An Open Framework for the Assembly of Micro- and Nano-Scale Artifacts

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Abstract

The design and manufacture of miniature devices have been increasing in both research laboratories and industry. The sizes of the devices continue to decrease to the nanometer scale. At the same time, the complexity of those devices has increased. To achieve the desired functionality, different materials are required for making different components. Consequently, micro- and nano-assembly has to be performed. A micro- and nano-assembly system using optical tweezers has been developed. This paper describes an information framework for a nano-assembly system. The framework contains the following components: a use case model, component model, activity model, class diagram, and interaction model. These components are all described using the Unified Modeling Language. An initial implementation based on this framework is presented and discussed.

1 Introduction

The intention to manufacture micro- and nano-scale devices has been increasing in recent years. On the micrometer scale, these types of devices include miniature pressure sensors used in the aeronautic and aerospace industry, air bag sensors used in automobiles, miniature devices used for medical diagnosis and treatment, optical switching devices for high-speed and high-capacity computer network communication, and ultra-small sensors used in environmental monitoring. On the nanometer scale, these types of devices include ultra-miniature electronic components, and chemical and biological processing packages. To achieve desired functionality, a variety of materials will be needed for manufacturing different components of a sophisticated miniature device. Micro- and nano-scale assembly technologies will enable such diverse sets of components to be assembled into a Micro ElectroMechanical System (MEMS) or a Nano ElectroMechanical System (NEMS). Developing nano-assembly techniques and systems is, therefore, becoming imminent. In order to develop such assembly technology, the first step is to develop a framework that describes both software/hardware and system/user interfaces. However, little has been done in developing the specification of design and communication architecture in this area. The Integrated Nano-to-Millimeter Manufacturing Technologies Program at the National Institute of Standards and Technology (NIST) has developed a set of framework specifications for a nano-assembly system utilizing optical trapping and virtual-reality technology. These specifications include a set of requirements, use cases, component architecture, an activity model, a class diagram, and an interaction sequence model using the Unified Modeling Language 0. This framework has the emphasis on information requirements and modeling for enabling the integration of software and hardware systems for micro- and nano-assembly.

This paper describes this framework and is organized as follows. Section 2 reviews previous work in the subject areas. Section 3 describes the framework in detail. Section 4 discusses an initial implementation of the framework and the ongoing efforts. Section 5 concludes the paper. A disclaimer and the references follow the conclusions.

2 Related Work in Assembly of Miniature Artifacts and Virtual Environment

The Virtual Assembly Design Environment (VADE) [2] is a Virtual Reality (VR)-based engineering application that allows engineers to plan, evaluate, and verify the assembly of mechanical systems. Engineers design the mechanical system using any parametric Computer-Aided Design (CAD) system. Furthermore, the VADE developers have extended their work from the conventional scale assembly to the micrometer scale assembly utilizing force feedback devices for the display of interaction forces [3]. Cave Automatic Virtual Environment (CAVE) was developed by the Electronic Visualization Laboratory of the University of Illinois, Chicago campus. The CAVE is comprised of three to four walls used as a screen. Multiple users can experience the scene [4]. Tracking devices are used to monitor the movement of the users in the virtual reality environment. There are a variety of technologies used for this purpose. Welch and Foxlin have done a survey [5]. Sitti and Hashimoto [6] used an AFM with a one degree of freedom haptic device to sense nanoscale forces. They demonstrated the two dimensional positioning of micrometer sized latex particles on a substrate. Guthold et al. [7] used a force feedback device coupled with an AFM tip to haptically sense and manipulate carbon nanotubes, DNA and viruses. Arai et al. [8] used micrometer size tools that were trapped by focused laser beam to manipulate microbes. Yu et al. [9] used a scanning electron microscope to manipulate carbon nanotubes along one rotational and three linear degrees of freedom. Hsieh et al. [10] used an AFM to image and manipulate gold nanorods on silicon dioxide surfaces.

