Real-Time Simulation of an Atomic Force Microscope Cantilever

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Abstract
One of the main research topic of our department is the advanced control strategies. The real-time simulation of the Atomic Force Microscope (furthermore AFM) offered us a remote environment for telemanipulation. A special master device for AFM is still under development at our department. In this paper, telemanipulation, and working of the real AFM device introduced, and the results are presented. Those advanced control strategies has used for this master device. The aim of this paper is to introduce the current state of the development.

1. Introduction to Telemainpulation

Telemanipulation is a process where the operator has some task done at the far environment where he/she cannot be physically. The first modern master-slave system teleoperator was developed by Goertz at Argonne National Laboratory [3] in 1945. Telemanipulation is divided into two strongly coupled processes. One process is the interaction between the operator and the master device, the other is the interaction between the slave device and the far environment contact. The master device represents the far environment at the operator site, and the slave device represents the operator at the remote site. The information flow between the operator and remote site can be seen on Fig.1, where only three types of information are feedback: visual, audio and sense of touch. The human beings get six types of sensing from the environment surrounding them but only some of these sensing are used during telemanipulation. When humans use this device only to move objects and the reaction force from the far environment has no significant effect on the performance, then measurement of the operator's position and visual feedback may be enough. But if such tasks are to be performed when the reaction of the environment is important and the slave device can make damage in the far environment like when screwing a bolt or assembling something, then we need force feedback to improve efficiency. Force feedback increases the feeling of telepresence. Telepresence is the psychological feeling of "being there" in an environment based on a technologically founded immersion environment.

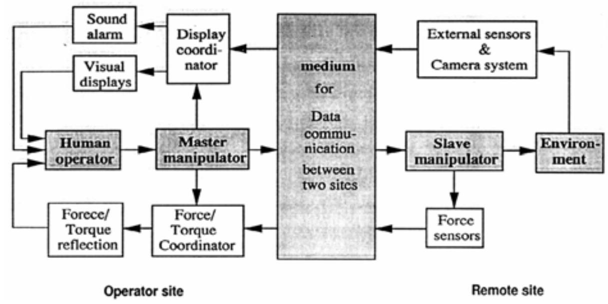

Figure 1: Information streams of the Telemanipulation

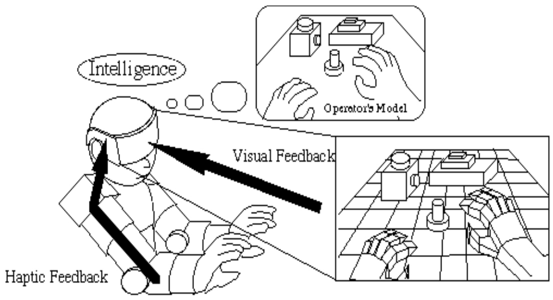

Figure 2: Telemanipulation in the virtual reality

It should provide the ideal sensation, i.e. we get the necessary information fed back from the slave to the master side in a natural way to have the feeling of being physically at the distant location. Force feedback not only increases efficiency, but it helps to filter the smaller imprecisions of the operator.

1.1 Telemanipulation in the virtual reality

A special instance of telemanipulation is telemanipulation in the virtual reality. It is beneficial when the operator is learning performing dangerous tasks such as working with radioactive materials or explosives; or when the operator is learning working in a special simulated virtual environment. For example real time airplane, helicopter or submarine simulators belong to this case. Telemanipulation in the virtual reality application is shown on Fig. 2. The operator wears a **head-mounted device** giving visual feedback and **an arm and glove type master device** giving tactical sensation. The operator can see the visual objects and can touch and move them. A short summary of the master devices can be found in the [1].

1.2 Micro/nano telemanipulation

A micro tele-operation system has been constructed, which enables human operators to operate micro tasks, such as assembly or manufacturing. A haptic interface provides the operator with the feeling that he/she touches the expanded micro objects with his/her fingers. A micro tele-operation system shown in Fig. 3. The local site system is the haptic device and the controller, and the remote site is the Nano-Robot System and it's controller. The Teleoperation Control responsible for a proper coupling between the macro and micro world. In the following section a possible solution is given for the proper coupling: virtual coupling impedance.

