An Internet of Things (IoT) Based Cyber Physical Framework for Advanced Manufacturing

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Abstract. This paper outlines an IoT based collaborative framework which provides a foundation for cyber physical interactions and collaborations for advanced manufacturing domains; the domain of interest is the assembly of micro devices. The design of this collaborative framework is discussed in the context of IoT networks, cloud computing as well as the emerging Next Internet which is the focus of recent initiatives in the US, EU and other countries. A discussion of some of the key cyber physical resources and modules is outlined followed by a discussion of the implementation and validation of this framework.

Keywords: IoT, cyber physical framework, advanced manufacturing

1 Introduction

The term **Internet of Things** (**IoT**) is becoming popular in the context of the on-going IT revolution which has created a greater awareness of emerging and smart technologies as well as phenomenal interest in IT based products in the world community. IoT can be described as the network of physical objects or "things" embedded with electronics, software, sensors and connectivity to enable it to achieve greater value and service by exchanging data with the manufacturer, operator and/or other connected devices [1]. In a nutshell, IoT refers to the *complex network of software and physical entities* which are embedded or implemented within sensors, smart phones, tables, computers, electronic products as well as other devices which have software elements to perform computing or non-computing activities. These *entities* are the '*things*' referred to in the term 'Internet of Things' which are expected to be capable of collaborating with other similar entities as part of the Internet and other cyber infrastructure at various levels of abstraction and network connectivity. The underlying assumption is that by interacting with each other, a large range of services can be provided using this network of collaborations. This subsequently enables these entities to provide greater value to customers and collaborating organizations.

Example of *things* are weather monitoring sensors, heart monitors, monitoring cameras in a manufacturing work cell in a factory, safety devices in a chemical processing plant, advanced home cooking equipment, etc. There are many risks and benefits to embracing such a vision. The benefits lie in being able to form collaborative partnerships to respond in a more agile manner to changing customer preferences while being able to seamless exchange data, information and knowledge at various levels of abstraction. Such an emphasis on adoption of IoT principles can also set in motion the realization of advanced next generation Cyber Physical relationships and frameworks which can enable software tools to control and accomplish various mundane as well as advanced physical activities.

In our IoT framework, we have explored the use of cloud principles to support information and data exchange among IoT devices and software modules. Cloud based technologies are becoming the focus of many industrial implementations [2-6]. In [7], a computing and service oriented model for cloud based manufacturing is outlined. Three categories of users are described including providers, the operators and consumers. Some of the benefits for cloud based manufacturing identified in [6] include reducing up-front investments, reduced infrastructure costs, and reduced maintenance and upgrade costs. In [5], the potential of cloud computing is underscored in transforming the traditional manufacturing business model and creating intelligent factory networks that support collaboration. A service oriented system based on cloud computing principles is also outlined for manufacturing contexts [5, 6, 8, 17].

2 Benefits of IoT based frameworks and emergence of the Next Internet

In an IoT context, one of the core benefits is from the cyber physical interactions which help facilitate changes in the physical world. The plethora of smart devices emerging in the market serves as a catalyst for this next revolution which will greatly impact manufacturing and manufacturing practices globally. Imagine being able to design, simulate and build a customized product from a location hundreds or thousands of kilometers away from engineering and software resources, manufacturing facilities or an engineering organization. Today, using cloud technologies and thin clients such as smart phones and smart watches, the potential of using such IoT principles and technologies for advanced manufacturing is very high. Such cyber physical approaches also support an agile strategy which can enable organizations functioning as Virtual Enterprise partners to respond to changing customer requirements and produce a range of manufactured goods. With the help of advanced computer networks, such cyber (or software) resources and tools can be integrated with physical resources including manufacturing equipment. Thin clients, sensors, cameras, tablets and cell phones can be linked to computers, networks and a much larger set of resources which can collaborate in an integrated manner to accomplish engineering and manufacturing activities. When customer requirements change, such an approach can also help interfacing and integrating with a variety of distributed physical equipment whose capabilities can meet the engineering requirements based on the changing product design. Against this backdrop, it is important to also underscore recent efforts to develop the next generation of Internets.

