Planning Micromanipulations Using Haptic Interaction Environment

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Abstract

The dominance of adhesive forces and the poor hand-eye coordination pose major challenges in the regime of micro assembly and related micromanipulation systems. The use of haptic technology can offer effective solutions to these challenges. This paper presents the development and use of a software tool which has been developed for planning micromanipulations with the aid of a haptic virtual environment. This development was realized through haptic simulations and a virtual environment representing a micro assembly domain. An assistive technique to guide the user during micro manipulation with the help of haptic interface has been proposed.

Keywords : Virtual reality, Haptics, Micromanipulation.

1 Introduction

The recent developments in the domain of micro and nano technology have made miniaturization as the buzzword in almost all industrial disciplines. At one end costly and dedicated machines meet the mass production requirement of micro products such as semi-conductors, micro-sensors etc. On the other hand there are requirements for flexible manufacturing systems to meet a wide range of high quality products. (e.g. Biomedical endoscopes, micro-optical devices etc.). Realization of these systems demand highly precise manipulation and assembly needs. The concept of reconfigurable miniaturized micro assembly work stations have emerged in this context [1].

Methods developed for conventional macro assembly cannot be applied directly to the microassembly tasks Uncertainties micro world such as the dominance of adhesive forces, poor hand-eye coordination, noisy visual information, limited range of magnified vision etc. calls for proper planning and training in executing the micro assembly tasks. Suitable supportive technology is essential to cater these needs.

Haptic technology has recently attracted attention into such applications. 3D Graphic simulations through haptic feed backs can be effectively used to generate virtual micro assembly environments. Such virtual reality (VR) domains are found useful in training the user to perform micro level activities..

This paper presents the development of a haptic interaction environment which can aid in generating strategies for micromanipulation planning and guidance through a simulator. A simulator enhances the capability of motion planning for manipulations and in this case supports the use of a haptic (force feedback) information for micromanipulation environments which are subjected to intermolecular and surface interaction forces. A brief overview of haptic interface technology is given in Section 2.0. The use of virtual simulations for micro assembly and related research in this field is discussed in section 3.0. The development of haptic interaction environment is presented in Section 4.0, followed by the description of test cases in section 5.0.

2 Haptic Interface Technology

Haptic technology enhances the human-VR interaction by incorporating a display technology through which virtual objects can be physically palpated. This is accomplished by integrating the force feedback with VR simulation to provide the user the feel of tactile sensation on virtual objects in the form of object stiffness, surface contact geometry, and friction [2].

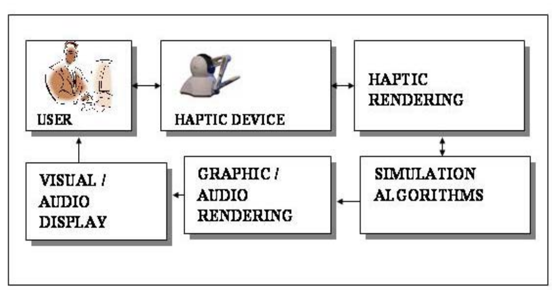

Figure 1: Virtual environment incorporating haptic and visual feedback. Haptic device serves as a bi-directional interface between the user and the environment.

In this work a haptic interface has been developed that consists of a haptic device and haptic rendering algorithms. In this environment the user can interact with the virtual environment of a micromanipulation situation through the haptic device. Fig.(1) shows the structure of the virtual environment incorporating visual auditory and haptic feedback [3].

The haptic rendering algorithms compute the force response towards the user upon the interactions with the virtual objects in the scene representing a typical micromanipulation environment. The haptic device captures the force signals generated by the haptic rendering algorithms and convert them into a form, which the user can perceive. The audio and visual rendering modules compute the graphic and sound responses to the user providing useful feedback towards motion plan update in the manipulation. The simulation algorithms work in real-time and provide dynamic response to the user for a typical simulated micromanipulation exercise.