1.3 Virtual coupling impedance

Force and position scaling is an important issue in the micro/nano remote environment. There are basically two approaches: linear and nonlinear scaling. In the case of linear scaling a single corresponding constant is used between the micro/nano force/position and macro force/position:

$$\begin{aligned} x_s^*(t) &= \alpha_p x_s(t) \\ F_s^*(t) &= \alpha_f F_s(t) \end{aligned} \tag{1}$$

where x_s^* and F_s^* are the scaled values, α_p and α_p are the constant position scale respectively. In case of nonlinear scaling which is also called impedance scaling [2], forces are scaled independently with respect to their length scaling power relation as follows

$$\begin{aligned} x_s^* &= \alpha_p x_s(t) \\ F_s^* &= \alpha_p^3 M_V \ddot{x}_s + \alpha_p^2 B_V \dot{x}_s + \alpha_p K_V x_s \end{aligned} \tag{2}$$

Where M_V is the virtual mass, B_V is the virtual viscosity constant and K_V is the virtual stiffness. Note that this scaling method is similar to the concept of virtual impedance, which is well-known in the control theory of manipulators. In this paper the name "virtual coupling impedance" is used instead of "virtual impedance concept" to avoid confusion of virtual impedance between information transfer and virtual impedance of an object in virtual reality. Impedance scaling gives better performance in micro/nano telemanipulation applications because of the bandwidth effect. In this approach, the inertial forces can be magnified so that the operator can feel close to his/her daily experience. But this approach requires precise environment parameters while the linear scaling does not.

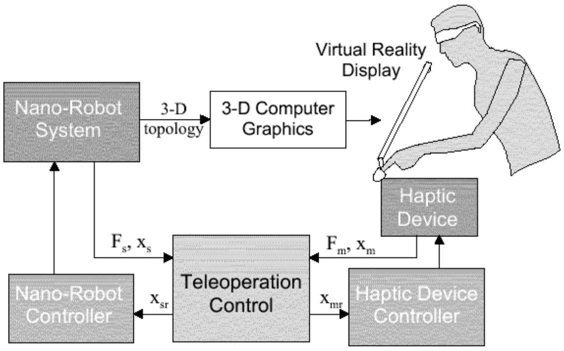

Figure 3: The structure of a teleoperated nano manipulation system.

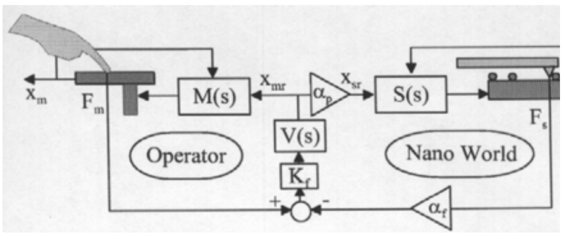

Figure 4: Telemanipulation in the micro/nano space using virtual coupling impedance

The bandwidth effect is the difference between the bandwidth master force feedback device and the slave micro/nano actuator. As a rule the micro/nano actuator has a smaller time constant than the macro force feedback device. So an impedance scaling is necessary to avoid instabilities and unreliable force feeling. Dynamically scaled telemanipulation of micro/nano environment is shown on Figure 4. The applied force by the operator is compared with the scaled micro/nano force.

The difference force is the input of the virtual impedance (V(s)). The output of V(s) is the reference position both of the master (M(s)) and the slave (S(s)) system. Let us suppose that the master and slave devices are faster than the virtual coupling impedance. In this chase the operator can feel the virtual coupling impedance loaded with the force from the nano word. This configuration is shown on Figure 5.

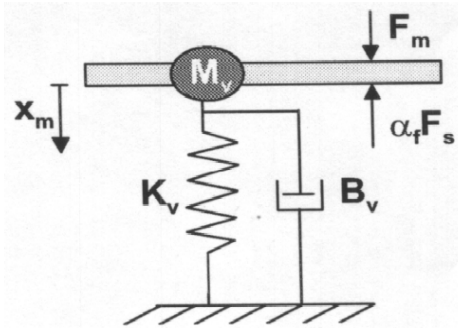

Figure 5: The concept of virtual coupling impedance for micro/nano telemanipulation

