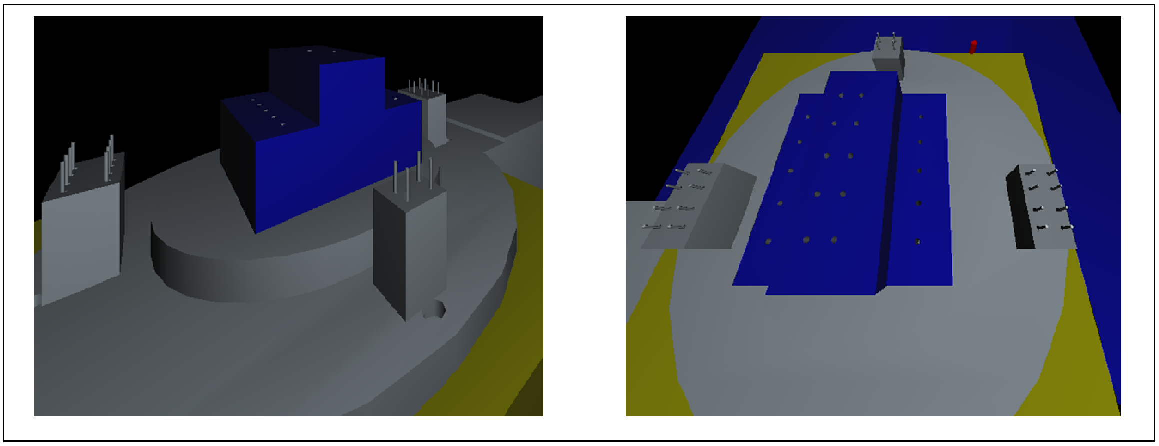

Figure.32a Start of the work cell assembly plan in the Virtual Environment

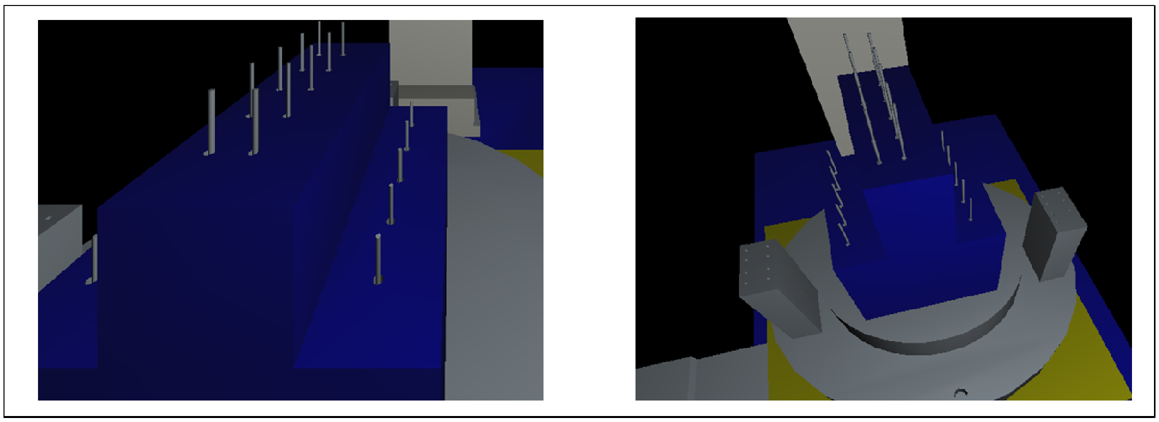

Figure.32b Completion of Work cell Assembly in the Virtual Environment

The GA output of user selected assembly sequence is shown in figure 32c. Here the user selected assembly sequence (3D coordinates) is represented as A->1 format. ‘A’ represents the source location of the micro device and 1 represents the destination location of the device. After the execution of GA completes, then the final assembly sequence generated by GA is also displayed in the similar format.