In the US, the Global Environment for Network Innovations (GENI) is a National Science Foundation led initiative focuses on the design of the next generation of Internets including the deployment of software designed networks (SDN) and cloud based technologies. GENI can also be viewed as a virtual laboratory at the frontiers of network science and engineering for exploring Future Internet architectures and applications at-scale. In the context of advanced manufacturing (such as micro assembly [16]), such networks will enable distributed VE partners to exchange high bandwidth graphic rich data (such as the simulation of assembly alternatives, design of process layouts, analysis of potential assembly problems as well as monitoring the physical accomplishment of target assembly plans). In the European Union (EU) and Japan (as well as other countries), similar initiatives have also been initiated; in the EU, the Future Internet Research and Experimentation Initiative (FIRE) is investigating and experimentally validating highly innovative ideas for new networking and service paradigms (http://www.ict-fire.eu/home.html). Another important initiative is the US Ignite (http://us-ignite.org/) which seeks to foster the creation of next-generation Internet applications that provide transformative public benefit using ultrafast high gigabit networks. Manufacturing is among the six US national priority areas (others include transportation and education).Both these initiatives herald the emergence of the next generation computing frameworks which in turn have set in motion the next Information Centric revolution in a wide range of industrial domains from engineering to public transport. These applications along with the cyber technologies are expected to impact global practices in a phenomenal manner.

GENI and FIRE Next Generation technologies adopt software defined networking (SDN) principles, which not only reduces the complexity seen in today's networks, but also helps Cloud service providers host millions of virtual networks without the need for common separation isolation methods such as VLAN [13]. SDN also enables the management of network services from a central management tool by virtualizing physical network connectivity into logical network connectivity [13]. As research in the design of the next generation Internets evolves, such cyber physical frameworks will become more commonplace. Initiatives such as GENI and US Ignite are beginning to focus on such next generation computer networking technologies which hold the potential to radically change the face of advanced manufacturing and engineering (among other domains).

3 Overview of IoT based Cyber Physical Framework

IoT entities and devices will greatly benefit from the evolution of Cyber Physical approaches, systems and technologies. The term ‘cyber’ can refers to a software entity embedded in a thin client or smart device. A cyber physical system can be viewed as an advanced collaborative collection of both software and physical entities which share data, information and knowledge to achieve a function (which can be technical, service or social in nature). In a process engineering context, such cyber physical systems can be viewed as an emerging trend where software tools can interface or interact with physical devices to accomplish a variety of activities ranging from sensing, monitoring to advanced assembly and manufacturing. In today’s network oriented technology context, such software tools and resources can interact with physical components through local area networks or through the ubiquitous Word Wide Web (or the Internet). With the advent of the Next Generation Internet(s), the potential of adopting cyber physical technologies and frameworks for a range of process has increased phenomenally.

In the context of manufacturing, collaborations within an IoT context can be realized using various networking technologies including cloud based computing. According to the National Institute of Science and Technology (NIST), Cloud computing can be viewed as a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (including networks, storage, services and servers) [9]; the computing resources can be rapidly provisioned with reduced or minimal management effort or interaction with service providers. Some of the benefits for cloud based manufacturing include reducing up-front investments and lower entry cost (for small businesses), reduced infrastructure costs, and reduced maintenance and upgrade costs [10]. In [11], Tao et al discussed the context of Internet of Things (IoT) and Cloud Computing (CC) which hold the potential to providing new methods for intelligent connections and efficient sharing of resources. They proposed a service system which consists of CC and IOT based Cloud Manufacturing.

The IoT based framework outlined in this paper was part of one US Ignite project dealing with advanced manufacturing and cyber physical frameworks [12]. The manufacturing domain of interest is the assembly of extremely tiny micron sized devices. This is one of the first projects involving Digital Manufacturing, cyber physical frameworks and the emerging Next Generation Internet (being built as part of the GENI initiatives).

The preliminary implementation of this IoT framework has been completed in the form of a collaborative Cyber Physical Test Bed whose long term goal is to enable globally distributed software and manufacturing resources to be accessed from different locations and used to accomplish a complex set of life cycle activities including design analysis, assembly planning, simulation and finally assembly of micro devices. The presence of ultra-fast high gigabit networks enables the exchange of high definition graphics (in the Virtual Reality based simulation environments) and the camera monitoring data (of the various complex micro manipulation and assembly tasks by advanced robots and controllers). Engineers from different locations interact more effectively when using such Virtual Assembly Analysis environments and comparing assembly and gripping alternatives prior to physical assembly.

