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An Industry 4.0 Cyber-Physical Framework for Micro Devices Assembly

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Abstract— **An advanced cyber manufacturing framework to support the collaborative assembly of micro devices is presented based on Industry 4.0 principles. The distributed cyber and physical components work together to plan, assemble and monitor micro assembly related tasks; micro assembly refers to the assembly of micron sized devices which cannot be manufactured by MEMS technologies. The collaborative framework proposed includes assembly planning and path planning modules, Virtual Reality based assembly simulation environments and physical assembly work cells. An ontology based approach was implemented to address semantic interoperability issues to support formation of temporary partnerships in a Virtual Enterprise context. The key to the design and implementation of this complex framework is an information centric process modeling approach which provides a data/information oriented basis for collaboration. A collaborative cyber physical test bed has been built to demonstrate feasibility of proposed framework and approach.**

I. Introduction

In today's global manufacturing contexts, the growing importance of adopting information centric approaches to support distributed collaborative manufacturing needs to be recognized. One such initiative which emphasizes information centric manufacturing principles is Industry 4.0. [1]. The four principles underlying Industry 4.0 include (i) information transparency (ii) communication relating to Internet-of-Things (IoT) concepts (iii) adoption of cyber physical systems principles, and (iv) autonomy in decision making [2]. The importance of integrating data/information 'hooks' as part of next generation cyber approaches supporting autonomous is reflected in the overarching themes of Industry 4.0 [1-14].

In this paper, an advanced collaborative framework to support planning, simulation and assembly of micro devices is presented. It has been developed in the context of Industry 4.0 along with incorporating key principles and practices relevant to involving Cyber-Physical Systems (CPS) and Internet of Things (IoT). A set of cyber and physical components collaborate using Next Generation networking technologies to accomplish a life-cycle of tasks resulting in the assembly of a target micro parts. Data and information exchange among these components play a key role in supporting this cyber physical life-cycle. As the various activities progress, they are monitored and communicated to the relevant software entities through cloud-based infrastructure. Cameras monitor the assembly activities and provide feedback to distributed sites as the physical assembly tasks progress.

The potential of Cyber-Physical System (CPS) and Internet of Things (IoT) to facilitate the integration of distributed engineering activities needs to be acknowledged. CPS based approaches [3, 4, 15, 16, 25-27] involves software (cyber) entities and physical devices interacting, interfacing and collaborating with each other to provide a range of engineering, service or other functions. The adoption of IoT to support manufacturing is becoming increasingly popular; the term 'IoMT' has been proposed which refers to Internet of Manufacturing Things where data/information exchange plays a key role in collaborative planning, analysis and manufacturing tasks; in such contexts, seamless and easy to access data and information is central to various functional activities. These data exchanges can occur between a camera sensor in an automated work cell on the shop floor and a smart phone 'app' for monitoring or troubleshooting functions [17-19]; it should be noted that in medical contexts, IoMT also stands for Internet of Medical Things. Industry 4.0 frameworks supporting manufacturing integration can benefit by adopting CPS and IoT and CPS practices and technologies. In manufacturing, several research efforts have outlined conceptual models and frameworks involving IoT technologies [20-23] supporting factory automation. In [1], a 5-level architecture for CPS implementation was outlined including connection, conversion, cyber, cognition and configuration. In [3], a methodology is discussed addressing the cyber physical interfaces in the context of these five levels (from [2]) for a cyber-physical manufacturing system. Cloud based networking can provide improved access and lower maintenance costs [24].

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Simulation environments using Virtual Reality and Mixed Reality (VR/MR) technologies [28-32] have become an accepted part of manufacturing and engineering frameworks; their primary benefits are in enabling adopting of concurrent engineering principles including support of cross-functional analysis involving compare assembly and other manufacturing alternatives from downstream perspectives early in the engineering life-cycle. Other researchers have explored the role of Virtual Reality (VR) based environments to assist in the assembly of micro devices [33]. Probst et al. [34] discussed the use of a VR environment to assist in assembly of micron sized devices. Other researchers have used VR environments to guide micro assembly tasks [35], to identify problems during physical assembly [36] and to study interactive forces during assembly [37].