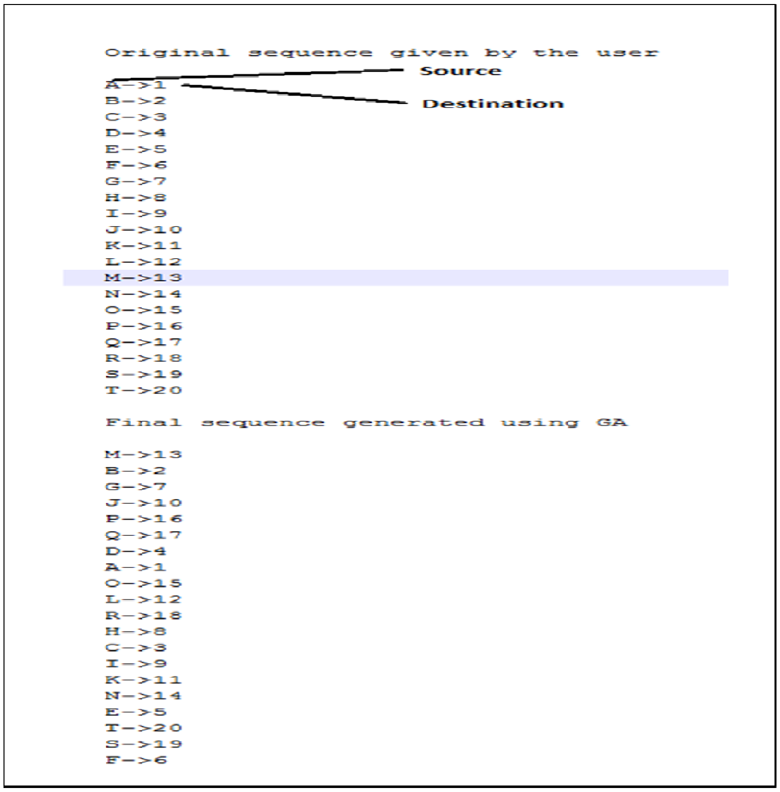

Figure.32c Final assembly sequence generated by GA

Assembly Constraints

If the precedence constraints are included in the program, then to find the near optimal solution using GA for 20 pins took 20 minutes (9804 iterations). On the other hand, without precedence constraints it took 15 (5023 iterations) minutes to find the near optimal solution. The total number of iterations considered for this program is a maximum of 1 Million.

In this algorithm, there are different approaches possible based on the mutation/crossover and selection of parent sequences in each iteration. Here five cases are considered and results are shown.

Option 1: In each iteration GA selects the existing sequences, applies mutation and crossover to generate new sequences. The percentage of mutation and crossover can be varied. This is represented as ratio between the crossover and mutation (C/M). The ratio of C/M 0.7 represents crossover selection is 70% and mutation selection is 30%.

Option 2: In each iteration GA selection of parents can be varied. If the selection is based on only the best sequences, the probability of falling into local minima is seen here. If there are 2n sequences rather than selecting the best n parents, first choose n * k best sequences and the remaining sequences are selected randomly. This reduces the chances of falling into local minima. The value of k is changed for different conditions and results are presented here. The ratio of best vs. random parents is represented as B/R. The B/R 0.8 represents parents with best fitness are selected for 80% and the remaining 20% parents are randomly selected.

X axis - the number of iterations,

Y axis - the assembly distance values (fitness)

Test Case 1: B/R – 0.85, C/M – 0.9

85 % of the best parent sequences are selected as the child sequences and 15% are randomly selected. Crossover is used to generate 90% of new sequences and mutation is used 10%. The best assembly distance is 147.29 at 23,324 iteration. The minimum iterations for every search to find the best assembly distance is beyond 20,000.

