Augmented Reality Human Machine Interface for a Teleoperated Nano-scale Interaction and Manipulation System

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Abstract—**Due to its size, objects at the micro/nano scale are very difficult for humans in the macro world to manipulate and interact with. Thus, instead of interacting directly with such objects, it would be advantageous for humans to interact teleoperatively through a micro/nano robot. Developing interfaces for such human-robot control, however, is no simple task. Challenges range from choosing the type of "robot" to intuitively interfacing the robot to the user. This thesis considers one such interface. Still in development, this interface's novelty is its realistic approximate nano-physical and geometry models and capabilities for integration with real-time data. Through simple touch feedback experiments, we will investigate the accuracy of these models and determine future improvements to the interface.**

Index Terms—**machine interface, nanorobot, teleoperation, haptic feedback, nanomanipulator**

1 Introduction

One of the most challenging tasks in the robotics field is manipulating smaller sizes objects that are beyond the capabilities of human sensing and precision. At this scale, surface forces and intermolecular forces dominate over gravitational and other more intuitive forces of the macro world (Sitti, et al; 2003). But, since we live in the macro world, we are not familiar with the effects that these will have on the nano-scale object and how we should interact with it; thus creating a scaling barrier.

To overcome this scaling barrier, one solution is to develop a teleoperation system through which a human could directly manipulate and interact with nano-scale objects. Teleoperation allows for control at a distance (Hollis, et. al; 1990) making it possible for users to comfortably explore an area that would otherwise be too dangerous or unreachable. In this case, the teleoperation system coupled with a graphical user interface, would allow users to interact intuitively with the micro/nano world.

This system also provides a useful tool for researchers in a variety of disciplines such as biology, chemistry and physics. They can use this tool to learn more about the micro/nano world as well as for specific applications such as nanofabrication and cell manipulation (Li, et al; 2003). In addition, it may even be used for educational purposes in classrooms for K-12 students and science museums.

The manipulation system considered in this thesis consists of using an Atomic Force Microscope (AFM) as the nanomanipulation tool. This is interfaced via a graphical user interface to a haptic feedback device. The haptic device, controlled by a human operator, along with approximate nano-physical and geometric models will act as a guide for nanomanipulation tasks. Given this system, the purpose of this thesis is to determine the accuracy of the modeling through a series of experiments. In these experiments, users will perform various nano-scale touch feedback tasks during which data is collected. The collected data will also act as a guideline for improvements to the user interface in the future.

The organization of the paper is as follows. Section 2 introduces the basic tools and definitions that are a part of our teleoperated manipulation system. Section 3 overviews related research in the area, and Section 4 follows by discussing how our system is innovative. Section 5 describes the goals of the thesis. Section 6 details the experiment setup and Section 7 discusses the results. Finally, Section 8 and Section 9 summarizes with some suggestions for future improvement.

2 Basics

This section gives definitions and brief explanations of technologies used in the development of this system.

2.1 Atomic Force Microscope (AFM)

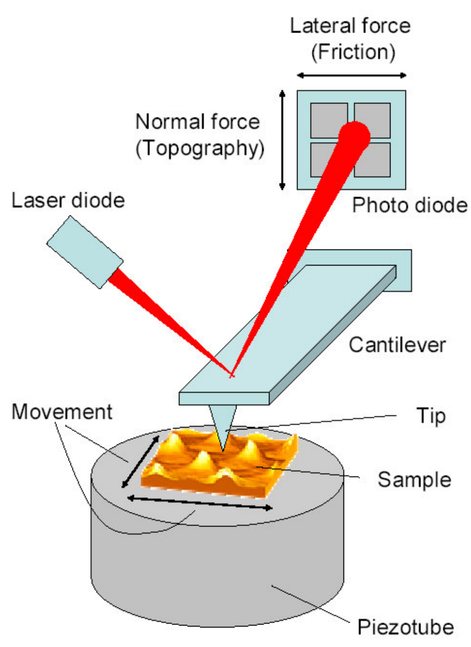


Figure 1: Typical AFM setup (Vogl, 2004).

In order to perform manipulation at the nano-scale, we must find a tool that is both small and versatile enough to manipulate nano-scale objects. For this system, we chose to use an Atomic Force Microscope (AFM). The AFM allows for both visualization and manipulation at the atomic level. The AFM produces topographical images by performing a linear scanning motion with a sharp tip (radius in the range of nanometers). As the tip scans over the sample, the cantilever will deflect relative to the topography of the sample. This changes the angle of deflection of the laser and thus changing the intensity of light that falls on the photo-diode. The photo-diode is divided into four quadrants; the forces acting on the probe is determined by the amount of light striking each quadrant (Morris, et al; 1999). Thus, we can extract the force data and use it to develop the geometric and physical models as well as provide input to the haptic force feedback device.

In addition, the AFM uses a piezoelectric scanner, which gives it a high positioning resolution (below 1nm), applicable for nano-scale manipulation. Thus, the AFM has two functions, imaging and manipulation. Finally, the AFM is flexible since its functionality is not limited to a specific material or environment; it can image and manipulate in most environments including air, vacuum, and liquid.

2.2 Haptic Interface

A haptic interface is an important component in the design of a teleoperated nanomanipulation system. Since the user is interacting with the object indirectly, it is helpful to get as much information about the object as possible. A haptic device provides force feedback information and is useful in helping users modify and extract information about an environment (DiFilippo, et al; 2000). Also, having force feedback is important if the user wants to manipulate fragile material such as cells or other biological samples (Vogl, 2004).

The benefits of using a haptic interface are emphasized by Guthold, et al. Using an AFM for manipulation, they found that using positioning and visual feedback alone was not enough to accurately manipulate an object; this was largely due to the drift and hysteresis effects, characteristic of piezoceramic positioners used in AFMs. With the addition of haptic feedback, they were successfully able to place the tip between two carbon filaments as well as locate an adenovirus even after experiencing large drift.

Our system uses the commercially available 3-DOF Phantom^{tm} by SensAble Corp., integrated using the vendor's Ghost SDK.