The Industry 4.0 based cyber physical framework for micro devices assembly (MDA) is the focus of this paper involving the use of VR based smart technologies and next generation networking principles. When a target micro design possesses complex shapes and composed of varying material properties, MicroElectroMechanicalSystems (MEMS) based approaches will not be able to manufacture them; in such contexts, MDA approaches are necessary. As MDA resources are limited and expensive (with only a limited number of manufacturing organizations having the expertise and resources to accomplish such manufacturing tasks), there is a need for collaboration and sharing of both cyber and physical resources using Industry 4.0 principles. In this paper, we focus on the design of the VR/AR environments and the adoption of an information centric design approach to support the monitoring of the distributed activities within the MDA life-cycle. The networking components of the framework have been discussed in previous papers [43, 45, 46]. The proposed approach has been implemented as one of the earliest cyber physical test beds; the underlying principles can be adopted for other manufacturing domains where there is a need for manufacturing partners to respond quickly to changing customer requirements using an array of cyber and physical resources and tools.

Earlier implementation for a limited functional scope of this cyber physical framework is discussed in [40, 43, 45-48]; in this current paper, detailed discussions of addressing semantic interoperability as well as the monitoring of cyber physical tasks is provided; further, this current implementation incorporates adoption of low cost VR platforms (such as the Vive). To the best of our knowledge, the approach discussed in this paper is the first Industry 4.0 based design and implementation of an advanced cyber physical approach supporting micro devices assembly. In this paper, an information centric modeling approach was adopted that was used as a functional basis to support the design of IoT / CPS based frameworks.

II. CREATION OF AN COLLABORATIVE TEST BED

Information Centric Modeling approaches were explored to facilitate software engineering principles; both engineering Enterprise Modeling Language (eEML) and IDEF-0 based approaches enabled the planning the design and implementation of the entire cyber physical system. The layout of the cyber physical framework is shown in Fig.1.

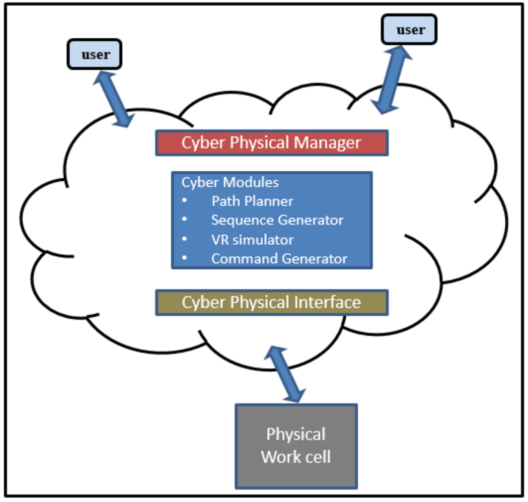

Figure 1. Layout of the CPS based framework

Creation of function models to design and build software systems have been explored in [41, 42]. The information centric approach involves a more extensive emphasis addressing three core elements revolving around modeling, simulation and exchange of information. The modeling facet focused on creating information rich process models which enabled planning as well as design of the overall IoT framework and approach. The simulation facet dealt with designing VR/Mixed Reality based approaches and environments to support collaborative planning and analysis of the micro assembly sequence and path planning generation tasks. The exchange facet addressed the network based data/information exchange using Next Generation Internet technologies as well as creating an ontology based approach to address semantic interoperability involving the cyber physical resources.

The complex process of tracking and updating the various activities in the cyber physical cycle was accomplished using process state charts. An eEML based information model was used as foundation to enable these monitoring activities. As shown in figure 2 (jn the yellow and blue boxes), the data/information inputs given to the physical work cells includes the physical controller commands for the various assembly steps. This included micro positioner movement commands, camera commands and gripper commands. As each command is completed or is in progress, this status information is sent to the cyber physical manager and communicated to the distributed components (at various sites). A higher level status update is also provided correlating to the tasks in Table 1.