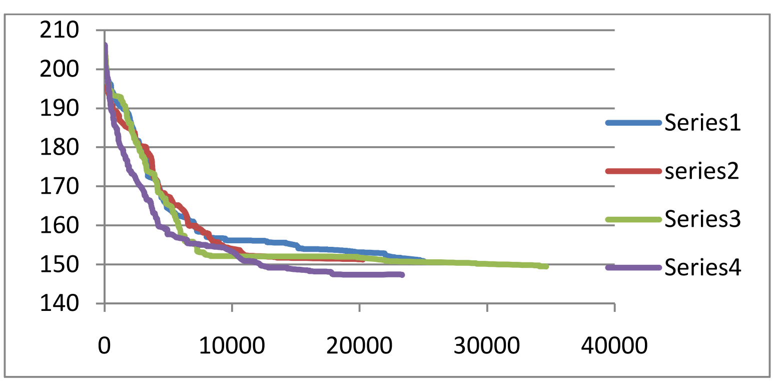

Figure.33a B/R – 0.85, C/M – 0.9

Test Case 2: B/R – 0.7, C/M – 0.7

The decrement of best parent sequences selection to 70% increases the probability of finding more new child sequences eliminating the local minima problem. The results show that the best assembly distance is 144.02 and the iterations in finding the best sequences are minimized to 10,000 – 24,000.

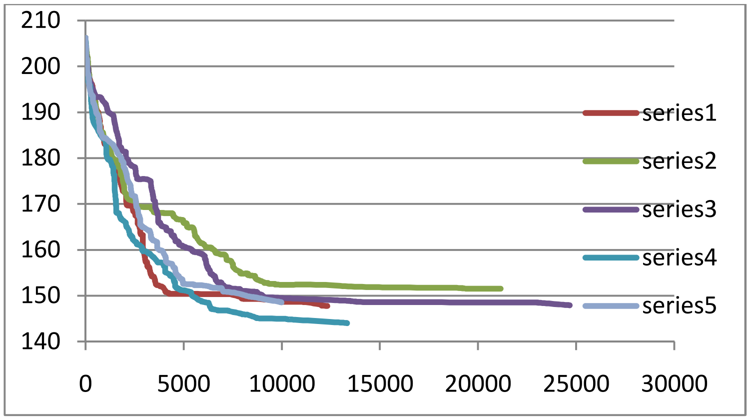

Figure.33b B/R – 0.7, C/M – 0.7

Test Case 3: B/M – 0.5, C/M – 0.9

The best parent sequence selection is 50% and remaining 50% of the sequences are selected randomly from the pool of existing sequences. Crossover is applied for 90% of the parents. If the ratio of C/M is high, the probability of finding new best sequences is also high. The reduction of B value to 0.5 results in the enormous increase of the iterations needed to find the best sequences. The iteration range is from 25,000-78,000.

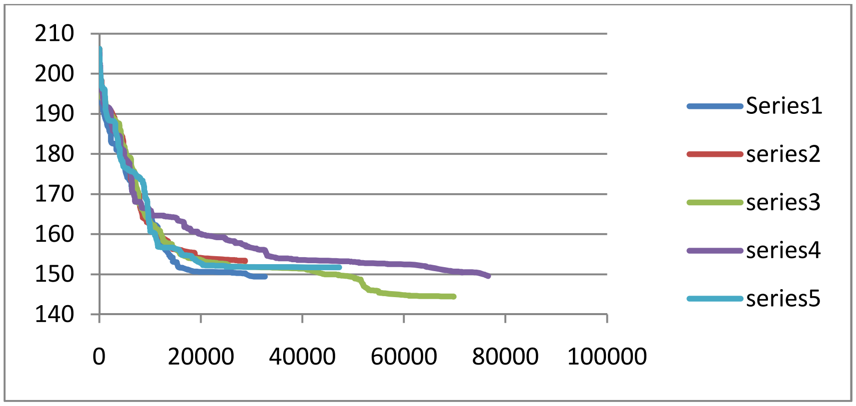

Figure.33c B/R – 0.5, C/M – 0.9

Test Case 4: B/M – 0.75, C/M – 0.85

The best parent sequence selection is 75% and remaining 25% of the sequences are selected randomly from the pool of existing sequences. Crossover is applied for 85% of the parents. The combination of this B/M and C/M values produced the best sequences with very less number of iterations ranging in 9000-24000. The assembly distances found are less than 150 and the best assembly distance is 144.91 found at 18981.