2.3 Augmented Reality (AR)

Extending from virtual reality visual interfaces is the Augmented Reality (AR) interface. Like virtual reality, AR allows the user to be completely immersed in a virtual world. However, AR further adds realism by incorporating elements of the real world (Azuma, 1997). This concept can be applied to our human machine interface in order to give the user a more realistic experience. This is further discussed in Section 4.

3 Related Work

Many teleoperated nanomanipulation systems have already been proposed and implemented in the last two decades. Hollis et al. were among the first to develop a teleoperated nanomanipulation system. They chose to use a Scanning Tunneling Microscope (STM) as the nanomanipulator. The STM allows for both visualization and manipulation at the atomic level (Hollis, et al; 1990). In addition, since the STM tip does not have to make contact with the object being manipulated, there is very little tool wear. However, it only works for conducting or semiconductor materials and is almost always used in a vacuum. This limits the range of objects that the STM can manipulate. Because of such limitations, the AFM is the most popular tool for these teleoperated nanomanipulation systems. Although many of these systems have been implemented as research prototypes, one system, the NanoManipulator, developed by a group at University of North Carolina, Chapel Hill (Guthod, et al; 1999) was actually commercialized.

The conclusions that can be drawn from previous work suggest that a haptic interface is a crucial component for telenano manipulation. In addition, physical modeling can greatly enhance the visual experience. Hence, both of these concepts are incorporated in our system.

4 Innovation

Although the AFM has both an imaging functionality as well as manipulation functionality, both cannot be performed at the same time. For both tasks, the AFM probe is required. In the case of imaging, the probe moves in a linear motion, scanning the surface and then returns the resulting image. Manipulation tasks require using the same probe, but for moving particles on the surface instead of scanning. Since the probe can only be used for one or the other, when the AFM is being used for manipulation, there is no real-time visual feedback to show the changes as a result of the manipulation. This makes manipulation a tedious and unintuitive task. The solution that our system proposes is to model these deformations in the graphical user interface. First, the AFM would be used for imaging to get an initial image of the surface. This image would then be imported to the visual interface. As the user teleoperatively controls the AFM using the haptic device, changes to the surface as a result of manipulation are modeled, then visualized through the visual interface in real-time (Figure 4).

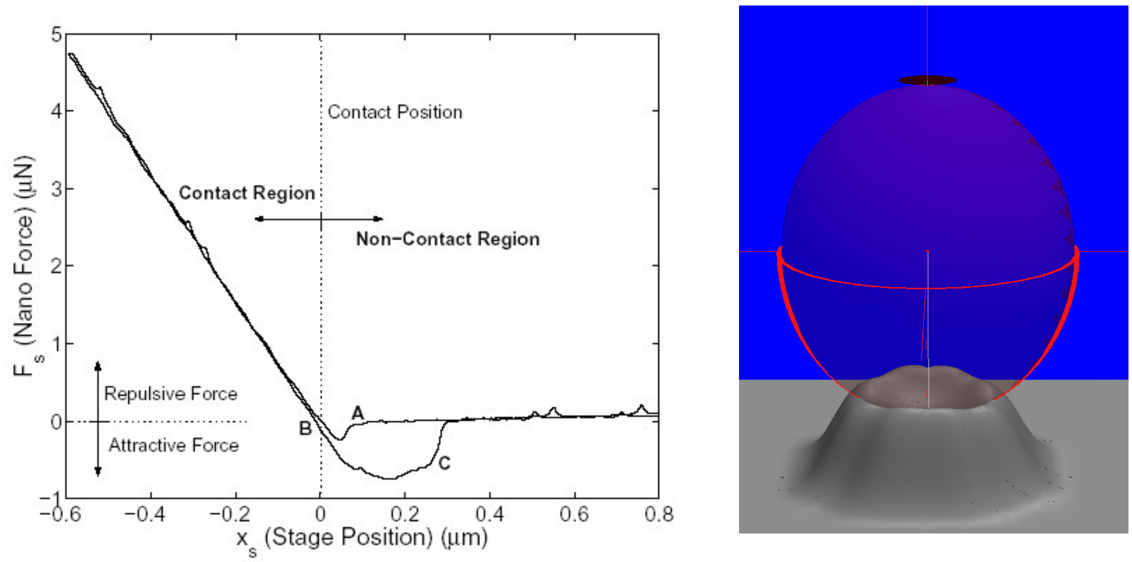


Figure 2: a) Force distance curve during approach to and retraction from a flat surface (Sitti, et al; 2003). b) Neck forming during retraction.

The nano-physical and geometric interactions that are modeled in the system are summarized in Figure 2a. As the probe approaches the surface (A), the main force that is felt is attractive. This force is generally made up of van der Waals, capillary, and electrostatic forces and increases nonlinearly, as the distance between the probe and the surface decreases. When the probe makes contact with the surface (B), several models are implemented including the Hertz Model, Maugis Dugdale, Derjaguin-Muller-Toporov, and the Johnson-Kendall-Roberts (Vogl, 2004), to determine the appropriate surface deformations. Finally, when retracting the probe, due to surface contact forces, the surface will often stick to the probe (Figure 2b) for a given distance before the probe exerts enough force to separate from the surface (C).

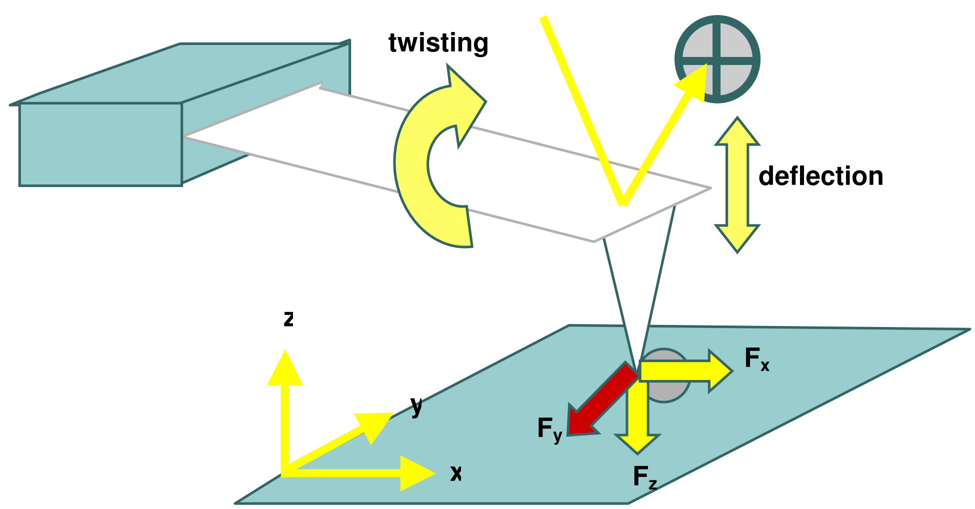


Figure 3: Force breakdown for cantilever during surface interaction.