In micro-assembly planning, Fatikow et al. [11] developed a planning algorithm for micro-assembly using a microrobot system. The paper describes elements in a plan and the structure of a plan. The developed system has basic functions for task planning, robot motion planning, resource allocation, and some error detection functions. Virkramaditya et al. [12] proposed a micro-assembly strategy for assembling magnetic devices, such as computer hard drives.

3 Micro- and Nano-Assembly System Framework

Nano-assembly systems consist of software and hardware components that collectively provide the user with the necessary capabilities. The purpose of our work is to specify a framework that enables the interoperability among different components. A framework provides an information infrastructure for software components to be interoperable. The framework contains component architectures, use cases, and information models. This section starts with the use cases.

3.1 Use Cases

Optical Tweezers (OT) is an instrument that uses laser to trap and manipulate micro to nanoscale particles. The NanoAssembly System is comprised of an optical trap (tweezers) controlled by a Virtual Environment (VE) that consists of a large stereoscopic screen (Immersadesk), position tracking devices (Spacepad), and a haptic device (PHANTOM). The user commands and controls the optical tweezers to move nano particles in a liquid. The control algorithm for tilting the micromirror that steers the path of the laser is developed using an instrument interface programming tool, such as LabView. The VE and the optical tweezers are networked. The position and orientation of the particle under control is displayed in the VE. Particle sizes are on the submicron scale.

The use case defines operations of nano-assembly systems. There are three operators to control the VE, optical tweezers, and the network communication. The VE operator (operator 1) has three major tasks. Task 1 is the initialization, and it has the following subtasks. Task 1.1 is to start the control software and devices, such as the shared memory, position tracker, haptic device, and the physical models for laser trapping of particles. Task 1.2 is to retrieve the trapping potential energy field description from the repository of trapping energy field descriptions. Task 1.3 is to retrieve the particle shape description from the repository of particle shape descriptions. Task 1.4 is to receive the initial position and orientation of the particle from the image system of the optical tweezers. Task 1.5 is to receive the initial position and orientation of the trapping shape defined by the optical tweezers operator. Task 1.6 is to display the particle in the display of the Immersadesk. Task 1.7 is to display the trapping potential energy field, also in the Immersadesk. Task 2 is to move the nano-particle, and it has the following subtasks. Task 2.1 is to move the stylus towards the destination. Task 2.2 is to send current stylus location to the optical tweezers controller. Task 2.3 is to receive updated location of the particle from the optical tweezers controller. Task 2.4 is to update the visual display. Task 2.5 is to calculate the force applied to the particle. Task 2.6 is to update the haptic device. Task 3 is to shut down the VE when all its tasks have been completed.

The optical tweezers operator (operator 2) performs one major task: Task 4. The task is to initialize the optical tweezers, and it has the following subtasks. Task 4.1 is to set up the laser instrument, including to adjust the laser intensity and to properly set the focus of laser beam. Task 4.2 is to select a laser potential energy field such that it will grab the particle of particular shape and provide proper trapping forces. Task 4.3 is to setup the Charge Coupled Device (CCD) camera. Task 4.4 is to locate the particle, using a microscope, and trap the particle. Task 4.5 is to send the initial position of the particle to the VE and pass the control to the network controller.

The network controller (operator 3) is a software agent that performs one major task: Task 5. This task is to manipulate the particle based on the commands sent by the VE operator. Task 5.1 is to receive the destination. Task 5.2 is to move the trap location towards the destination. Task 5.3 is to report the current particle and trap locations and orientations to the VE operator. Tasks 5.1 through 5.3 are in a loop. The time to exit the loop is when the VE operator terminates the control of moving the particle.

Based on this use case, an activity model can be developed.

3.2 Activity model

The activity model identifies functions, information flow, and decisions in micro-/nano-assembly. An activity model is necessary to specify the requirements for software components. The notations used in this activity model are defined in the UML for creating activity diagrams. As shown in Figure 1, the first function is to initialize the system, including optical tweezers, the VE, and a network communication controller. After the system is initialized, particles are selected for possible assembly in the VE. The command is sent to the optical tweezers. Users can manipulate the particles in the virtual reality environment by changing the position and orientation of the particles so that they are ready to be assembled. During the manipulation, users can feel the trapping forces that are exerted to the particles. When the two particles are identified and trapped, they are then called artifacts that will be joined together as an assembly.