3 Haptic VR Simulations for Microassembly Systems

Manipulation of parts in a microassembly domain is carried out through sub millimeter sized micro manipulators. Typical micro assembly tasks need sub-micron precision and hence a good user interaction with the assembly system is a must. Generally the feedback to the user is in the form of a magnified visual display through a microscopic camera system. User has to perform the 3D operations with the aid of this 2D visual display.

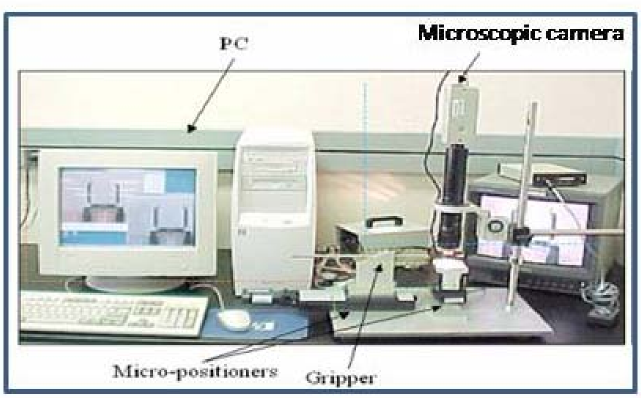

Figure 2: A typical micro assembly work cell. User depends on the magnified 2D visual display provided by the microscopic camera to perform the assembly.

The forces in the micro level are very small in magnitude as compared to gravity based and other interactive forces in macro level and can be considered negligible to be felt by the user in the absence of a force magnification system.

This results in a lack of hand-eye coordination during the micro assembly tasks. Moreover the visual information is constrained by the working range of microscopes and there is limited viewing flexibility. Fig. (2) shows a typical micro assembly cell. equipped with a magnified visual display .

Another major challenge in micromanipulation is the dominance of adhesive forces. An adhesive force comprise three major components namely the van der Waals, electrostatic and surface tension. In the micro level, these forces dominate over gravity and make the micro level operations complex. Fig. (3) illustrates the well-known problem of sticking of micro parts onto the gripper [4]. As the gripper approaches the object (1) it moves and sticks to the gripper (2). Similarly the object sticks to the gripper when it opens for release (5) and get displaced from its originally intended position.

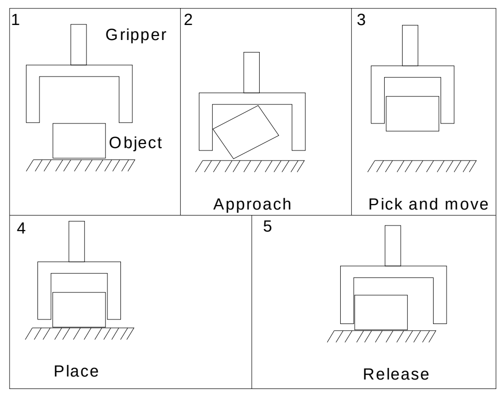

Figure 3: Effect of adhesive forces during micro manipulation. The micro part sticks to the manipulator and make the task complex.

From the above description it can be seen that the adhesive forces have the potential to make the dynamics of manipulation non-linear and non-intuitive. An integrated approach to manipulation and planning in real-time with simulations in order to assist the user to plan motions in such environments is presented here.

In this paper the authors present the approach towards the use of haptic VR applications that can assist the user to counter the above problems. A virtual domain with which the user would be able to 'feel' the micromanipulation environment through the haptic device and visual display is proposed here. The virtually simulated adhesive forces aid the user to get familiarize with the dynamics of the micro world. A proper combination of magnified force/visual display helps to tackle with the problem of hand-eye coordination. Various means of micro assembly tasks can be planned and experimented using these applications. Coupling the haptic VR domain with the real world micro assembly systems can facilitate a tele-operated working environment. Realization of such virtually interfaced micro assembly stations will simplify the complexity of micro level tasks to a mundane real world activity.