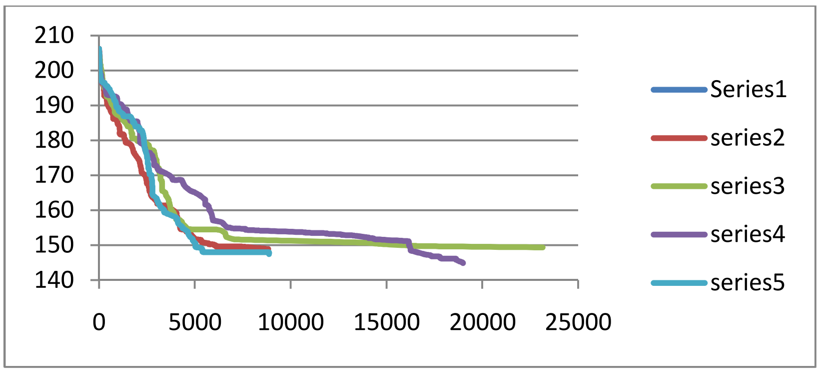

Figure.33d B/R – 0.75, C/M – 0.85

Test Case 5: B/M – 0.5, C/M – 0.7

The decrement in the values of B/M and C/M to 0.5 and 0.7respectively shows that the GA did not find the best assembly distance that is seen in other test cases. The iterations required to find the minimum assembly distance is average 15000 – 35000.

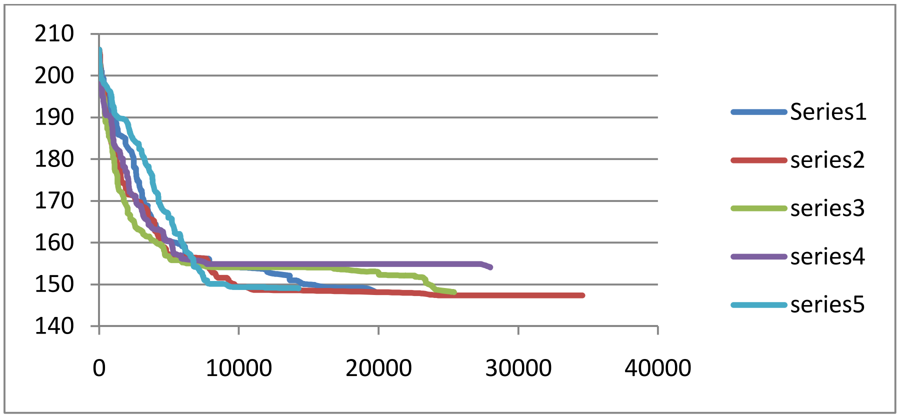

Figure.33e B/R – 0.5, C/M – 0.7

From the above results, test case 2 and 4 show better performance in finding the least assembly distance and the required iterations are less than other cases. The B/M value in between 0.7 and 0.8 and the C/M value range is 0.7-0.9 produces the best results.

5.2.3 Path Plan

The assembly area from the top view is shown in the figure 34. There are three feeders (A, B, and C) and a destination block at the center. The assembly plan gives the details of pins movement from feeders to the destination block. The input from the user is obtained through an external file as shown in figure 9.