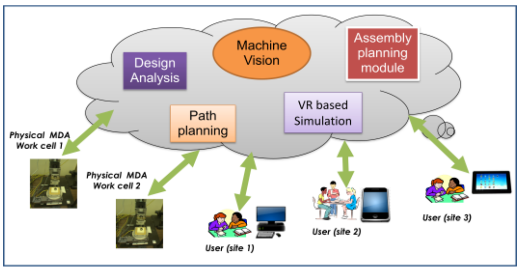


Fig. 1. The IoT based cyber physical test bed **Fig. 2**. The Virtual Assembly Environment

The resources of the cyber physical system (CPS) using cloud technologies are illustrated in figure 1. The users in different locations can access the CPS modules/resources through thin clients and IoT devices including tablets, cell phones, work cells, computers, and other thin clients. Thin clients refer to devices with less processing power that relies on the server to perform the data processing [14]. In this IoT based cyber physical frameworks, engineers can collaborate from geographically distributed locations and share resources as part of an agile collaboration process; they can interact with CPS resources using computers and/or thin client such as smart phones and tablets.The main cyber physical tasks were modeled using Extended Enterprise Modeling Language (eEML) shown Figure 3. The overall 'mini' life cycle activities in this cyber physical collaboration includes obtaining target micro design, generating assembly plan, developing path plan for assembly,performing assembly simulation and analyze using VR, assembling micro device and updating WIP/ assembly outcomes. The resources in this Cyber Physical implementation include the following (figure 1): assembly / path planning modules, VR based simulation environments (to analyze assembly/path plans, etc.), assembly command generators, machine vision based sensors/cameras (for guiding, monitoring physical assembly) and physical micro assembly equipment (to assemble the target micro designs). An overview of some of these resources is provided in the following sections.

Assembly Planning: The assembly planning module aims at determining the optimal assembly sequence to be completed by the micro gripper using various cyber physical resources for the assembly of micro devices. The outcome of the assembly plan generated is input to the Virtual Reality based assembly simulation environment. The Greedy Algorithm (GRA) is used to generate near optimal assembly sequences for the assembly planning module. Typically, a GRA seeks to make a locally optimal choice that looks best (at that current state) which help identify a nearly optimal global solution; this is the origin of the term 'greedy' in the context of a GRA. The key steps of such an algorithm are summarized below for the assembly of micro:

1. Initialize the distance d (i, j) between any point (i) and point (j) where i, j $\in \{0, 1, 2 \ldots n\}$.
2. Find the point (k) which is the shortest distance to Home Point (0); then the total distance T (0, n) = d (0, k) + T (k, n).
3. Next, we need to find the solution of sub-problem total distance T (k, n). Find the point (m) which is the shortest distance to Point (k); then sub-problem total distance T (k, n) = d (k, m) + T (m, n).
4. Likewise, we can get the solution of sub-problem T (m, n) as step 3; T (m , n) = d (m, p) + T (p, n) where point (p) is the shortest distance to the point (m);
5. Using the above recursive algorithm, we can determine the total traveling distance (which is also the shortest distanced travelled during a candidate assembly sequence) corresponding to a feasible assembly sequence and path plan.

Virtual Assembly Analysis Environments: A set of advanced Virtual Reality (VR) based simulation environments was built using Unity3D platform to assist the analysis of the assembly/path plans interactively by engineers from different locations. The distributed engineers used the Next Internet (being developed under GENI) to propose, compare and modify assembly /path plans rapidly. The high gigabit data relating to these VR images were transmitted using this Next Generation Internet technology. Figure 2 is an example showing a view of the virtual environment with an avatar to help engineers and users interact with it; the VR assembly analysis environments were built using Unity 3D engine, C# and Java. Through these interactions, the most feasible assembly plan was identified. Subsequently, a different module in the cloud generated the various physical robot assembly commands based on the outcomes of the simulation analysis and assembly; these were then communicated to the work cell (in Stillwater, Oklahoma) selected to assemble the target micro designs.

Physical resources: Two physical work cells are available in Stillwater for physical assembly which were part of this Cyber Physical Test Bed (CPTB). Work cell 1 has an assembly plate, cameras, and an advanced micro gripper. The base support of the assembly area has two linear degrees of freedom in the X axis and Y axis and one rotational degree of freedom. The gripper of the work cell can move in the Z axis. This work cell is capable of assembling micron-sized parts rapidly automatically using machine vision cameras. A second work cell was also part of this cyber physicalwith a shape memory alloy based gripper and an assembly plate with 3 linear degrees of freedom along with cameras is also available. Figure 4 shows a view of one of the physical micro assembly cells used in this CPTB.