Another limitation of the AFM is that it only outputs two dimensional force data even though it allows for motion in three dimensions (Figure 3). Namely, we can extract the deflection force ($\mathbf{F_z}$), but the twisting force couples two forces ($\mathbf{F_x}$ and $\mathbf{F_y}$). Many solutions exist to work around this limitation. For example, we can choose to manipulate only in the *y* direction. This way, the twisting force will only have *y* components of the force. Although this may work, it is not a practical solution. In addition, there will always be a component of the force in the *z* direction that is not accounted for. Our system addresses this problem using geometric modeling to determine all the forces. These forces can be computed given the angle and speed at which the probe contacts the surface.

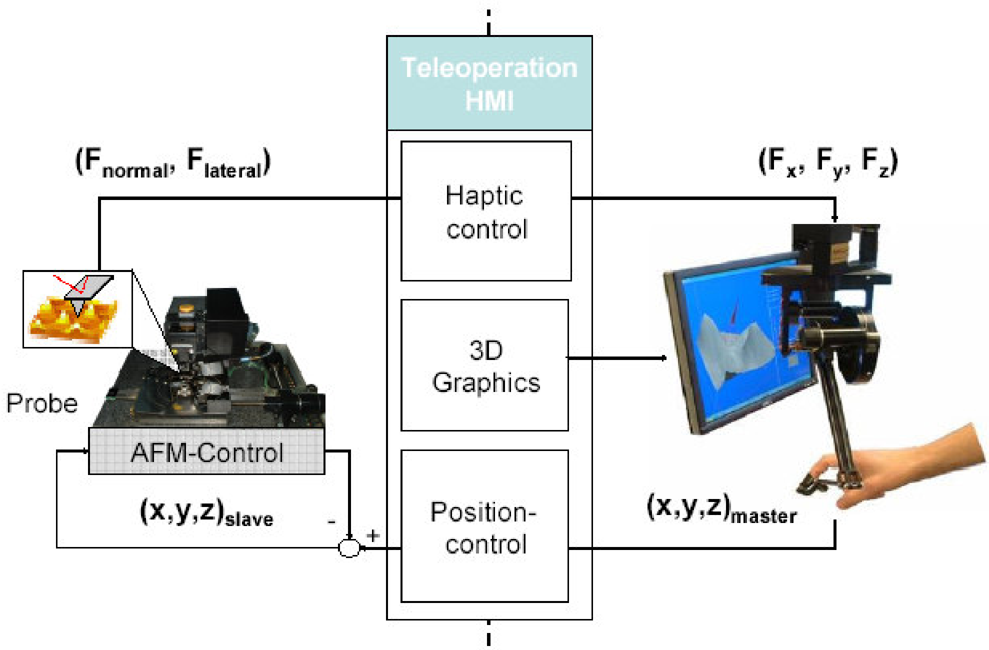


Figure 4: Human Machine Interface setup (Vogl, 2004).

Finally, the system has the capability to integrate with real-time data. Most existing systems only simulate the forces as a result of interactions and forward these forces to the haptic device. In other words, the forces that the user feels are simulated forces, not real-time forces. By merging modeled forces with real-time data from the AFM, we can apply the concept of Augmented Reality to develop a more realistic human machine interface.

5 Goal

This thesis is a continuation of the work started by Wolfgang Vogl. In his thesis, Vogl implemented the nano-physical and geometrical modeling. In addition, he developed a working visual interface (Figure 5), which was integrated to a joystick. My goal with this thesis is to integrate that visual interface to the Phantom^{tm} haptic device in order have force feedback. Afterwards, I want to determine the accuracy of the modeling through a series of experiments. The data collected from these experiments will provide important feedback concerning the accuracy, usability, and reliability of the current system.

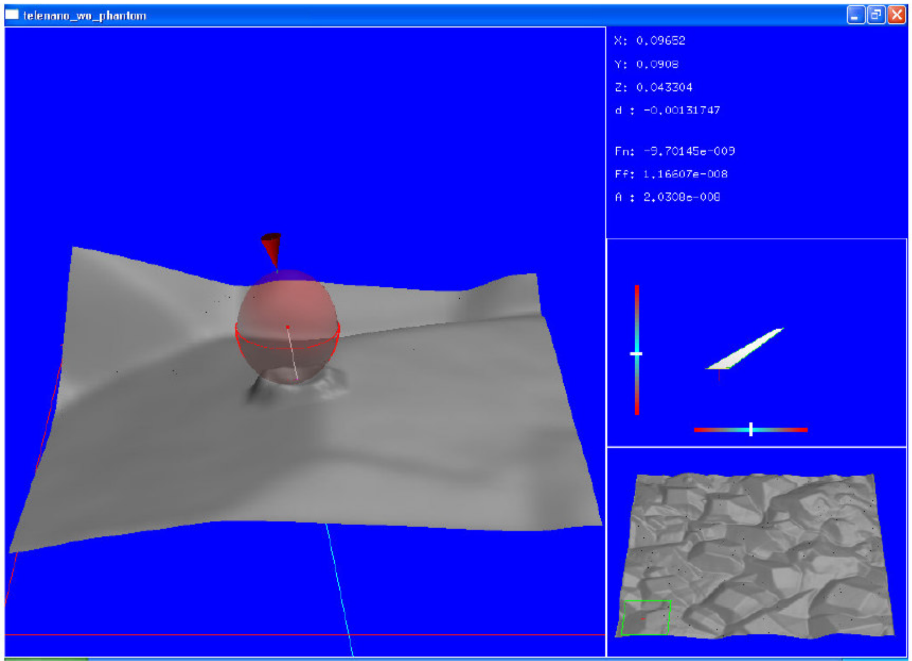


Figure 5: Snapshot of implemented graphical user interface (Vogl, 2004)

6 Experiment Design

This section is an overview of the different components of the experiment. Given our system, the experiment aims to determine the accuracy of our models through various interaction tasks while providing feedback for further improvements to our interface.