3.1 Related work

Research carried out in this field generally focus at the tele-operated environments coupled with haptic VR simulations. An automatic micro assembly system assisted by virtual simulation can be found in [1]. A micro manipulation system through tele-interface with haptic assistance is presented in [5]. The development of a virtual tool kit with visual and haptic feedback to test manipulation strategies at nano-scale is described in [6]. A 3D micro world developed with haptic feedback for simulating the effects of van der Waals and electrostatic forces is presented in [7].

4 Haptic Micromanipulation Planning Environment

The haptic micromanipulation environment has been designed and implemented at the Real time collaborative environment lab of IIT-Kharagpur, India. A virtual micro world was developed on a desktop PC running on the operating system Fedora Core-4.

The micro world development was realized through the generation of the 1) graphic environment created by Open GL API, 2) haptic environment created using Open Haptics API, 3)simulations developed by C++ and with the support of Haptic interface device Phantom Omni Sensable Technologies[8] (Fig. 4).

Figure 4: The Phantom Omni haptic interface device by Sensable Technologies. (Courtesy: Phantom manual from Sensable Inc.)

The graphic environment consists graphic models which represent micro objects, micromanipulators and substrates. The Haptic environment interfaces the Haptic device with the graphic environment.

The virtual environment initially presents the user a micro assembly domain to the user which consists of various micro objects located on a substrate and a micromanipulator. Through the haptic device user can feel the micro environment as if in a real world. The following features provided in the system enable the user to perform and plan the micromanipulation.

a) Selection and control of micro objects: User can select the micro objects from the_geometry model data base. The position and orientation at which the micro objects to be initially located can be pre-set. An offline programming module is provided to set the default positions prior to the application. Once the environment is initiated, user will be able to feel the environment through the haptic device along with visual display.
b) Manipulation: User is provided with virtual manipulators in the environment. Once the required manipulator is activated, the haptic device movements will get coupled with the manipulator model. Micro objects can be virtually picked up and manipulated using the haptic device operations.
c) Manipulation guidance: It is possible to define the path through which the micro objects are to be manipulated to the final locations. This has to be defined using an off line module. A guidance system which can physically guide the user's hand movements through this path has been provided in the environment. Once initiated this guidance system gets into action whenever the user picks the micro object from the initial location. The guidance system physically guides the user to manipulate through the designed trajectory from the initial location to the target location with the aid of an attractive field
d) Data recording: This feature facilitates real-time capture and record of positional and haptic force feedback information. User can activate this feature for the period of simulated experiment or motion plan.
e) Viewing selection: The micro domain can be viewed from different angles using the animation features supported by openGL.

The above features are simulated with a modular software architecture which comprises five basic modules.

- Geometry data base,
- Manipulation control module,
- Manipulation guidance system,
- User interface module and
- Master simulation control.

The following sections discuss in brief the functions of each module.

4.1 Geometry data base

This module acts as a library of openGL models representing micro objects, manipulators, substrates and 3D buttons required for the user interaction. Each model is associated with an independent animation feature. User can design the micro environment by importing these models into the main scene. These geometries are imported into the main environment based on the application requirement.

4.2 Manipulation simulation module

The simulations relevant for micromanipulation are controlled by this module. Functions of this module are 1) to couple the movements of manipulator geometry with the haptic device movements, 2) avoid collision between geometries during manipulation and 3) to model the adhesive forces. There are three sub-modules to accomplish these functions as shown in Fig. (5).

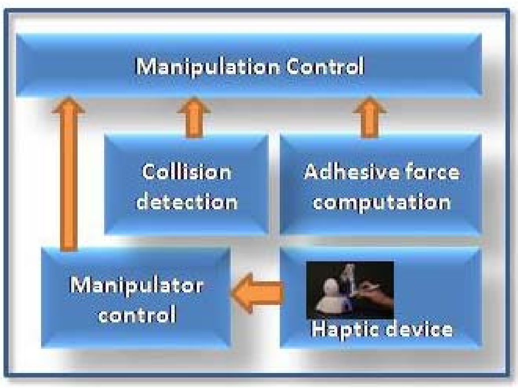

Figure 5: Architecture of Manipulation control module

The following sections describe the functions of these sub-modules.