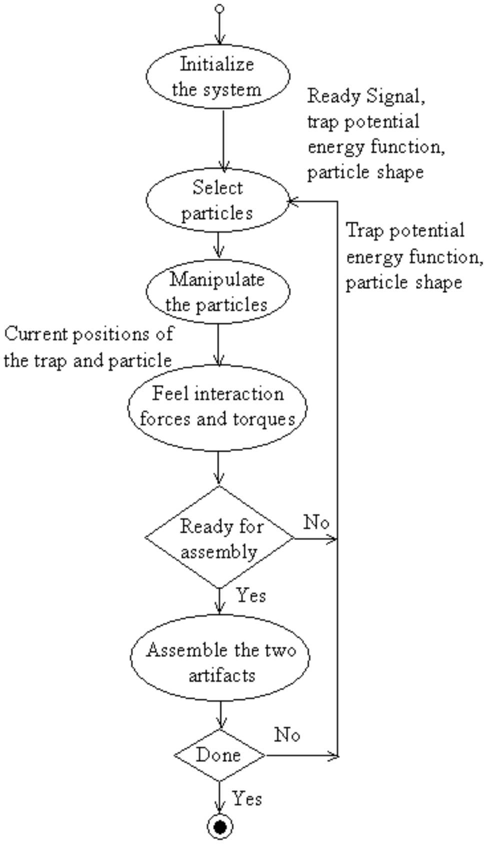

Figure 1 Activity Diagram

Figure 2 shows the assembly activity. Artifacts are moved in proximity and in the right orientation for being joined. They can be either assembled by themselves or by optical tweezers. Those artifacts that can be joined by chemical bonding, electrostatic forces, or magnetic forces are assembled by themselves. Otherwise, the two artifacts (particles) are brought in proximity and oriented for joining. The predefined assembly plan specified assembly feature and joining orientation. Next, the two artifacts are trapped and put together. The last activity is to release the assembled artifact in the assembly space.

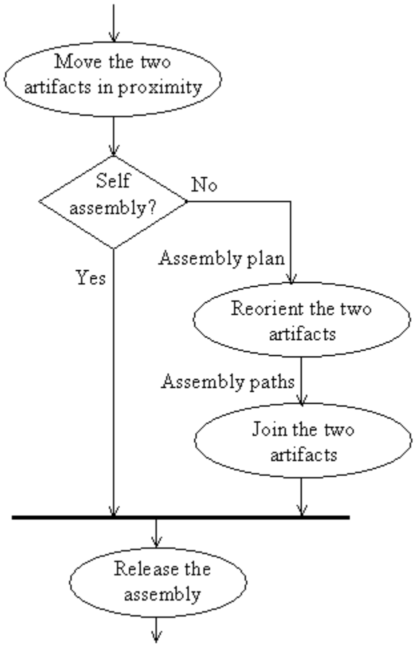

Figure 2 Subactivity of Assembly

3.3 Component diagram

Figure 3 shows the components used in the virtual reality environment and the laser entrapment and movement environment. The two major components are the VE and the optical tweezers. The VE provides human operators with look and feel in manipulating micro- or nano-particles. It has four subcomponents: (1) the haptic device that handles outputting forces and torques to the operator's hand, (2) the visual display that enables the operator to see three-dimensional particles along with laser-generated traps, (3) the audio device that provides sound effects, and (4) the tracking system that tracks operator's movement.

The optical tweezers has three subcomponents: (1) the laser controller controls the laser focus and intensity, (2) the CCD camera provides images of laser-trapped particles, and (3) the micropositioning system controls the table position.

Transmission Control Protocol/Internet Protocol (TCP/IP) [13] is used to link the communication between two major components.