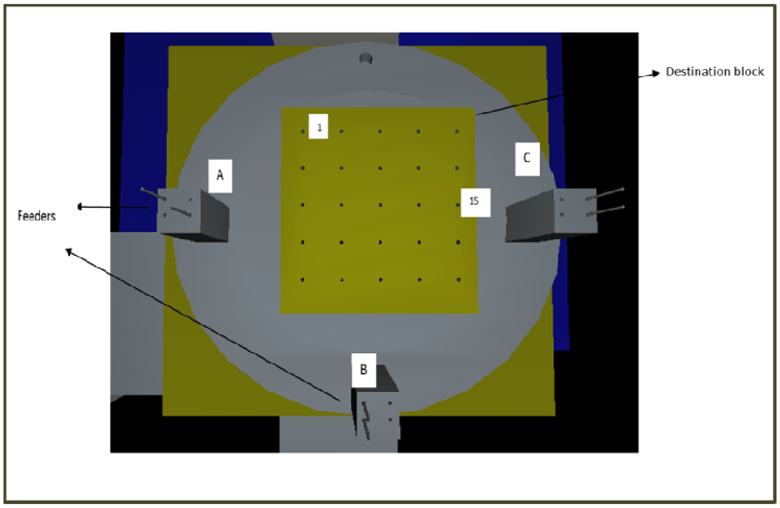

Figure.34 Assembly Area from the top view

Test Case 1: The complete assembly area is divided into a floor map depending on the size of the micron as in fig 35. Source is node 1 (X) and the destination is node 203 (Y). All the obstacles are colored in blue (202, 102, and 103). Here the distances between the nodes are equal, so the path would be 1->2->3->4->104->204->203. As the distances between the nodes are equal it can be considered as an implementation of Breadth First Search algorithm.

6401					6500
301	302	303			
201	202	203			
101	102	103			
1	2	3	....	99	100

Figure.35 Path Planning Layout of Assembly Area

Test Case 2: Here the assembly area is divided into a floor map as explained before. But in this case the distance between two nodes are different. The distance between two nodes is represented in red color. The source is node 1 and the destination is node 103. If the distances are equal then the path would be B1->B2->B3->B103 of length 4. The number B1 or Bn represents the 1st or nth block in the Figure 36.

Path 1: B1 (0) -> B2 (4) -> B3 (9) -> B4 (15)

Path 2: B1 (0) -> B2 (4) -> B102 (8) -> B4 (13)

Path 3: B1 (0) -> B101 (1) -> B102 (10) -> B103 (15)

Path 4: B1 (0) -> B101 (1) -> B201 (2) -> B301 (3) -> B302 (5) -> B303 (8) -> B203 (9) -> B103 (10)

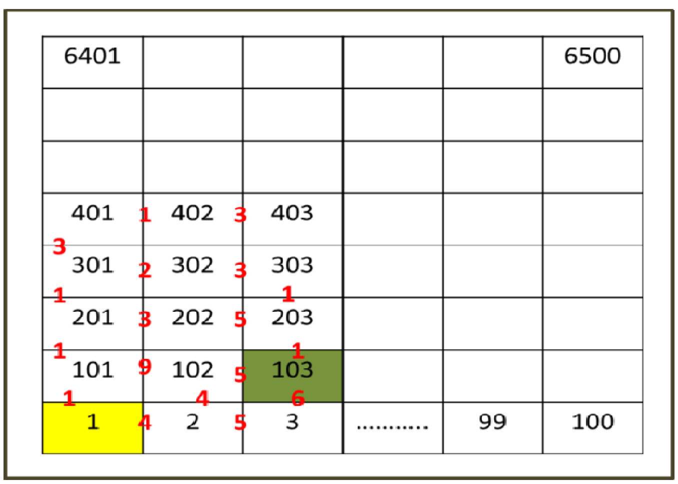

Figure.36 Path Planning Layout of Assembly Area with varying distance between cells

The distance between the nodes are varied due to the obstacles present in-between them. The best path is path 4 of distance 10.

Dimension of block size: The total assembly area is 4*4 units. The hole on block is of 0.01 units that is used to place the pin. So the assembly area is divided by 400 in both length and breadth wise such that each in the figure 36 represents 0.01 units. In this implementation the tests are performed only for this block size. The variations of the block size is out of scope of this paper.

Implementation of this approach is performed using python. The results are shown in figure 37. The array indicated as “before” in fig 37 represents the blocks/obstacles in the floor map.