4.2.1 Manipulator control module

Algorithms in this module couples the manipulator geometry transformations with the stylus movements of the haptic device. This is accomplished by capturing the required position and orientation of haptic device stylus and suitably transforming it to update the geometry translation and rotation. By this way user of the virtual manipulator can have a real time control through the haptic device. User can define up to 6 degrees of freedom for the virtual manipulator.

4.2.2 Collision detection and control module

The collisions between the geometric models in the environment are controlled by this module. Axis Aligned Bounding Box (AABB) technique [9] is adopted for determining the collisions. The focus here is only to avoid collision between the geometries. Once the collision is detected between the geometries, the algorithms arrest the movements of the objects towards the direction of collision.

4.2.3 Adhesive force simulation module

Adhesive force in the micro domain consists of three components namely the van de Waals, electrostatic and capillary forces. With proper humidity control the capillary force can be avoided. Similarly the use of static charge controlled clean room can reduce the effect of electrostatic forces. For our simulation we assume these two forces are taken care and only van der Waals force exist between the objects. The van der Waals force is originated by the momentary dipole moment between atoms resulting from interaction between electrons in the outermost bands rotating around the nucleus. It is influenced by the material and the contact surface area. This force modeling is realized by considering the following three situations [10] as shown in Fig. (6). The van der Waals forces experienced between the micro objects, between micro object and manipulator and between the micro object and the substrate in the scene are modeled based on these three situations.

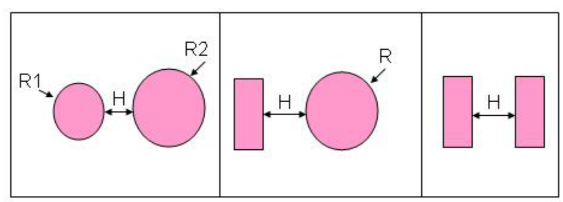

Figure 6: Notations for van der Waals force determination

The van der Waals force *Fvdw* between two spheres of radius R1 and R2

$$\boldsymbol{Fvdw = AR/12H^2} \quad (1)$$

$$\text{Where, } R = \sqrt{R1R2} \quad (2)$$

Between a spherical particle of radius R and a flat surface

$$\boldsymbol{Fvdw = AR/6H^2} \quad (3)$$

Between two plane surfaces

$$\boldsymbol{Fvdw/Ac = AR/6H^3} \quad (4)$$

Where, *Ac* is the contact area and *A* is the Hamaker constant [11]. The gravitational force is influenced by the mass of the object and is generally negligible in the micro domain.

$$\boldsymbol{Fg} = \boldsymbol{V}\rho g \qquad (5)$$

Where, V is the volume of the object, ρ is the density and g is the acceleration due to gravity.

This module computes the van der Waals between the manipulator and object at real time and compares it with the gravitational force. As soon as the van der Waals force exceeds the gravitational force during manipulation, the algorithms will simulate the object movement towards the manipulator and sticking phenomenon through animations.

4.3 Design of manipulation guidance system

A force controlled manipulation guidance method is developed to assist the user during manipulations. This is designed in a view to assist the user in making straight line motions which are most often compatible with straight line motions creatable by table / manipulator tip movements that are available in most machines. In the current work interpolated motions are not being considered to keep errors of interpolation out of consideration.

The guidance system facilitates the user to design the path with straight line segments through which the manipulation has to be carried out (Point to point motion planning with intermediate waypoints using linear interpolation). Based on the user information the algorithms generate a geometrical representation of the path of the micromanipulator which can be seen on the simulator and later also be used for a machine when hooked up in the loop.