6.1 Tasks

Our experiment is made up of three parts. Each involves positioning the probe in a pre-defined position on, above, or below the surface (Figure 6). Each task has its own set of challenges, given that our models accurately approximate the nano-physical properties of the surface. Task A should be the most difficult to achieve. Since Task A requires positioning the probe at such a small distance above the surface, nonlinear forces pulling the probe towards the surface may prevent the probe from being held at that distance. However, this is a crucial task to consider since many applications, such as manipulating carbon nanotubes, require holding the probe up close to but not touching the surface. Task C may not be applicable to surfaces that are very stiff, such as glass.

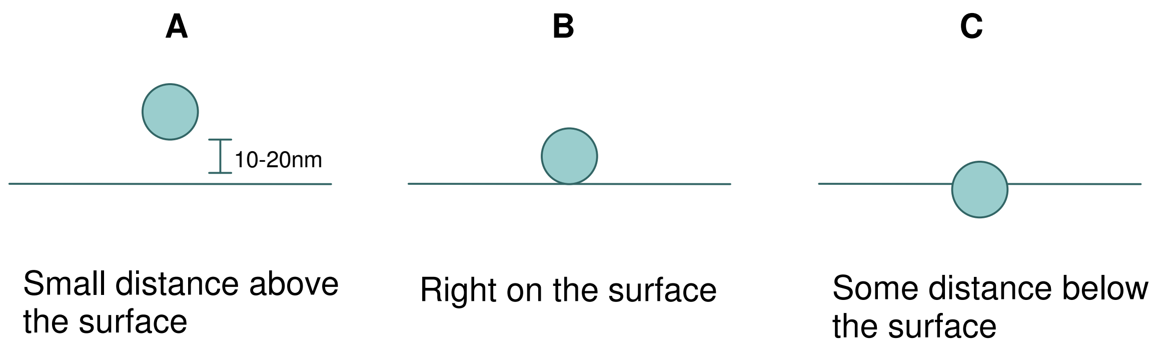


Figure 6: Experiment Tasks

6.2 Constants

For all tasks, we kept our system, consisting of the visual and haptic interface, constant. In addition, in order to decrease the complexity, we performed our experiment on a flat surface. The tip size of our AFM was kept at 15nm (which is the standard tip size for most commercially available AFMs). Finally, we kept the probe stiffness high (14 N/m). This is preferable for two reasons. First, since a stiff probe applies more force on the surface, it is more responsive to topographical changes. In addition, a soft probe would easily be subjected to the attractive nature of the non-contact forces. This makes it difficult to perform tasks that require the probe to be above the surface (such as Task A from Figure 6) since the probe will have a natural tendency to be pulled towards the surface. Thus, high probe stiffness allows us to perform experiments on a larger variety of surfaces.

6.3 Physical Parameters

There are three parameters that we varied in our experiments. One is the Young's Modulus which represents the hardness of the material or surface. Second is the Adhesion or surface energy of the surface; this factor determines how sticky the surface is. Finally, the Poisson ratio is a ratio of the transverse strain to the normal strain of the material. We will use three different types of material ranging from a hard surface (glass) to a soft surface (rubber) each having its own set of values for the above parameters.

Material	**Young's Modulus (*GPa*)**	**Adhesion (*J/m^2*)**	**Poisson Ratio**
Silicon Oxide	70	0.2	0.27
Polystyrene	2	0.066	0.4
Silicon Rubber (PDMS)	0.001	0.022	0.5

Table 1: Material Properties (Whitesides, et al; 2001)

6.4 Method

At the beginning of the experiment, each user was briefly introduced to the system. They had about five minutes to familiarize themselves with the haptic device as well as the visual interface. Afterwards, they began the experiment. For each task, the user's probe position would start approximately in the middle of the surface. They then had to use the global view (Figure 7a) to locate the target (in green), and move towards the target. The goal is to position the probe as close to the target position as possible. The target in the interface is depicted by a three dimensional crosshair (Figure 7b); its center is considered the target position. Hence, the error is measured from this point to the probe's center.

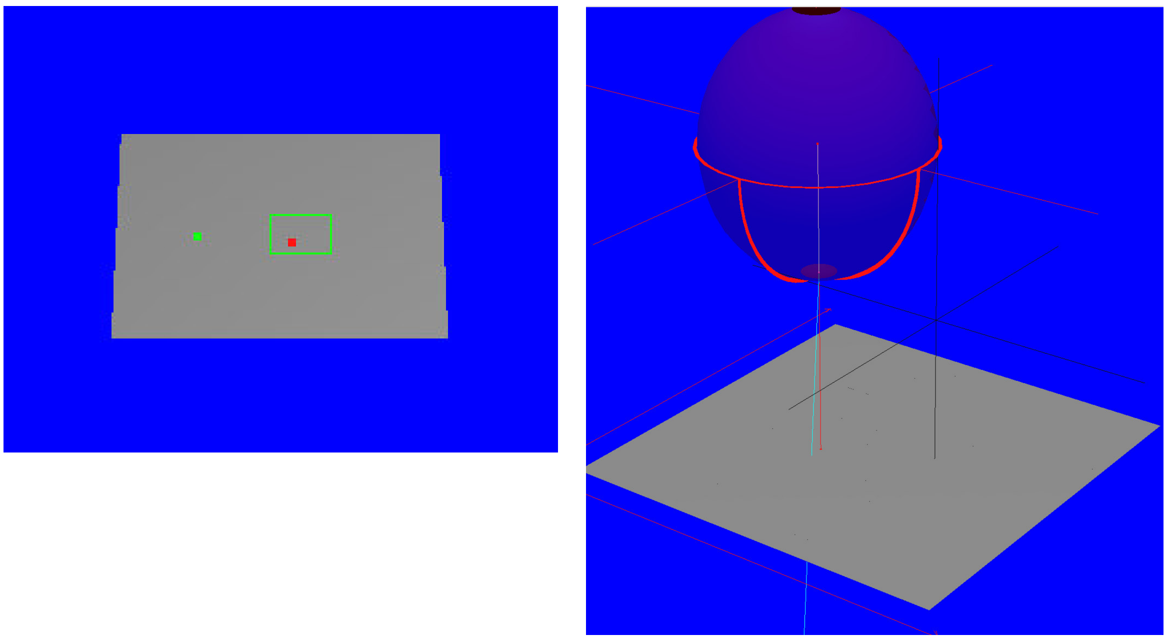


Figure 7: a) Global view of target (in green) b) Detailed view of target (black crosshair).