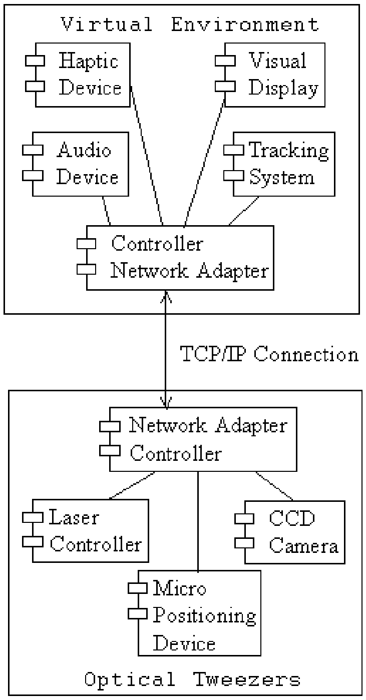

Figure 3 Component diagram

3.4 Class diagram

Based on the activities described previously, the classes are developed to control equipment and provide communication between devices. Figure 4 shows the developed class diagram. The **NanoAssembly** class is the root class in this diagram and has four associated classes: **NanoArtiface**, **OpticalTweezers**, **VirtualEnvironment**, and **NetworkCommunication**. It has one attribute for describing the assembly object and four methods for starting VE and the Optical Tweezers (OT) and exiting from them. **NanoArtifact** defined the form, structure, and assembly relationships of a single artifact or an assembly of artifacts. The **OpticalTweezers** class defines the parameters to the control of the equipment. Its attributes are to record the number of particles, the positions and orientations of the particles, and the shape descriptions. The position and orientation of a micro- or nano-scale particle can be detected by using laser, CCD camera, and some mathematical calculations. The image of a micrometer size particles can be captured by a CCD camera. The depth can be detected by changing the focus of the camera to view features of the particle in various depths. For nano-scale particle, one method is to put at least three nano-scale light emitting markers (dots) that are not co-linear on the particle. These three dots must have some different optical properties. The images of these dots can be detected by the CCD camera, and the depth of the dots can be detected and calculated using the laser instrument. Different dots are discernible because of their different optical properties. The **LaserController** class controls the laser. The class has an attribute of laser parameters to define the state of the laser beam. The class also has methods to trap the particle, move it, and dither it to change its orientation. The **PositioningSystem** class defines the state of the micro/nano positioning system and controls it by moving the table to a new location, starting/stopping the table and receiving commands from the operator. The **CCDcamera** class defines and controls the camera to get and send images of observed particles. The **NetworkCommunication** class defines the parameters of the network device and controls the communication between the optical tweezers and Immersive CAD.