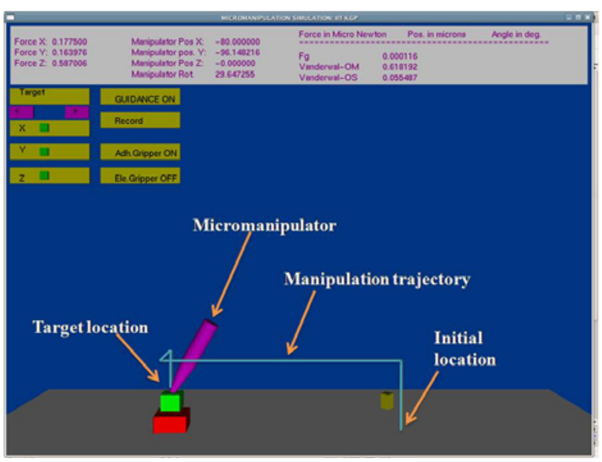

Figure 7: Simulation environment showing manipulation trajectory. User experiences an attractive force towards the trajectory.

The haptic interface point in the virtual environment is made to co-locate with this path geometry. This results in a situation that unless user exerts an opposite force, the device stylus remains to stay in a state of collision with the path geometry. This in turn creates the effect of an attractive force to the user during manipulation. This feature is accomplished with the aid of built-in features supported in the Open Haptics library, which facilitates the customized movement control of haptic device.

The guidance system gets initiated as soon as the user picks up the object for manipulation. The geometry of the path will get displayed in the environment. As explained above User will experience an attractive force towards this path geometry and will be guided towards the final location. (Fig. 7).

4.4 User interface system

A novel haptic user interface system has been created in which the menus can be operated through the haptic device. This feature avoids the practical difficulty of operating the haptic device and the mouse / keyboard simultaneously so that user can concentrate mainly on the haptic device. This improves the level of user immersion in to the virtual domain. The menu system consists of 3D buttons and sliders which the user can operate as if in the real world. This also consists of graphical user menus for the non-frequently used functions. The information related to force feedback, manipulator positions, adhesive forces etc are displayed in the environment. Fig. (8) shows the user interface system.

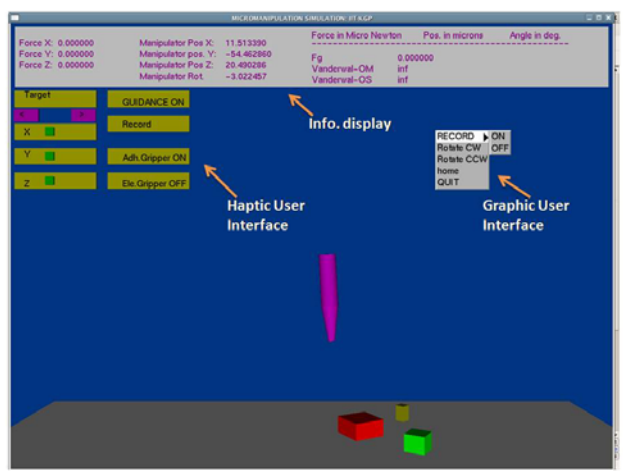

Figure 8: User interface system. Haptic user interface consist 3D menus which can be operated through haptic device.

The user is allowed to view the environment from different angles through the animation functions. A data-recording feature is provided to capture and record the position and force feedback information in real time during the simulation.

4.5 Master simulation control

This module is responsible for the overall control and integration of all the other entities to accomplish the simulation. Algorithms in this module initiate the haptic device and interface the haptic and graphic libraries and execute the simulations based on user input. Fig. (9) illustrates the basic architecture of this module.