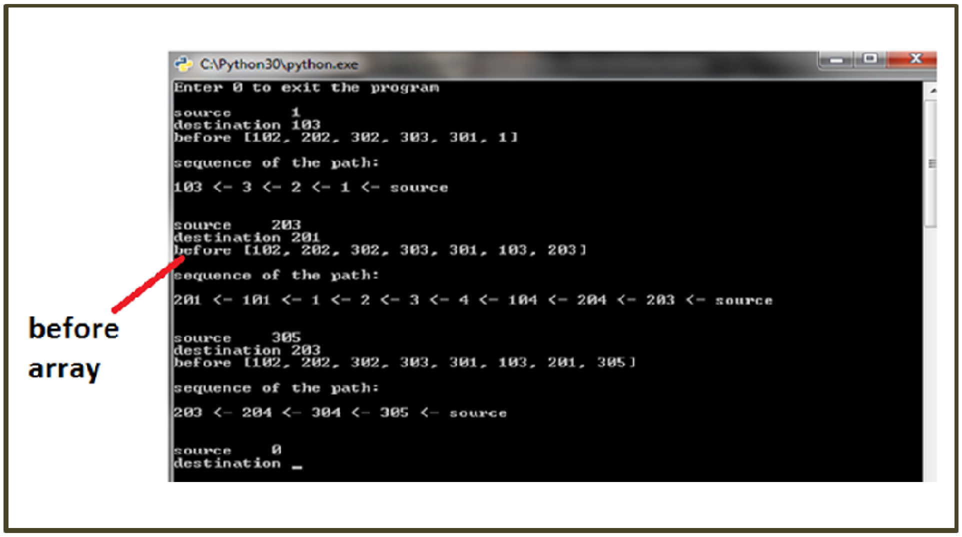

Figure.37 Execution of Path Plan module

5.2.4 Cloud Computing

OnTimeMeasure (OTM) supports the measurement services to the distributed systems in this approach. OnTimeMeasure analyzes and derives measurements that can be used in the video sharing applications that improve the performance. Fig 38(a) &(b) shows the round trip delay measurement results that are collected using OTM before and after the start of the experiment. User can clearly see the variations in the round trip delay and change the encodings of the video being sharing across the systems. These timely measurements improve the performance better than UltraVNC. Fig 39(a) & (b) shows the throughput measurements collected using OTM.

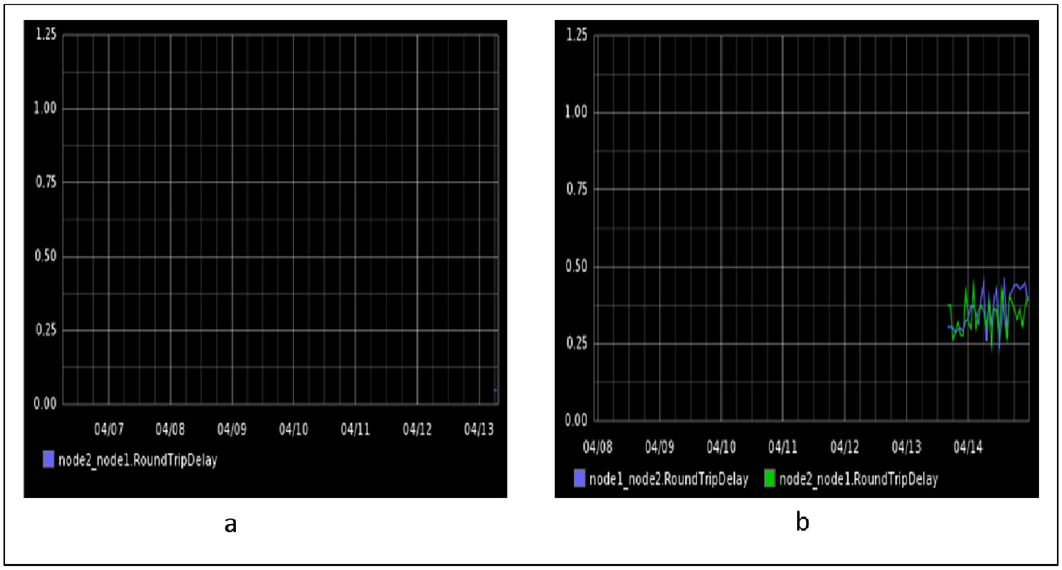

Figure.38(a) Round Trip Delay collected using ontimeair before the simulation (b) Round Trip Delay collected using ontimeair while simluation is being shared