For each task, the user would press a button to begin, and the same button again when they feel that they have positioned the probe as accurately as possible. Directional buttons allowed the user to rotate the view vertically and horizontally along the plane. After each target acquisition, the material properties would be changed, and the procedure repeated. Each task is performed with all three materials, with the exception of the third task. The third task omits the first material (silicon oxide) since the third task requires deforming the surface; elastic deformation is unrealistic for hard surfaces. Finally, each task is repeated two more times. A total of 162 data points were collected for six different users.

6.5 Evaluation

Positioning error and average time is calculated for each task and material. If our nano-physical and geometry models are accurate, Task A should produce the highest percent error since it is the hardest task to achieve given the nature of the task. Also, Task C should be more difficult with Silicon Rubber than Polystyrene. The softness of Silicon

Rubber will give the user less force feedback, which facilitates overshooting the deformation position. In addition, user's performance should improve with the number of trials since it is expected that they will need some time to become familiar with the interface. For analysis purposes, trajectories and forces are also recorded.

7 Analysis

Before any experiments were conducted, one untrained user was put through certain parts of the experiment and asked for feedback. This was used to make quick improvements to the experimental setup. With the exception of one user, all further experiments were performed with untrained users. For these users, this was their first time using the interface. Data related to the positioning error as well as the time required to complete each task was collected for each task and each material.

This section shows the results and discusses its implications.

7.1 Results

Among the untrained users, it was expected that the percent error would decrease with the trials. We expected to user to become more and more familiarized with the interface and hence, make more accurate target acquisitions. This was not the case however. In fact, we found no correlation between the number of trials and the accuracy of the results. Also, we expected Task A to be the most difficult, and anticipated that it would have the highest percent error. Based on our data (Figure 8), Task B had the highest average percent error, followed by Task C and then Task A.

		Task A	
% Error	1.2043	0.5834	1.0815
Standard Deviation	0.0042	0.0015	0.0033
		Task B	
% Error	4.9840	5.4377	3.7258
Standard Deviation	0.0290	0.0292	0.0182
		Task C	
% Error	--	0.3849	2.8754
Standard Deviation	--	0.0017	0.0210

Table 2: Average error for each task and material.

The difficulties in terms of materials are fairly even for Task A (Figure 8). Silicon Oxide and Polystyrne made Task B more difficult than Silicon Rubber. And Task C was much more difficult in Silicon Rubber than Polystyrene.

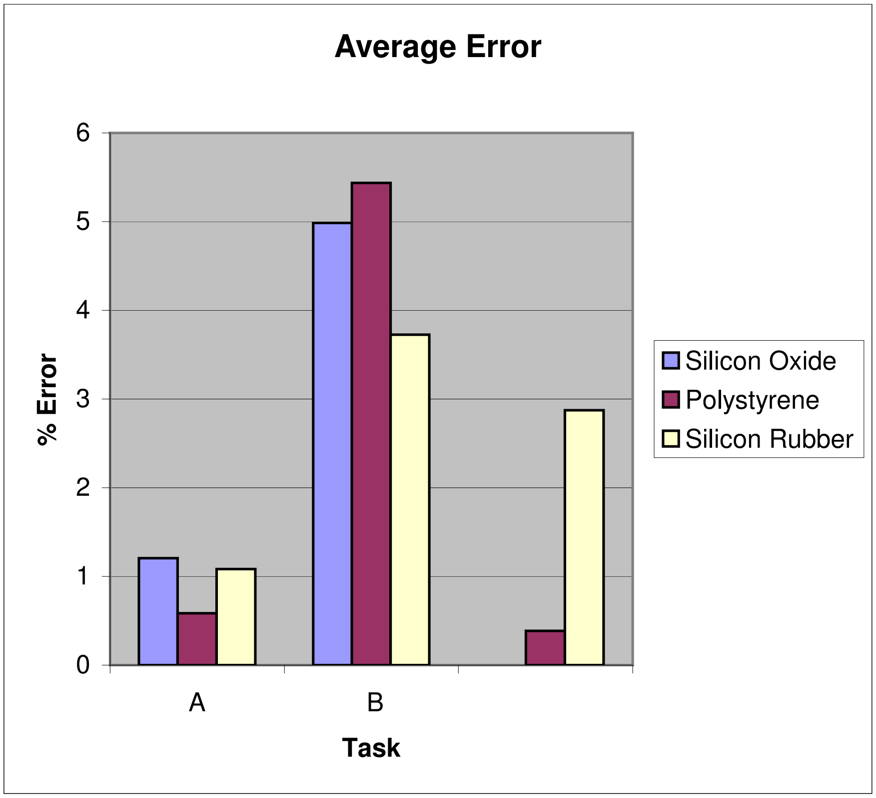


Figure 8: Comparing the average error for each task and material.

As for time, we expected the time required to perform each task to decrease with the trials. This was also not the case. In addition, it was expected that if the average time was longer, then the percent error should be less. This is because the user would be taking more time to perform the task, hence making fewer accuracy errors. With the exception of Task C, no correlation was found between how accurate a user was, to the average time required to complete the task. The faster users did not necessary have a higher average error and likewise, the slower users did not necessarily have a lower average error.

	Task A		
Average Time (s)	55.1718	53.9956	66.1701
Standard Deviation	42.3996	44.3393	37.8873
	Task B		
Average Time (s)	45.968	58.652	58.5855
Standard Deviation	31.7144	40.5768	46.2726
	Task C		
Average Time (s)	--	85.8862	47.4735
Standard Deviation	--	106.8324	27.2539

Table 3: Average time to perform each task.

