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Telerobotic Macros for Remote Handling of Protein Crystals

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Abstract

A combined University / Industry team has developed a prototype system for handling protein crystals aboard the space station. This system uses a miniature direct drive robot, CCD television cameras, and a client-server computing system using internet protocols to support the capture of protein crystals from aqueous growth solutions. The system was demonstrated between Huntsville AL. and Seattle WA. An operator in Huntsville controlled the mini robot by invoking pre-defined relative and absolute macro files. A set of movement macros (a predefined sequence of multi-device movement commands) were developed to support precision motion between task locations in the glovebox. The operator can invoke the macros by clicking icons in the remote control interface. The system is a promising start for the development of a space-station based remote protein crystal analysis facility.

Introduction and Literature Review

Growing crystals of biologically significant proteins in microgravity is a scientific opportunity unique to space. Protein crystals are necessary for X-ray crystallography, the major technique for determining the chemical structure of proteins. It is hoped that the use of microgravity will allow determination of the structure of new and medically significant proteins. So far, no crystal has been grown in space which could not be grown in the earth's gravity field. However, controlled studies have shown that crystals with fewer flaws can be grown in microgravity which leads to higher signal to noise ratio in the X-ray diffraction results (Normile, 1995, Stoddard, et al., 1992, 1993).

There are concerns about the availability of crewtime for experiments planned for the space station. Telerobotics may provide a solution to this problem by allowing some scientific operations to be conducted from earth by remote control. This paper describes an initial demonstration of telerobotic capabilities for the handling of materials and samples in micro-gravity protein crystal growth experiments.

Protein crystals grow in aqueous solutions under delicately controlled conditions in days or weeks. They are about 0.5 mm in size and of a gelatinous consistency. Before they can be analyzed by the X-ray beam, they must be "mounted" in glass capillaries of about 1 mm inside diameter. The process of mounting protein crystals is a delicate manual operation considered to be challenging for trained human operators. In one commonly used method, the crystal is first aspirated from its growth medium into the water filled capillary. Then water is removed from the capillary, causing the crystal to adhere to the capillary wall by surface tension, and the ends are sealed. This process is usually accomplished by a human operator looking through a dissecting microscope, and is often performed in a cold room kept at 4 degrees centigrade.

Our project was designed to determine whether it is feasible to perform the initial steps of protein crystal mounting via remote control over an internet link. The eventual goal is a functioning system aboard the space station in which ground-based scientific investigators can handle most or all of the protein crystal mounting steps by remote control.

Direct drive (DD) robots have been studied for the past several years, primarily at a size scale similar to human arms (Asada & Kanade, 1983, Kazerooni, 1989). One of the key problems with direct drive robots is excessive power dissipation under gravity loads. Clearly this is not a problem in space. It turns out that even in the 1g environment, scaling analysis shows that as DD robots are made smaller, the excessive heat dissipation problem rapidly decreases (Hannaford et al., 1996). Thus the benefits of direct drive, high precision and high speed, are available at this smaller scale for both earth and space based applications. The University of Washington Mini-DD Robot is a small 5-axis manipulator designed to support precision manipulation tasks in biomedical applications. Engineering details of the robot have been previously reported (Hannaford et al., 1994, 1995, 1996). It is ideal for the protein crystal mounting application because of its small size

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Figure 1: Hardware Configuration

(about 15 cm x 30 cm x 10 cm), weight (800g moving parts), and power consumption (7 W nominal, 63 W peak). The small system size allows it to fit within existing space station facilities (such as the European Space Agency (ESA) Microgravity Glove Box) with sufficient extra room for experimental equipment.

Recently, the internet has been used for telerobotics. Kim and Bejczy (1993) teleoperated a 7 degree of freedom robot using a transcontinental internet link for joint motion commands and a satellite link for returning video. Goldberg et al. (1995) created a teleoperation user interface supporting point-to-point motion commands with still video returned to the operator using the world wide web standard, Hypertext Transfer Protocol (HTTP).

The currently planned space station communication link is the same TDRSS system used by the space shuttle; this link is expected to be a tightly contested resource during space station operation. Boeing Defense and Space is studying alternatives through which internet links can be provided via one of the Low Earth Orbit cellular satellite networks now under commercial development. This link could then provide internet services to the space station.

Hirzinger et al. (1993) have performed the only telerobotic experiment actually flown in orbit. Their ROTEX experiment, which included control from the ground, confirmed the ability of an advanced, sensor rich, arm to control contact forces and capture a free floating object. However, the ROTEX arm was a full-sized robot arm and was not integrated into an existing space research task.

This paper will provide a high level overview of the protein crystal growth demonstration system (PCGDS) designed by University of Washington, Boeing Defense and Space, and Vanderbilt University during the last year.

Hardware Description

The system hardware can be divided into four groups: workspace, power control, manipulation, and video. The workspace (Figure 1) is contained within a physical mock-up of the ESA spacestation glovebox—a ventilated work area with a clear plastic front, approximately 0.9m wide by 0.6m high by 0.5m deep. Two ports in front allow an astronaut to insert gloves to directly manipulate an experiment. In the demonstration task, simulated protein crystals (0.5mm plastic cubes) must be captured and extracted from a drop of water in a 3 mm diameter well which is part of a 24-well CrysChem tray (standard biological labware used for growing protein crystals). The tray is situated on the stage of a microscope to provide a close-up view of the well, the crystal and the robot end-effector.