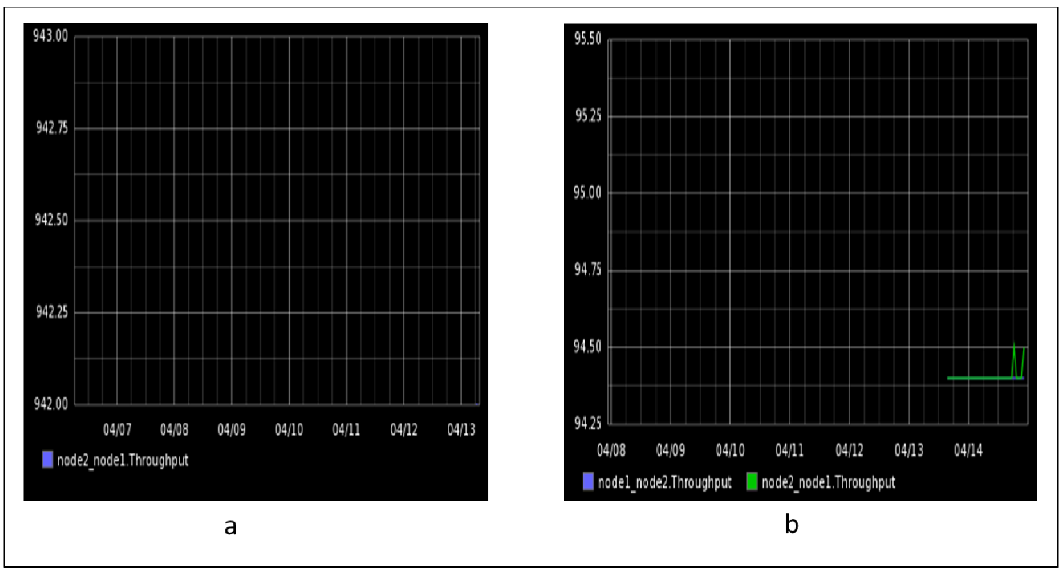

Figure.39(a) Throughput collected using ontimeair before the simulation (b) Throughput collected using ontimeair while simluation is being shared

5.3 Conclusion

In this chapter, several examples involving use of VIRAM-2 is discussed. Two examples of user interaction with the virtual environment are outlined here. Numerous test cases are performed on Genetic algorithms and best cases are selected in the final implementation of the algorithm. BFS algorithm is implemented to avoid collisions in the path plan. Virtual environment results are shown in fig 31a (before the simulation started) and 31b (after the simulation ends). Measurement results queried by the OTM are shown in cloud computing section.

CHAPTER V

CONCLUSION

5.1 Introduction

In this thesis, a Cyber Physical Framework (CPF) is developed to support rapid assembly of micro devices using virtual environments. Section 5.2 summarizes this thesis research; section 5.3 outlines the limitations of this work. In section 5.4, the scope and future research extensions are discussed. Section 5.5 concludes this chapter.

5.2 Summary

An innovative approach Cyber Physical Framework (CPF) is proposed for the domain of micro devices assembly. This CPF is the first cyber physical environment developed in the entire world for the domain of micro assembly. This CPF enables collaborative use of the distributed resources (including assembly planning, path planning, simulation resources as well as physical equipment). Genetic Algorithms is used in the assembly plan generation module and the path planning module uses BFS algorithm to generate feasible paths. The physical micro assembly work cell consists of a micro gripper, 3 linear positioners (3 Degrees of freedom), an assembly plate, illumination lights, camera mounted on the top of work cell, and a computer is connected to the work cell. Cloud computing enables the use of remote servers hosted on the internet to store our software modules and business applications.