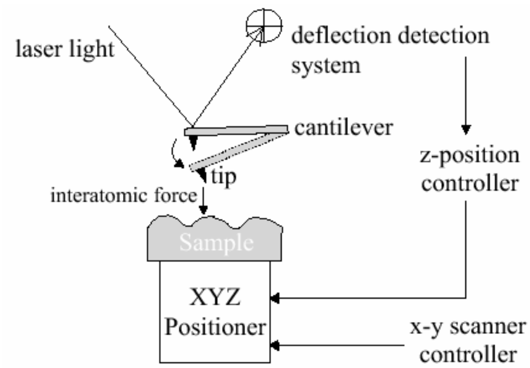

Figure 6: The Basic structure of a conventional AFM device

2. The AFM Device

2.1 Layout of the AFM device

The Atomic Force Microscope (AFM) is used as a 3-D topology microscope, contact manipulation tool, or a force sensor. The basic structure of a conventional AFM system is shown in Figure 6. The basic components of AFM are the MEMS fabricated flexible cantilever beam, the deflection measurement system with atomic resolution, and XYZ positioner with atomic resolution. Cantilever has a measured spring constant k_c, resonant frequency f_r, 100-400 μm length and few micrometer thickness and very sharp conical, pyramidal or cylindrical tip with 10s of nanometer apex radius. Cantilever beam deflection can be measured using a laser light with four-cell photodiodes, conductance measurements, or piezoresistance or piezoelectricity measurement depending on the cantilever type and purpose. Using piezoelectric actuators with or without integrated sensors, the z position of the tip or sample is changed until there is a contact between the cantilever tip apex and sample atoms. Due to long-range or short-range attractive or repulsive interatomic forces, the cantilever is deflected as depending on the tip-sample distance.

2.2 The simple model of AFM device

This section contains the model of the AFM which was used as a real-time remote environment for telemanipulation. The cantilever of AFM can be modeled as a simple 1DOF Spring-Mass-Damper system. This model is valid only during approaching and/or touching the sample. In this paper focused on this basic movements of the AFM. Because of the bandwith effect, the local site “see” only the virtual coupling impedance. For this reason it is not necessary a high computing capacity to model the AFM device with 100 kHz natural frequencies. Computing capacity is focused only the Spring-Mass-Damper system which shown on Fig. 7. But the computing of the nano forces is necessary and these forces are highly nonlinear. The following forces was modeled:

- Non contact forces: Van Der Waals, Elektrostatics and Capillar
- Contact forces: stiffness and damping of the sample

The gravity force can be neglected.

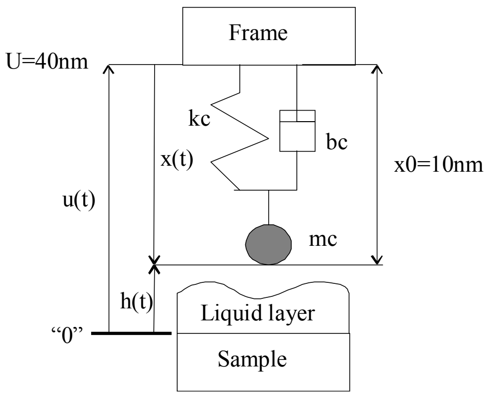

Figure 7: The real-time model of the AFM as a simple harmonic oscillator

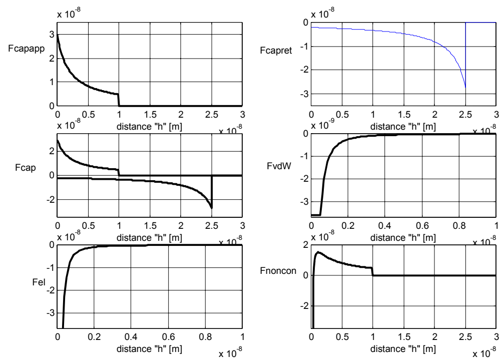

Figure 8: The non contact nano forces

$$m_c\ddot{x}(t)+2m_cb_c(\dot{x}(t)+\dot{u}(t))+k_c(x-x_0)=\begin{cases}F_{non.con}(h(t))-B_0^l\dot{h}(t)u(h(t)-L_l) & h(t)<a_0\\ F_{con}(h(t))-B_0^s\dot{h}(t) & h(t)\geq a_0\end{cases}\qquad(3)$$

Where m_c the mass, k_c the stiffness and b_c damping coefficient of the cantilever. F_{noncon} is the sum of the noncontact forces and the F_{con} is the contact force.