For Task C however, the average time required to complete the task for Polystyrene is much higher than more Silicon Rubber (Figure 9). Consequently, the average error is much less for Polystyrene than for Silicon Rubber.

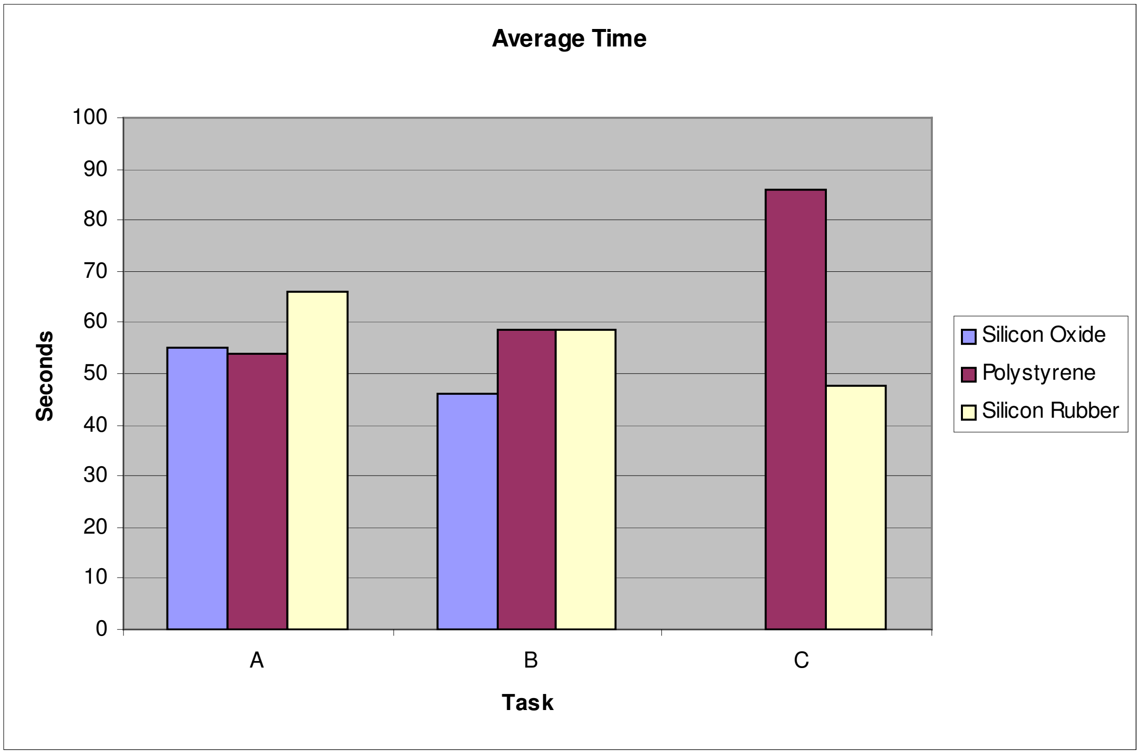
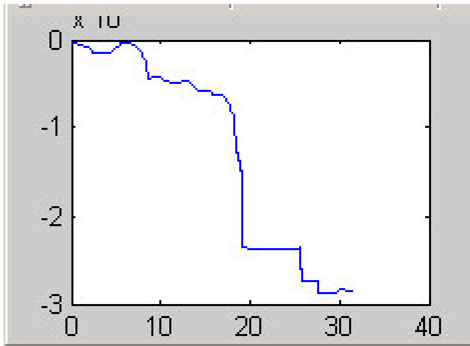


Figure 9: Comparing the average time for each task and material.

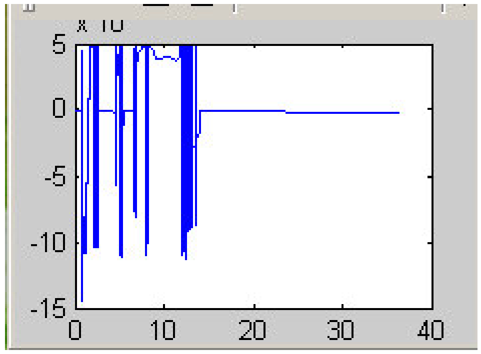
7.2 Discussion

Although Task A (positioning the probe slightly above the surface) seemed like the hardest task, most users did not have much difficulty completing it. It seemed manageable, especially if the user made contact with the surface first. Using this strategy, the user did not have to feel the nonlinear forces, since they were already making contact with the surface. Hence, they simply had to apply a force to counter the contact forces, which are much more stable than the nonlinear forces. This strategy was not as successful for Silicon Oxide. Silicon Oxide has a higher Young's Modulus. Since it is a harder material, when pulling up from the surface the probe does not stay in contact with the surface as long as for softer materials. Users who made contact with this type of surface had to first apply a force to disengage from the surface in order to reach the target position. The extra force caused the user to go beyond the target, requiring them to then reposition.

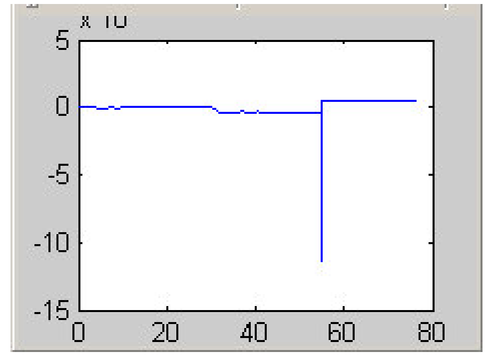
Task B (positioning right on the surface) was the most challenging. Most users wanted to position the probe slightly above the surface, instead of on the surface itself. Therefore, they were constantly fighting the nonlinear forces. These forces caused the haptic device to oscillate, making if difficult for the user to hold it still. In essence, this task unexpectedly represented the difficulties of what we initially predicted Task A would represent.