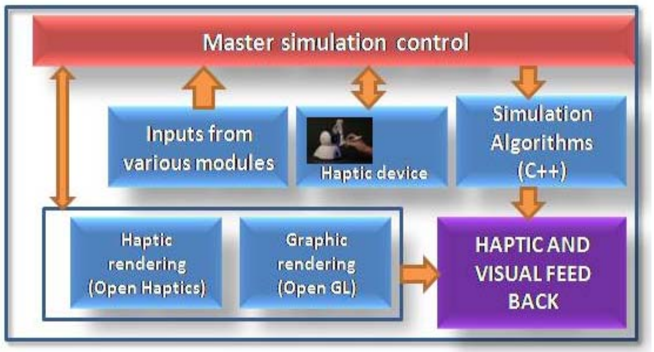

Figure 9: Basic architecture of master simulation control module.

The above components are integrated together in a software environment where in a simulated micromanipulation experiment can be carried out. Different types of micromanipulation experiments have been encoded in the simulator with which the functioning of the simulator are verified. The simulator is also designed in such a manner that it may easily be integrated to an experimental micromanipulation environment which may be developed and interfaced later for practical verification. In this paper however, the simulator and planning of motions in the virtual environment is addressed for experiments as detailed in the next section.

5 Test Cases

To test and evaluate the performance and capabilities of the development the following three cases have been considered 1) Manipulation and assembly of a micro gear into a shaft using a mechanical gripper, 2) Pick and place manipulation of rectangular blocks using an adhesion based gripper and 3) Manipulation of nanoparticles by controlled pushing. Fig. (10) shows the test set up used for the development.

Figure 10: Test set-up showing Phantom Omni haptic interface device connected to the simulation system.

5.1 Virtual micro assembly

In the first case, an assembly of micro gear in to a micro shaft has been simulated. The simulation environment is modeled with a mechanical micromanipulator, the micro parts to be assembled, a holding vice and the substrate. The micromanipulator was modeled with 4 degrees of freedom in X,Y,Z and Roll directions and is synchronized with the haptic device movements.

The parts were initially positioned in a random fashion. The simulation commenced with picking up and manipulating the shaft towards the holding vice. After the shaft is being held by the vice, the gear was picked up and manipulated towards the vice for assembly. A manipulation guidance is activated which helped the user to locate the gear with the shaft axis. It also provided a constraint motion of the gear onto the shaft. During the assembly, the assembly forces were felt to the user in a magnified scale

A force range constraint was defined for performing the assembly. User needs to apply a minimum amount of force to accomplish the assembly. If the force tends to exceed a value which can damage or deform the parts, user is alerted with an opposing force and a graphical indication. Fig. (11) shows the various stages of assembly simulation.

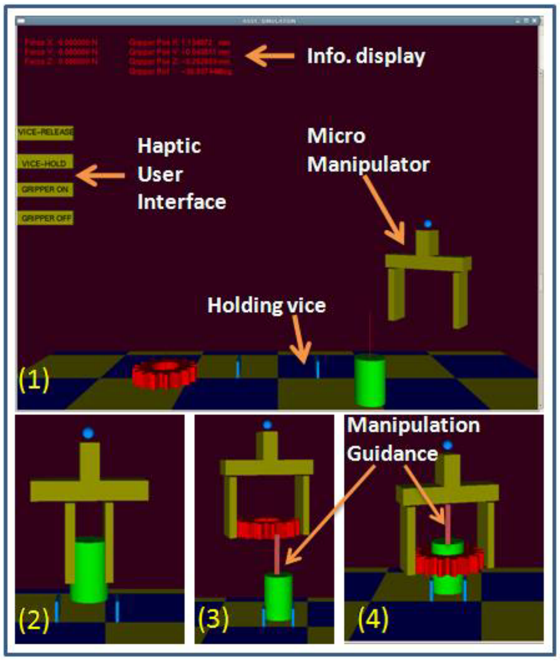

Figure 11: Sequences in virtual micro assembly. The manipulation guidance helps user to locate the gear with the shaft axis.

5.2 Pick and place manipulation

The second case has been simulated by modeling an adhesion based micromanipulator. The adhesion based manipulator makes use of adhesive forces for the gripping and release. For gripping the adhesive forces between the gripper and the object must be greater than the sum of adhesive forces between the object and substrate and the gravitational forces. While releasing the object, this condition has to be reversed. One of the techniques to accomplish this is to decrease the contact area between the manipulator and the object by rotating the manipulator and thus reduce the van der Waals forces [12]. This method was simulated for the manipulation.