These applications are managed and the data is processed on the cloud network rather than a local server. OnTimeMeasure is a measurement service for the GENI users. OTM provides measurement results on network path monitoring, network weather forecasting, network performance anomaly detection. In this thesis, OTM was used to improve Quality of Experience (QoE) of users/ engineers geographically located sharing the simulation and physical assembly videos using measurement results. Simulations and results on the use of these various resources are discussed in the next chapter. The setup of OnTimeMeasure was tested on the computers located at Oklahoma State University and Emulab (GENI).

Remote users can access the CPF and find out if a sample micro design can be assembled using virtual resources and if necessary subsequently a prototype can be physically assembled. This is a benefit of using CPF with cloud computing technology.

5.3 Limitations and Future Research

5.3.1 GA based approach

Assembly sequence can only be generated using GAs. Other methods have not been incorporated. Future research can develop other algorithms for assembly sequence generation.

5.3.2 Interfaces

The input interface was text file based and does not automatically extract 3D information of target assembly from CAD file. Future research can consider more complex micro designs as well as develop a more advanced user interface which can read CAD files of target micro designs.

5.3.3 Physical Assembly Scope

The physical work cell used in this CPF was used to demonstrate micro devices assembly for a maximum of 6 pins. Future research can expand the scope of the assembly capabilities. The

Cyber Physical Framework approach can be extended from a single work cell to an advanced factory. In this factory, several work cells can be considered which collaborate to assemble the target micron sized parts. Conveyors between work cells can be used to move the parts around the factory. Other extensions to this thesis research can include camera feedback to control the MDA tasks.

5.3.4 Use of Cloud Computing

In this thesis research, the physical MDA resources used are not distributed across different locations but are only in one location (OSU). Future research can demonstrate the feasibility of cloud computing in the context of distributed physical work cells.

5.4 Conclusion

In this chapter, a brief introduction of the thesis research is outlined. The limitations of the thesis research methodology along with possible future research extensions are also discussed.

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VITA

RAVITEJA GUNDA

Candidate for the Degree of

Master of Science

Thesis: DESIGN OF A CYBER PHYSICAL FRAMEWORK FOR THE ASSEMBLY OF MICRO DEVICES

Major Field: Computer Science

Biographical:

Education:

Received the Master of Science in Computer Science at Oklahoma State University, Stillwater, Oklahoma in May, 2012.

Received the Bachelor of Science in Computer Science and Information Technology at JNTU, Hyderabad, AP/India in 2009.

Professional Experience:
Jan 2011 – May 2012: Graduate Research Assistant, Center for Information based Bioengineering and Manufacturing (CINBM) Stillwater, Oklahoma (this has been renamed Center for Information Centric Engineering CICE). Responsibilities included: Design of Information centric framework involving cyber architectures and virtual reality simulations; Simulation based assembly analysis for Micro Devices domain. Proficiency in creating immersive Virtual Reality environments using Coin 3D (C++), Cavelib and VRScape (Python) graphical tool kits.

Name: RAVITEJA GUNDA Date of Degree: May, 2012

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: DESIGN OF A CYBER PHYSICAL FRAMEWORK FOR THE ASSEMBLY OF MICRO DEVICES

Pages in Study: 80 Candidate for the Degree of Master of Science

Major Field: Computer Science

Scope and Method of Study: Micro Devices Assembly (MDA) is an emerging domain with a significant economic potential. Existing methods for assembly of micro devices are tedious and costly. For this reason, it is important to develop a collaborative framework for the field of MDA. In this thesis, a Cyber Physical Framework (CPF) is proposed to support a collaborative approach using software and physical resources for rapid assembly of micro devices in a distributed environment. CPF adopts the cloud computing principles to improve the Quality of Experience (QoE) of users accessing the simulation videos and physical assembly videos. The cloud computing principle enables the distributed engineers/users to access the cyber physical resources from various locations.

Findings and Conclusions: An innovative approach Cyber Physical Framework has been developed. A Genetic Algorithm based approach is used in the assembly plan generation. A virtual reality based simulation environment has been developed as part of this CPF. The feasibility of Cloud computing approaches in this Cyber Physical Framework was successfully demonstrated.

ADVISER'S APPROVAL: Dr. J. Cecil