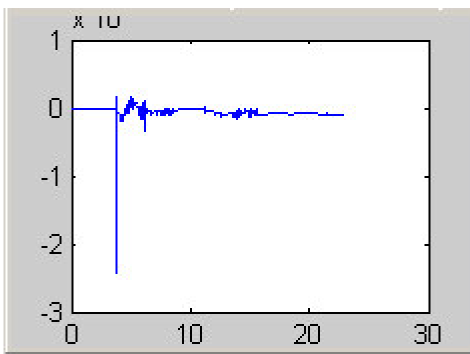
Task A – Silicon Oxide



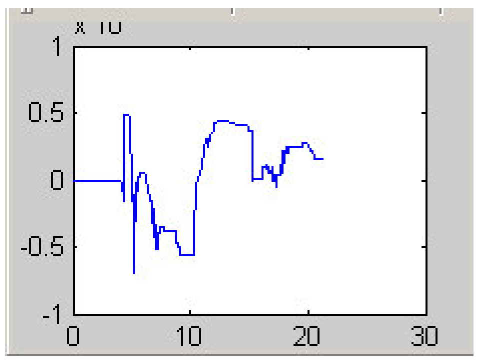
b. Task A - Polystyrene



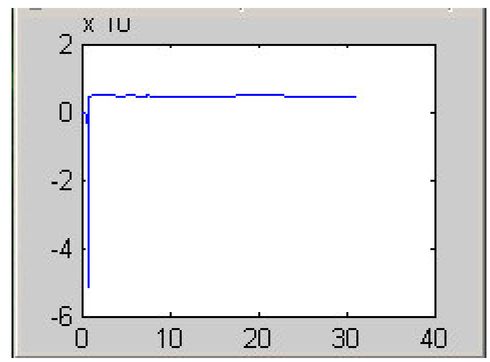
c. Task A – Silicon Rubber



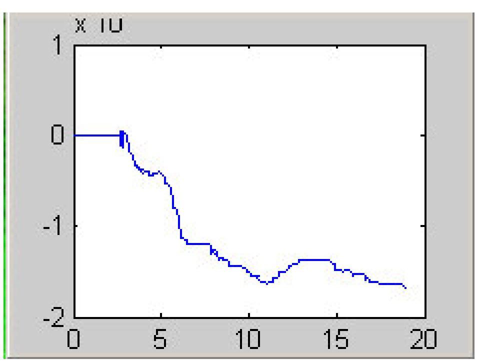
d. Task B – Silicon Oxide



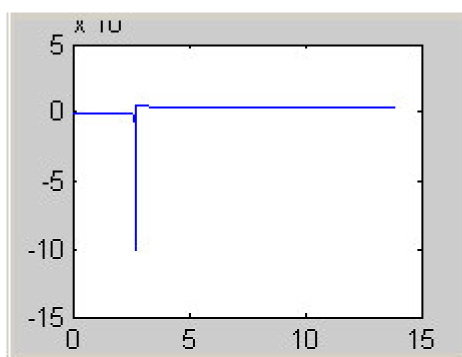
e. Task B – Polystyrene



f. Task B – Silicon Rubber



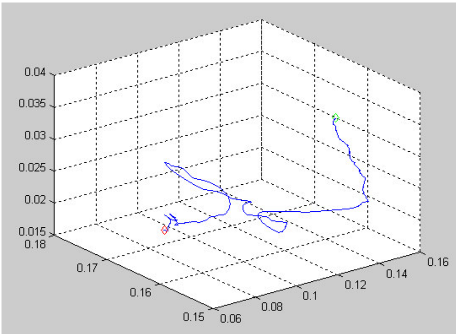
g. Task C - Polystyrene



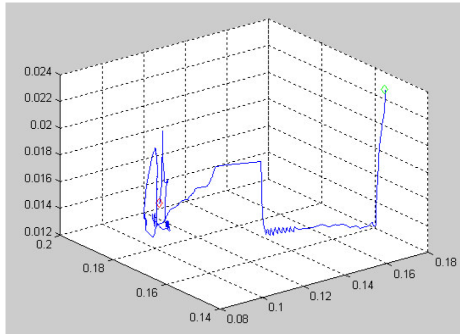
h. Task C – Silicon Rubber

Figure 10: Sample force plots for each task and material.

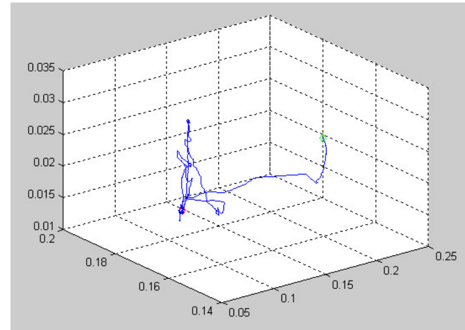
As predicted by our models, Task C (positioning below the surface) had a higher percent error for Silicon Rubber than Polystyrene. The softness of Silicon Rubber resulted in less normal force feedback (Figure 10c, 10f, and 10h); this made it easier for users to unnoticeably push too far into the surface, surpassing the target position.