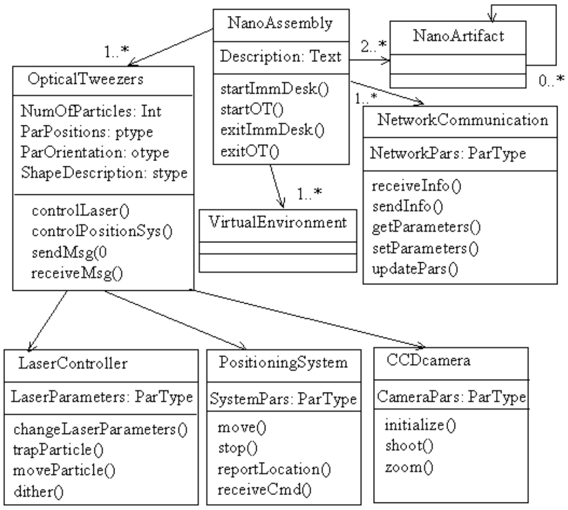

Figure 4 Class diagram

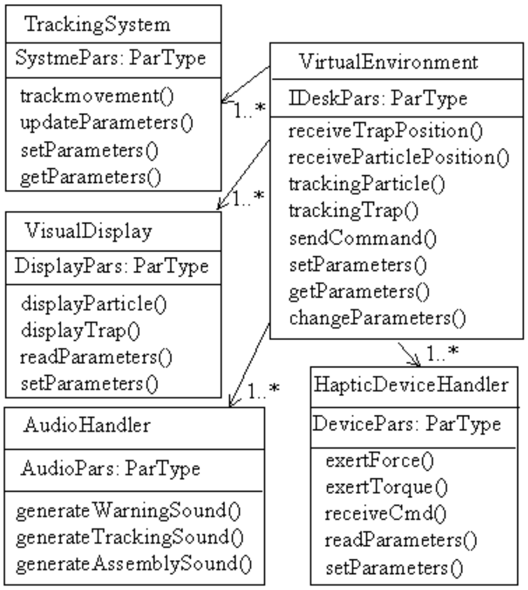

Figure 5 Detailed class diagram for VE

The **VirtualEnvironment** class has four associated classes, as shown in Figure 5. It defines the virtual reality parameters and controls the equipment. To control the VE, the class has methods to receive the trap position and particle position from the optical tweezers controller. The class also has methods to track the particle and trap positions. Furthermore, it has methods to set, get, and change the VE parameters and send commands to the optical tweezers controller. The **VisualDisplay** class defines the display parameters and controls the display of the particle and trap in the virtual reality environment. The **AudioHandler** class defines the parameters that set the state of the audio device and controls it by allowing users to generate different warning, tracking, and assembly sounds. The haptic device is an output device for force and torque, used in a virtual reality environment. The **HapticDeviceHandler** class defines the state of the device and controls the timing and magnitude of the output force and torque. Lastly, the **TrackingSystem** class defines the system and tracks the movement of the operator's hand and head.

All the classes defined in the class diagram are for defining the state of the equipment and controlling the equipment for generating proper functions. Their interactions are described in an interaction diagram.

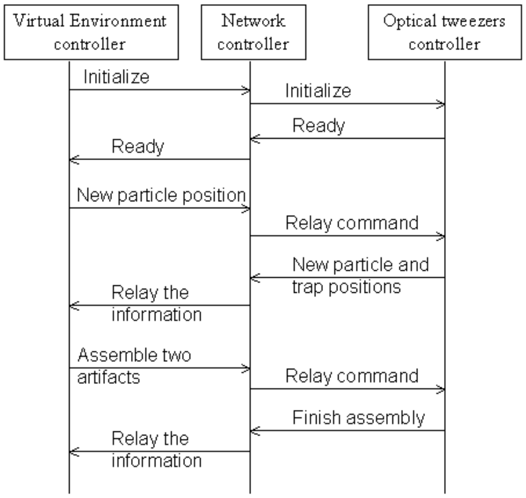

Figure 6 Interaction diagram

3.5 Interaction model

The interaction model specifies the timing and sequence of function calls – the interaction among classes. Figure 6 shows the interactions among the VE controller, network controller, and optical tweezers controller. The VE operator first sends commands to initialize both the network controller and optical tweezers controller. Then, it sends a command to select and move particles to the network controller, and it relays the command to the optical tweezers controller via a computer network. When the two particles are in the ready positions and orientations, the VE sends an assembly command to the optical tweezers controller to start to assemble the two particles (artifacts). When it finishes, the optical tweezers controller sends a finish signal back.

The VE controller also interacts with devices within the VE, as shown in Figure 7. It sends commands to the visual display to enable the visualization of particles and traps, to the haptic device to output forces and torques for the operator to feel them, and to the audio device to output appropriate sound signals. The tracking system keeps sending the movements generated from the operator back so that the VE can update the display and haptic device.

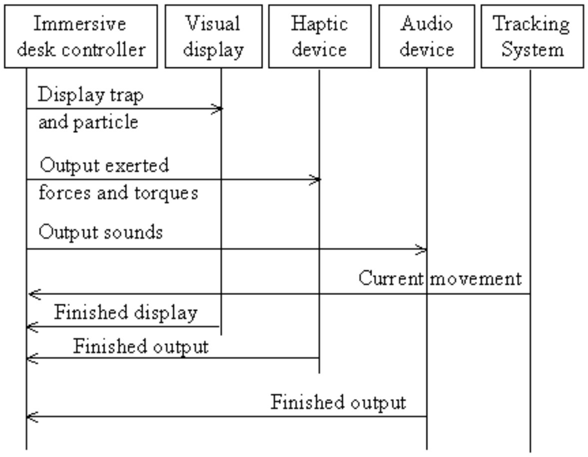

Figure 7 Interactions in VE

The optical tweezers controller interacts with the devices that cooperate with the laser tweezers device, as shown in Figure 8. It sends commands to the laser controller to trap the selected particle, to the CCD camera to capture an image, and to the positioning device to move the table to the right position.