TABLE I. TOP LEVEL STATUS OF CYBER-PHYSICAL INTERACTIONS

Top level Tasks	Status
Assembly Plan Generation	Completed
VR Simulation/Analysis	In Progress
Physical Command Generation	Not Started
Physical Assembly	Not Started

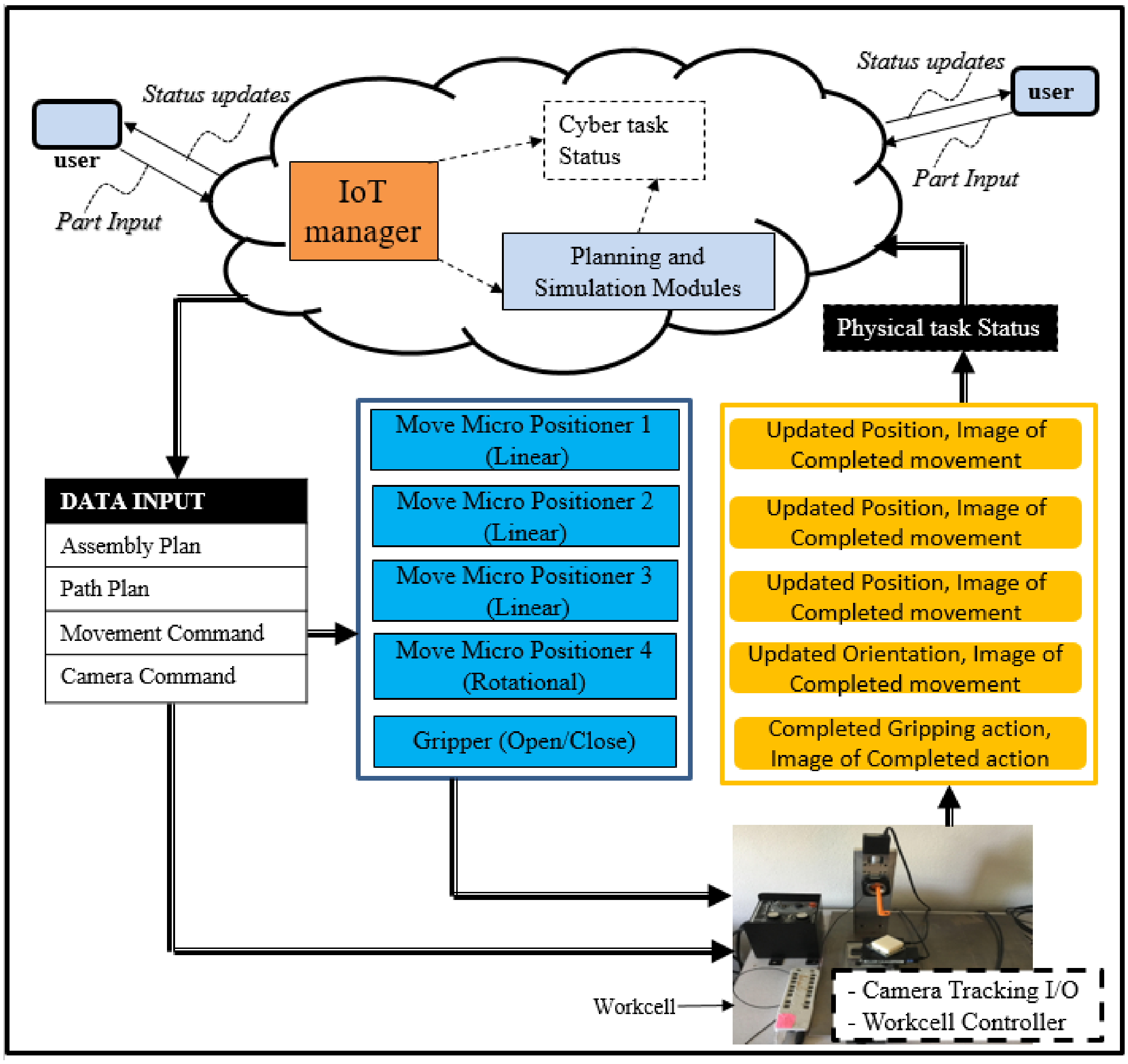

Figure 2. Data/information inputs and outputs in the IoT based Framework

III. THE ASSEMBLY GENERATION MODULES

To mimic a Virtual Enterprise (VE), where potential partners may have software modules based on diverse assembly planning approaches, we have implemented several assembly planning approaches in our Test Bed; the goal was to mimic a Virtual Enterprise context where various engineering organizations may be capable of generating assembly plans or sequences using their own approach; using the cloud based VR simulator, the feasibility of their assembly plan can be studied from different locations and the most feasible plan can be selected or modified. In the Test Bed, 3 approaches have been supported based on Genetic Algorithms (GA), Insertion Algorithms and Greedy Algorithm; in this paper, for brevity, we discuss only the GA based assembly planning approach.