3. Experimental Results

3.1 Simulation of the nano forces

The nano forces can be seen on Figure 8. The upper row is the capillar force. The capillar force is acting, when the tip of cantilever reach the liqud layer on the sample. The thickness of the liquid layer is 10 nm, which can be seen on the upper left corner. The van der Waals and the electrostatic force has same shape, but the electrostatic force is about 10 times stronger.

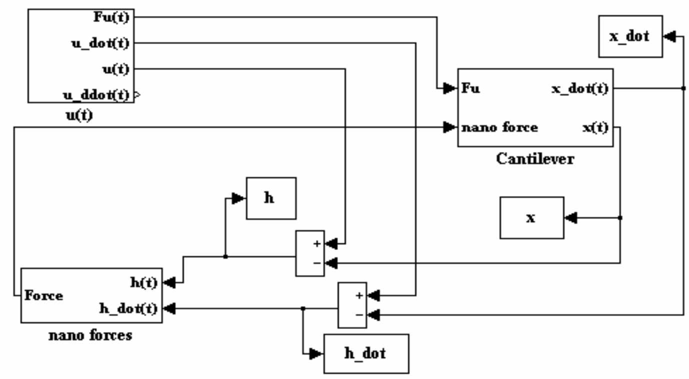

Figure 9: The block diagram of the experimental results

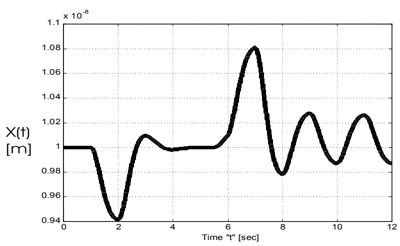

Figure 10: The movement of peak of the cantilever

3.2 Simulation of the AFM device

The connection diagram of the real-time simulation of the cantilever can be seen on Figure 9. The cantilever box contains the state space model of the cantilever. The nonlinear nano forces are in the „nano forces ” block. The first step of the simulation to build the block diagram into Simulink. Simulink is a block-oriented simulation environment under Matlab. Then comes the non-real-time simulation. In this case the simulation running on the PC’s own CPU. Parameters can be easily change in this stage. The last step, when the program of the simulation is downloaded into the DSP. The deflection of the cantilever “x(t)” can be seen of Fig 11. When the frame on (Figure 7.) accelerating toward sample then the state position ”x_0=10nm” decreased. When the frame has stop, the deflection increasing. The vibration caused by the non contact forces. The “h(t)” denote the distance between the sample and the tip. An approaching can be seen On Figure 11. The initial distance is 30nm. After the first second the frame starts to approach the sample. When the tip reach h(t)=10 nm, then the tip connect to the water layer. Capillar force is acting between the tip and the liquid layer. After the 8^{th} second the frame has stopped. The tip is in the liquid layer, where acting the capillar, electrostatic and the van der Waals forces. Those forces excited the vibration.

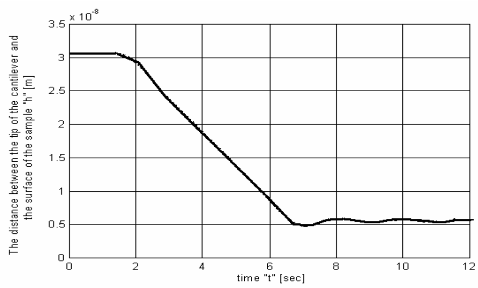

Fig. 11. The distance between the tip of the cantilever and the surface of the sample h(t)

Conclusion

In this paper a real-time simulated nano virtual reality is introduced. This virtual reality used as a far environment for telemanipulation. In the experimental results nano forces and real-time simulation was introduced. Floating point DSP is used as a real-time hardware.

In this paper focused only the nano virtual reality. A special master device is under development at our department. The floating point DSP hardware has enough computing power to control the master device and calculate the nano world. Master device will connect to the DSP hardware, which contains the control of master device and nano virtual reality.

Acknowledgement

The authors wish to thanks to Prof. Hideki Hashimoto and his research fellows from University of Tokyo and PhD. for their support.

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