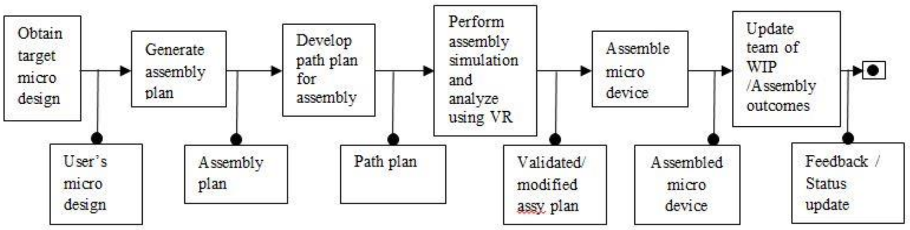
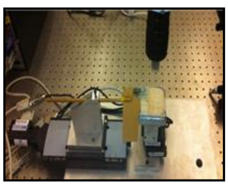


Fig. 3. Overview of the main cyber physical tasks in the collaborative framework



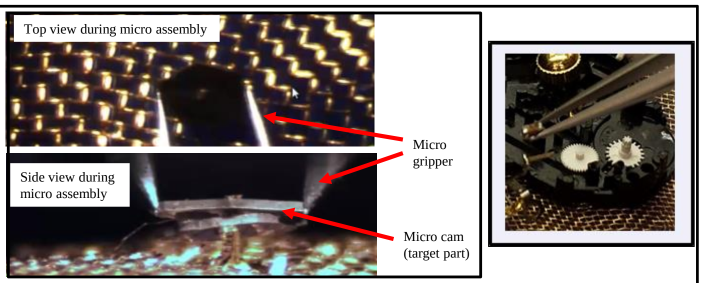


Fig. 4. (left): a physical micro assembly cell **Fig. 5.** a, b (middle/right): micro assembly tasks in progres

4 Discussion and Test Cases

In our implementation, the cyber physical resources collaborated using the IoT cloud framework discussed in previous sections; user inputs were given through the web; subsequently, assembly plans were generated which were then compared and modified using the VR based simulation environments; finally, the validated plan was assembled using physical work cells. Several target micro and meso assembly designs (figure 5 a, b) were assembled using the implemented cyber physical framework; meso/micro composite part designs were built to study the capabilities of the two work cells; While there is no universally accepted definition of Meso assembly, we use the term meso scale to include part sizes greater than 1 mm, with accuracies greater than 25 microns.

The IoT based framework outlined in this paper is a step towards ubiquitous computing where engineers and users will not be required to have computing resources to accomplish engineering tasks; instead, they will be able to access and use resources in a 'cloud' through thin clients to conduct engineering activities. The approach developed uses a cloud based approach which seeks to make it easier for engineers who may be geographically distributed (and collaborating from different parts of the world) be able to conduct simulation and physical engineering activities using next generation Internet technologies.

Two rounds of validation was conducted. In the first set of collaborative activities (within the US), users at multiple locations (3 locations including Stillwater, Tulsa and Washington DC) were able to interact and collaborate on the assembly planning, path planning and gripping approach activities through the cloud based framework; they were able to propose, compare and modify assembly plans which could be visualized and studied using the Virtual Reality environments. Subsequently, during the physical assembly activities, the monitoring cameras were able to share the progress of the assembly tasks through the cloud based framework. In the second round of validations, we tested the robustness of the overall cloud based approach with users in France (ENSAM, Aix En Provence) interacting with engineers in Stillwater (USA). This intercontinental demonstration involved supporting collaborative activities including proposing/modifying assembly plans and studying the alternatives using simulation based environments. This was a milestone achieved as it highlighted the capabilities of the Next Internet across continents.

Cyber physical frameworks hold significant potential in support agile collaborations in industry; when customer requirements changes, adoption of such cloud based frameworks enables engineers and manufacturing partner organizations to exchange and interact using thin clients, computers and other devices that are part of the IoT landscape. The emerging Next Internet enabled the sharing of data and information among the distributed teams.

5 Conclusion

This paper outlined an IoT based framework to support collaborations among distributed partners in engineering and manufacturing contexts. This is being used as basis to develop a more comprehensive Cyber Physical Test Bed for the emerging domain of micro assembly. In most situations, micro devices assembly (MDA) resources are not located at a single organization; resources will be distributed among different organizations across different locations. For this reason, an IoT based framework is needed to support the collaborative and rapid assembly of micro devices. A cloud based approach was used to facilitate the collaboration of the various cyber physical components using advanced cyber infrastructure (related to the Next Internet as part of the GENI initiative).

Our cyber physical framework enabled the sharing of engineering resources using next generation Internet technologies. Such ICE frameworks facilitate the realization of global virtual enterprises where collaboration between distributed partners is possible especially when responding quickly to changing customer requirements. As IoT devices become ubiquitous, such interfaces and thin clients are expected to play an important role in facilitating collaborations in advanced manufacturing. The use of cloud technologies also helped in the design of this IoT based framework; with the popularity of such technologies in industry today, the next wave of manufacturing collaboration is underway which will further enable national and global collaborations.

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