The micromanipulator was modeled with five degrees of freedom in the X,Y,Z,Roll and Pitch directions and its movements were coupled with the haptic device. The gripper material was considered as gold coated glass. The micro objects were considered as copper blocks placed on a polystyrene substrate. Among the adhesive forces, the van der Waals force has been modeled based on the Hamaker constant of the materials [11]. In this development it is assumed that the manipulation is carried out in humidity and electrostatic charge free controlled clean room. The objects were initially positioned and oriented in a random fashion. The final position and orientation of the objects are set in the environment. The trajectory through which the objects are to be manipulated were predefined to create the appropriate manipulation guidance paths. The objects were picked up by the gripper using the van der Waals forces and manipulated towards the final positions. The manipulation movements were controlled and constrained by the manipulation guidance. The objects were oriented to the required angle before release. Release operation was performed by pressing the objects against the surface and rotating the gripper. Fig. (12) shows the different stages of this simulation.

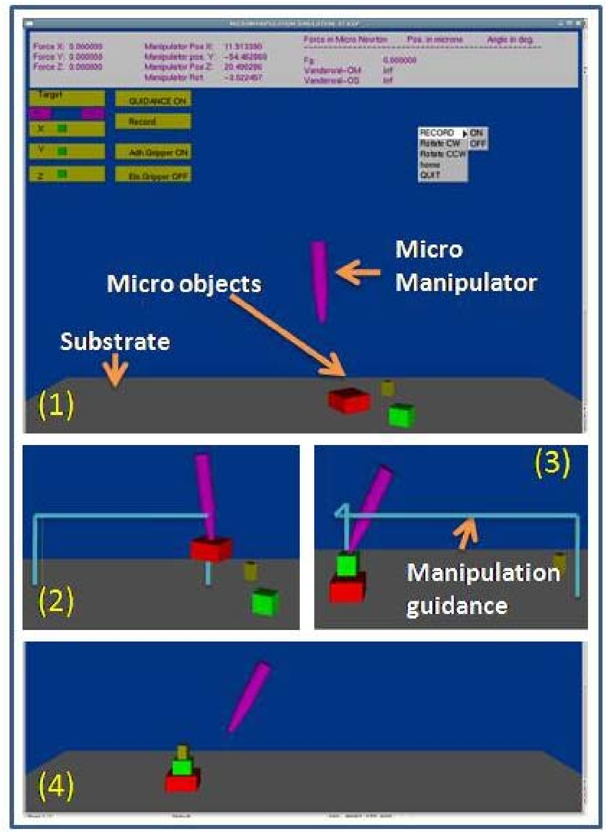

Figure 12: Stages of virtual pick-place manipulation using an adhesion based micromanipulator tip and manipulation guidance system.

5.3 Nano manipulation by controlled pushing

An attempt has been made to augment the simulation environment for modeling a nano manipulation scenario. A virtual nano environment has been simulated with virtual models of an Atomic force microscope (AFM) manipulator, nano particles and substrate [13]. The substrate was modeled with an assumed surface topology. User is initially presented with randomly positioned virtual nano particles on the substrate. The AFM manipulator is provided with 4 degrees of freedom in the X,Y,Z and Roll directions. The virtual nano particles were manipulated to the desired locations using the manipulator by controlled pushing. We have assumed that the adhesive forces between the substrate and the nano particles are more than that of between the manipulator and particles. The nano level forces during manipulation were presented to the user in a magnified scale. Fig. (13) shows the various stages of the simulation.