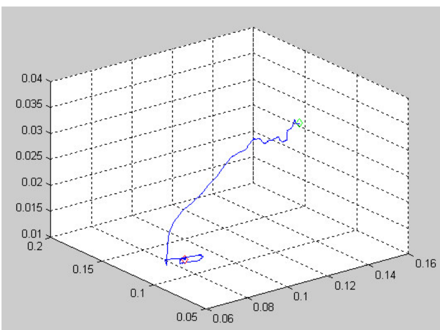
a. Task A – Silicon Oxide



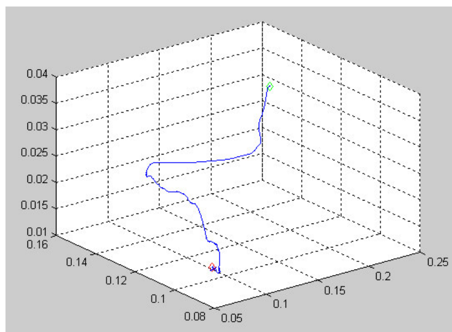
b. Task A – Polystyrene



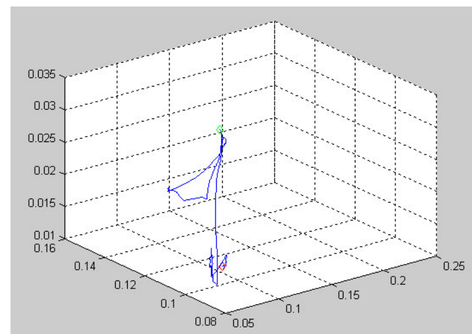
c. Task A – Silicon Rubber



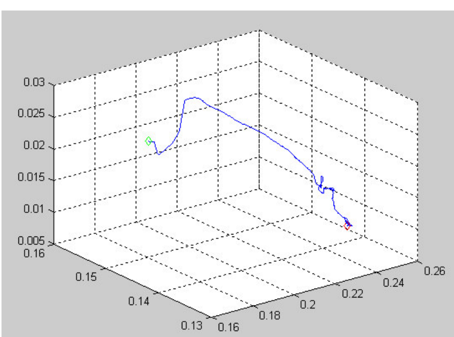
c. Task B – Silicon Oxide



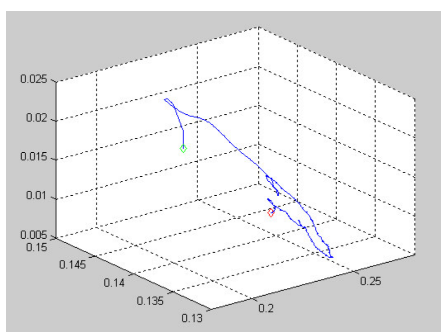
d. Task B – Polystyrene



e. Task B – Silicon Rubber



f. Task C – Polystyrene



g. Task C – Silicon Rubber

Figure 11: Sample trajectory plots for each task and material of trained user. The green diamond represents the starting position, and the red diamond represents the target position. A trained user is one who has used the interface for more than 10 hours.

The average time required for each task did not vary based on the number of trials. Depending on the trial, some users encountered more difficulties with one trial than with another trial of the same task and material. This was caused by unexpected interactions that took place during the trial. For example, for Task A on one trial, the user might easily move to the target position without any complications. For another trial, however, they may accidentally make contact with the surface; therefore, they will have to adjust the probe, taking more time. As a result of these random interactions, the time required to complete each task does not necessarily decrease with each trial as predicted. By the same reasoning, it is also not necessarily true that the more time spent on a trial the more accurate the trial.

These results suggest that many challenges exist in the nano-scale manipulation. Despite these challenges, with some training, it is possible to achieve good accuracy and smooth trajectories (Figure 11).

8 Conclusion

The results show that our approximate models are accurate given a simple flat surface and the above tasks. Although, the results for Task A did not support our initial hypothesis, this was not due to incorrect modeling. In our prediction, we did not account for the approach the users would use in order to accomplish the task; the common approach eliminated what we had intended to be the challenge. Task B effectively replaced the challenge expected for Task A. Thus, making it the most difficult task as supported by our results. In addition, the results for Task C, by distinguishing between Polystyrene and Silicon Rubber, suggests that the users had realistic feedback both visually as well as haptically.

9 Future Work

For most users, the main challenge with each task was aligning the probe with the target in three-dimensional space. In many instances, although visually they thought the probe was aligned with the target, it was actually off-target on one more or planes. The users quickly developed strategies to overcome this difficulty. The most common strategy was to orient to a top view, align the target on those two axes, and then orient to a side view to align the last axis. The success of this strategy suggests that the interface should include a top and side view panel or a toggle button, which would orient to those views automatically. In addition, in order to test the robustness of the models, further experiments should be conducted using a different series of tasks and a more complex surface. These tasks should also involve more manipulation.

Since the forces that act on the probe are in the order of nanoNewtons, we need to scale those forces so that the user in the macro world can feel them intuitively. This is not an easy task since the forces can vary greatly; normal forces can be two or more magnitudes more than the friction force. Also, normal forces are much higher for harder surfaces than for softer surfaces. Thus, for the purpose of these experiments, the scaling factors were chosen based on intuition. However, in the future, a more accurate method to determine these scaling factors should be implemented, maybe as a form of calibration before the system is used for manipulation.

After the accuracy of the models is verified, the system should be integrated with the AFM in order to obtain real-time data. Only after a fully developed system is implemented can we start to explore other areas of improvement. One such area, suggested by Vogl, is to take the graphics to a new level by creating animations of objects being manipulated.

References

[1] R. L. Hollis, S. Salcudean, and D. W. Abraham, "Toward a tele-nanorobotic manipulation system with atomic scale Force Feedback and Motion Resolution," *Proc. of the IEEE Int. Conf. on MEMS*, pp. 115-119, 1990.

[2] G. Li, N. Xi, M. Yu, F. Salem, D. Wang, J. Li, "Manipulation of Living Cells by Atmoic Force Microscopy," *IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, 2003.

[3] W. Vogl, "Tele-presence at the nano scale: augmented reality interface to scanning probe microscopes," 2004.

[4] R. T. Azuma, "A survey of augmented reality," *Presence: Teleoperators and Virtual Environment*, pp. 355-385, August 1997.

[5] M. Guthod, M. Falvo, W. G. Matthews, et al., "Investigation and modification of molecular structures with the nanoManipulator," *Journal of Molecular Graphics and Modelling*, vol. 17, pp. 187-197, 1999.

[6] M. Sitti and H. Hashimoto, "Teleoperated touch feedback from the surfaces at the nano-scale: modelling and experiments," *IEEE/ASME Transactions on Mechatronics*, vol. 8, March 2003.

[7] V. Morris, A. Kirby, A. Gunning, "Atomic Force Microscropy for Biologists," *Imperial College Press*, 1999.

[8] D. DiFilippo and D. K. Pai, "Contact interaction with integrated audio and haptics," *ICAD*, 2000.

[9] G. Whitesides, E. Ostuni, S. Takayama, X. Jiang, and D. Ingber, "Soft Lithography in Biology and Biochemistry," *Annual Review of Biomedical Engineering*, vol. 3, pp. 335-373, August 2001.

[10] National Council of Examiners for Engineering and Surveying, "Fundamentals of Engineering (FE) Supplied-Reference Handbook", *6th Edition,* 2003.