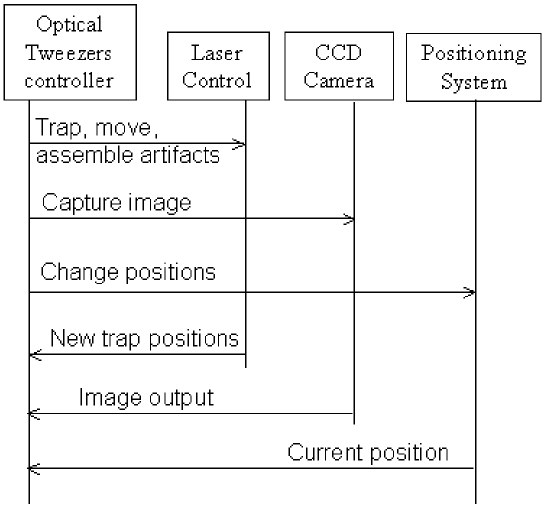

Figure 8 Interactions in Optical Tweezers

4 An Implementation of Micro- and Nano-Assembly System

The Virtual Environment for Nano-Scale Assembly (VENSA) has been implemented at the NIST, based on the open framework. We have an Immersadesk for the stereoscopic visual display, a Spacepad for sensing positions and orientations and a PHANTOM for the haptic device. Each system is managed by a separate computer. The computers communicate with each other through Ethernet by TCP/IP communications. The organization of the components is consistent with the architecture described in Section 3.3. The interactions among components conform to the interact model described in Section 3.5.

The control algorithm in the laser controller for tilting the mciromirror that steers the path of the laser is developed using LabVIEW. Thus we need to communicate through LabVIEW in order to control the laser path. This is done through the TCP/IP and LabVIEW socket module. Similarly, Micro Positioning and CCD Camera component are developed under LabVIEW. LabVIEW provides interfacing routines for various physical devices and basic image processing routines to detect particles from the incoming video stream.

The haptic device component handler is built utilizing the C++ library provided by the haptic device vendor. The library provides many functionalities but we only use a few basic routines to send computed forces to the haptic device. Pre-computed lookup tables are extensively used to minimize the computational time. The visual device component uses OpenGL, a computer graphic language, for the graphics and GLUT, a window management system, for windowing and setting up the graphics card. Since the scene is relatively simple, we have not yet used any special techniques to enhance the display speed. The audio device component handler was built using the IRIS Digital Medial Libraries. The sound is generated by using some sound effects. The Tracking System component is built using the CAVELib. The developed software was derived from the class diagrams described in Section 3.4.

5 Conclusions

The trend in industry is to take a variety of micro- and nano-components and assemble them into a device to meet customers' demands. The device often have complex functionality. Integration of individual components and modules into a system generally requires assembly in micro- and submicro-scale. Micro- and nano-assembly is, therefore, crucial to the success of future MEMS and NEMS. A software/hardware framework has been designed and specified. Major components include use cases, component architecture, interaction diagrams, and an object-oriented software model. It is an open architecture, which is designed to enable plug-and-play of software components across ownership boundaries.

An initial implementation has shown the feasibility of micro- and nano-assembly system comprised of an optical tweezers, a micro-positioning system, and a virtual environment. The virtual environment enables human visualization, sensing, and control of moving artifacts. This provides a platform for micro- and nano-assembly.

Disclaimer

No approval or endorsement of any commercial products by the National Institute of Standards and Technology is intended or implied. Certain commercial software and hardware systems are identified in this paper in order to facilitate understanding. Such identification does not imply that these systems are necessarily the best available for the purpose.

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