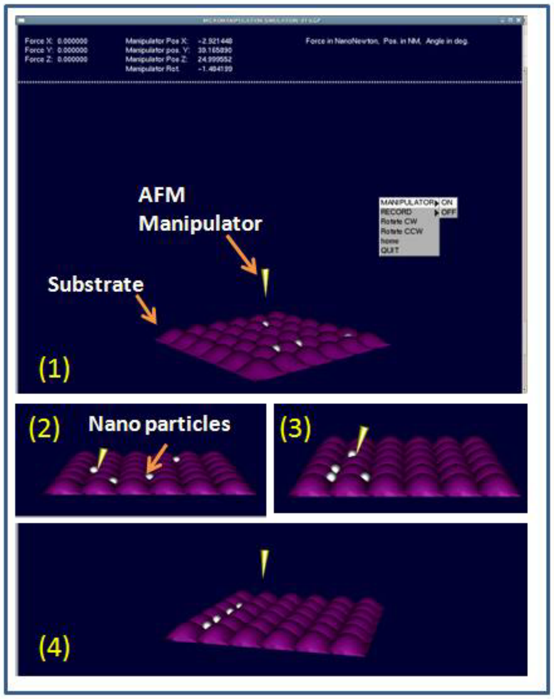

Figure 13: Different stages of virtual nano manipulation by controlled pushing using the virtual AFM manipulator.

6.0 Conclusions

Micromanipulations in the presence of predominant adhesion and related surface forces pose challenge to the planning and design of strategies for manipulation. This paper addresses the guidance and manipulation in such environments using a haptic interaction on a desktop system with a virtual reality like simulator. A simulation environment has been created which can be interfaced to a real micromanipulation set up and work as an augmented reality tool for micromanipulation. The paper discusses the details of such a tool that has been developed and demonstrated for some simple micro and nano manipulation examples.

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References

[1] Antoine Ferreira el al., “Automatic Microassembly system Assisted by Vision Servoing and Virtual Reality” *IEEE/ASME transactions on mechatronics*, Vol 9, No. 2 June 2004.

[2] Burdea, “Force and Touch Feedback for Virtual Reality”, *John Wiley & Sons, New York, USA*, 1996.

[3] Kenneth Salisbury et al., “Haptic rendering: Introductory concepts”, *IEEE Computer Graphics and Applications*, Jan 2004, pp. 24-32.

[4] Ronald S Fearing, “Survey of sticking effects for micro parts handling”, *IEEE International conference on Robotics and Intelligent systems, IROS ’95, Pittsburg*, Aug 1995.

[5] Mehdi Ammi et al., “Virtulized Reality Interface for Tele-Micromanipulation”, *Proc. IEEE International conference on Robotics & Automation, New orlands*, 2004.

[6] Aydin Varol et al., “A virtual reality tool kit for path planning and manipulation at nano scale” *Proc. Symposium on haptic interface for virtual environment and teleoperator systems*, 2006.

[7] C.J van Strijp et al., “The Application of Haptic Interface on Micro assembly”, *Proc. Symposium on haptic interfaces for virtual environment and teleoperator systems*, 2006.

[8] Massie and Salisbury,”The PHANTOM Haptic Interface: A Device for Probing Virtual Objects”, *Proc. IEEE International conference on Robotics and Automation, Minopolis*, 1996.

[9] A.Garica Alonso et al., ” Solving the collision detection problem”, *IEEE Computer Graphics and Applications*, 13(3):36-43,1994.

[10] N.Israelachvilli, “The Nature of van der Waals Forces”, *Contemporary Physics*, Vol 15, No.2, pp.159-177. 1974.

[11] Hamaker.H.C, "The London-van der Waals: Attraction between spherical particles," *PhysicaIV*, No. 10, 1058, 1937.

[12] John. T. Feddema et al., “Assembly planning at the micro scale”, Workshop on precision manipulation at the micro and nano scales” *Proc. IEEE international conference on Robotics and Automation, Leuven* , 1998.

[13] Guangyong Li et al., “3D Nanomanipulation Using Atomic Force Microscopy”, *Proc. IEEE International conference on Robotics & Automation, Taipai,Taiwan*, 2003.