A. GA based Assembly Planning

The GA based Assembly approach exploits a randomized search which tries to narrow down the search space by directing the search to better regions within the search space. GA is designed to mimic the natural survival of chromosomes in a critical environment where the fittest dominates the weak. In our approach, we create new children using two types of operators: mutation and crossover. The fitness score represents the distance involved by the assembly robot (during assembly) which involves picking up a target micro part from a feeder and inserting/placing it in a target location;

the chromosome in the GA is any feasible assembly sequence. Fig. 3 provides a summary of this GA based approach.

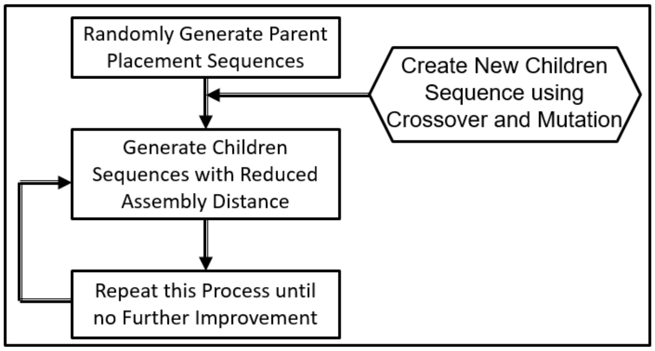

Figure 3. Flowchart of the main steps in the GA based approach

IV. THE VR ASSEMBLY ANALYSIS ENVIRONMENT

The advanced VR assembly simulation environment is at the core of this Industry 4.0 approach; it interfaces with the cyber planning functions (upstream) and then interfaces with the downstream physical micro assembly activities; the primary emphasis in the VR environment is to support analysis of the feasibility of an assembly plan taking into consideration process limitations and alternatives; the layout of the target assembly environment can be modified interactively; depending on the capabilities of the various micro assembly work cells, the type of gripper, the positions of the feeders and other details can be modified; various assembly sequences can also be studied and the most feasible can be identified by teams of engineers. The VR environments were built using Unity Game development software, which utilizes two programming languages C# and JavaScript.

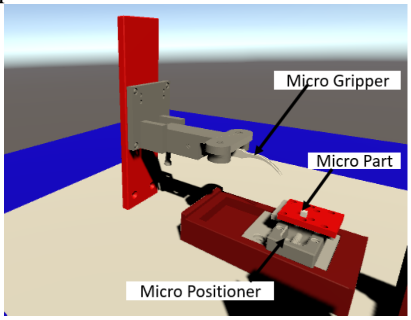

Figure 4. Assembly analysis supporting VR environment

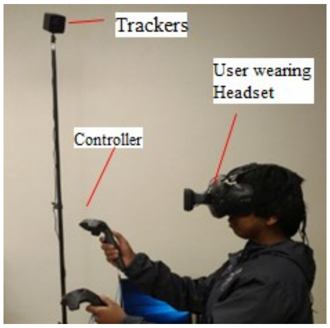

Figure 5. A user interacting with the Vive simulator

A fully-immersive VR environment has been created using the Vive platform (Fig. 4). The user can interactively modify the layout of the feeder trays, the grippers to be used, etc. within the VR environment. The assembly environment (in the simulation module) corresponds to the physical assembly work cell. This work cell is capable of assembling micro and meso scale parts from 10 microns to a few millimeters. It has an assembly plate with a rotational degree of freedom; the gripper is mounted on a column and is capable of moving vertically as well as can rotate around its own axis. The assembly plate can also move in two X and Y linear directions.

The Vive simulator (Fig 5) is equipped with trackers and sensors for easier interaction. In the assembly analysis environment, a candidate assembly plan can be virtually analyzed. Problems such as collisions are identified and modified accordingly. A validated assembly plan is used as a basis to generate physical commands that can be downloaded through the IoT framework (running on the cloud infrastructure) to a control computer linked to the physical Work cells. Through the VR environment, users are able to propose their own assembly plans and compare it with the automatically generated plan.

V. ADDRESSING SEMANTIC INTEROPERABILITY

This IoT based cyber-physical approach also addresses semantic interoperability issues in a Virtual Enterprise context involving formation of temporary partnerships in response to rapidly emerging engineering opportunities. When such temporary partnerships involving a diverse group of engineering partners and organization has to be formed, one of the major obstacles involves addressing semantic interoperability issues. In this framework, an ontology based approach was designed and implemented to demonstrate the feasibility of the proposed approach. Several organizations were considered to be engineering partners with various capabilities for each of the various cyber-physical activities in the life cycle including assembly planning, path planning, VR based simulation and physical assembly. The capabilities of each of the competing organizations my first published in a service directory using OWL-S. An ontology of the cyber-physical life cycle and related activities was built using OWL. For each of the Cyber physical activities based on the part design input, the engineering vendors were identified. For example, (in the context of assembly plan generation), potential assembly generation methods from competing engineering organizations can be studied along with associated costs and constraints before selecting a specific vendor or organization. Further, the sequences generated by competing vendors can be compared and studied using VR based environments. For the physical assembly activities based on the capabilities of the available manufacturing organizations, an appropriate partner can be selected. The appropriate manufacturer can be selected based on their capability to assemble a Target Micro Design. Subsequently the target Micro Design can be assembled using the cyber-physical framework and approach outlined earlier. Various micro and meso scale part designs for assembled demonstrate feasibility of this cyber-physical approach.

Based on this overall cyber physical approach, an assortment of micro-meso designs were assembled using the cyber and physical components discussed in this paper; meso scale refers to part sizes greater than 1 mm, with accuracies greater than 25 µm. Fig. 6 shows a view of the corresponding physical micro device assembly in progress.

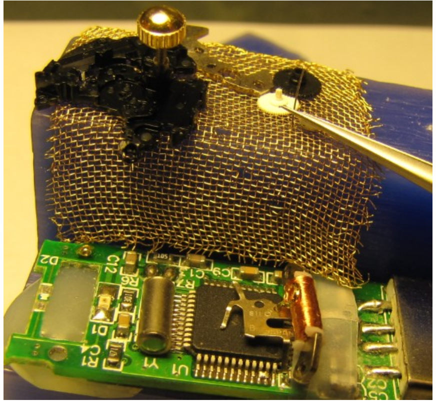

Figure 6. View of a Physical assembly in progress which is a counterpart of the virtual model shown in figure 6

The test bed demonstrated in this paper is proposed for MDA. However, the general principle behind this approach can be used in any other manufacturing field. The input and output data based interactions of the process flow were captured in Fig. 2. In order to ensure the implementation of the IoT testbed, multiple changes had to be implemented. The conversion of the simulation data into real world data which could be used by the robotic work cells was one of the initial problems faced during implementation. The limitation of physical assembly was another problem encountered. Moreover, the micron sized parts sticking to the grippers due to interactive forces coming into play during assembly was another major problem. Research involving minimizing the impact of Van der wall's and other forces during assembly is ongoing. A major issue was attempting to reduce the time involved in designing, building and ensuring correctness of the various approaches and algorithms encapsulated in the software modules developed as part of this IoT framework.

The demonstrations involving the successful implementation of the cyber physical test bed underscored the feasibility of such frameworks supported by cloud based infrastructure. The role of such next generation collaborative environments is highly signficant in today's global manufacturing domain. Such framework enables cross functional, interdisciplinary and distributed engineering teams to accomplish engineering activities in an agile manner. Such an Industry 4.0 approach will allow manufacturing organizations to adopt the IoT based cyber physical practices. The approach will enable them to respond to changing customer requirements using distributed cyber and physical resources. Such information centric approaches have been explored to design other collaborative frameworks in domains such as telemedicine involving training simulators for orthopedic surgery [39].

VI. CONCLUSION

An advanced Industry 4.0 cyber physical framework to assemble micro devices was discussed in this paper. The field of micro devices assembly is an emerging process domain which requires collaboration of distributed resources including cyber and physical components. The engineering life cycle included assembly planning, VR based simulation, command generation and physical assembly of target micro components. A semantic based approach was also implemented to enable addressing semantic interoperability issues involving multiple organizations coming together to respond to emerging manufacturing opportunities. A Cyber Physical Manager was used to coordinate the overall task activities along with a cloud of resources which hosted the cyber components for the engineering activities. Several demonstrations involving assembly of target micro designs were completed to demonstrate feasibility of the overall approach, which can be also adopted for other manufacturing domains [43].

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