Below the glovebox is an electronics bay containing power supplies, motor controllers, and power control relays. A programmable logic controller (PLC*Direct* series 205 Micro PLC) controls power for all subsystems. Both logical combinations of inputs, and time sequencing can be programmed to control the state of the power distribution system using ladder logic. The PLC will initialize the entire system to a desired state after a power failure.

Although the PLC is not envisioned as a component of a flight system, it provides a highly flexible and robust means to support the demonstration system.

Manipulation capability is provided by the UW five-axis mini DD robot mounted on a linear motion base with up to 30cm of travel to extend the robot's reach to multiple work stations. The robot end-effector is a micro-pipetting system consisting of a capillary connected by flexible tubing to an automated syringe pump. The robot subsystem consists of the 5-axis mini-robot itself, power amplifiers to run the robot actuators, and a control computer (TMS320C30 floating point Digital Signal Processor (DSP)). The DSP board generates smooth trajectories between commanded end points using a 3rd order polynomial. PID control software for each joint generates actuator current commands for the power amplifiers. Control and trajectory generation operate at a clock controlled interrupt rate of 1000 Hz.

The linear motion base is actuated by a stepper motor, ball-screw, and controller, which is capable of positioning the robot base to a precision of 25 microns. The syringe pump (KD Scientific, Model 210) displaces fluid in the capillary by precision displacement of a disposable syringe in an adjustable mount. Control for both the motion base and the syringe pump is provided by the server software (described below) through serial-port interfaces. A fluid valve controlled by the server and PLC and connected to a water reservoir can introduce fresh water into the tubing to purge the system of air bubbles.

Visual feedback to the operator comes from three video cameras mounted at different points in the workspace. The signals from these cameras are sent to a video switch for distribution. One of the cameras is a specialized microscope camera used to provide a detailed view of both the crystal position and pipette tip (Figure 2). A second camera is attached to the moving robot base and provides a

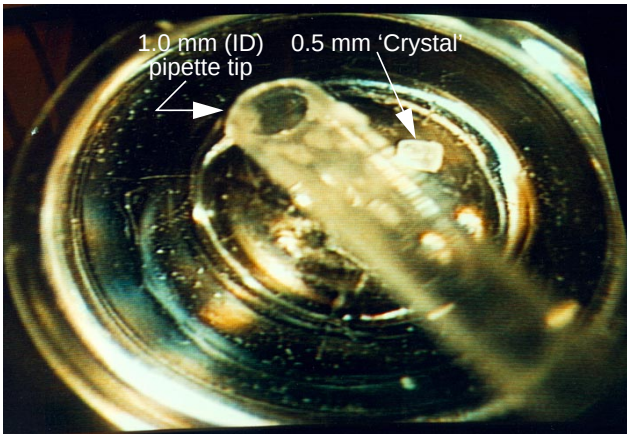

Figure 2: CU-SeeMe video from microscope camera showing simulated protein crystal and pipette tip held by robot.

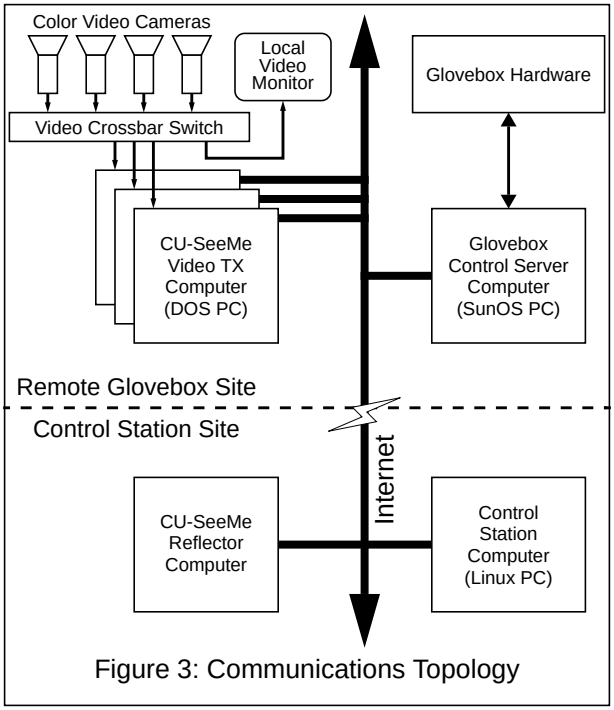

Figure 3: Communications Topology

view of the robot manipulation workspace, and a third is set up so that the capillary can be positioned close to the lens to provide visual verification that the crystal has been captured. Another camera is wall-mounted for video conferencing between experimental teams at the two sites. The video switch routes NTSC video signals to a local monitor and to the network via three PC's with capture boards. Video signal routing can be controlled through commands from the server via a serial port on the video switch.

System Overview

The glovebox system containing miniature robot, microscope and cameras at the remote site (The University of Washington Biorobotics Laboratory in Seattle, WA) communicates with a user control station site (Boeing Defense and Space in Huntsville, AL). The two sites communicate via internet protocol (IP) (Figure 3). The system was tested in two communication configurations, first, a private T1 line running internet protocol between Huntsville and Seattle and later, the communication was switched to the commercial internet.

At the remote site, a 'server' computer handles all commands and data with the exception of the video feeds. Video is currently handled by three identical 486 PC's with Creative Labs VideoBlaster video digitizer cards. The cards digitize NTSC standard video from small color cameras within the robot work-cell using CU-SeeMe internet video conferencing software[1] (Feterman, 1996).

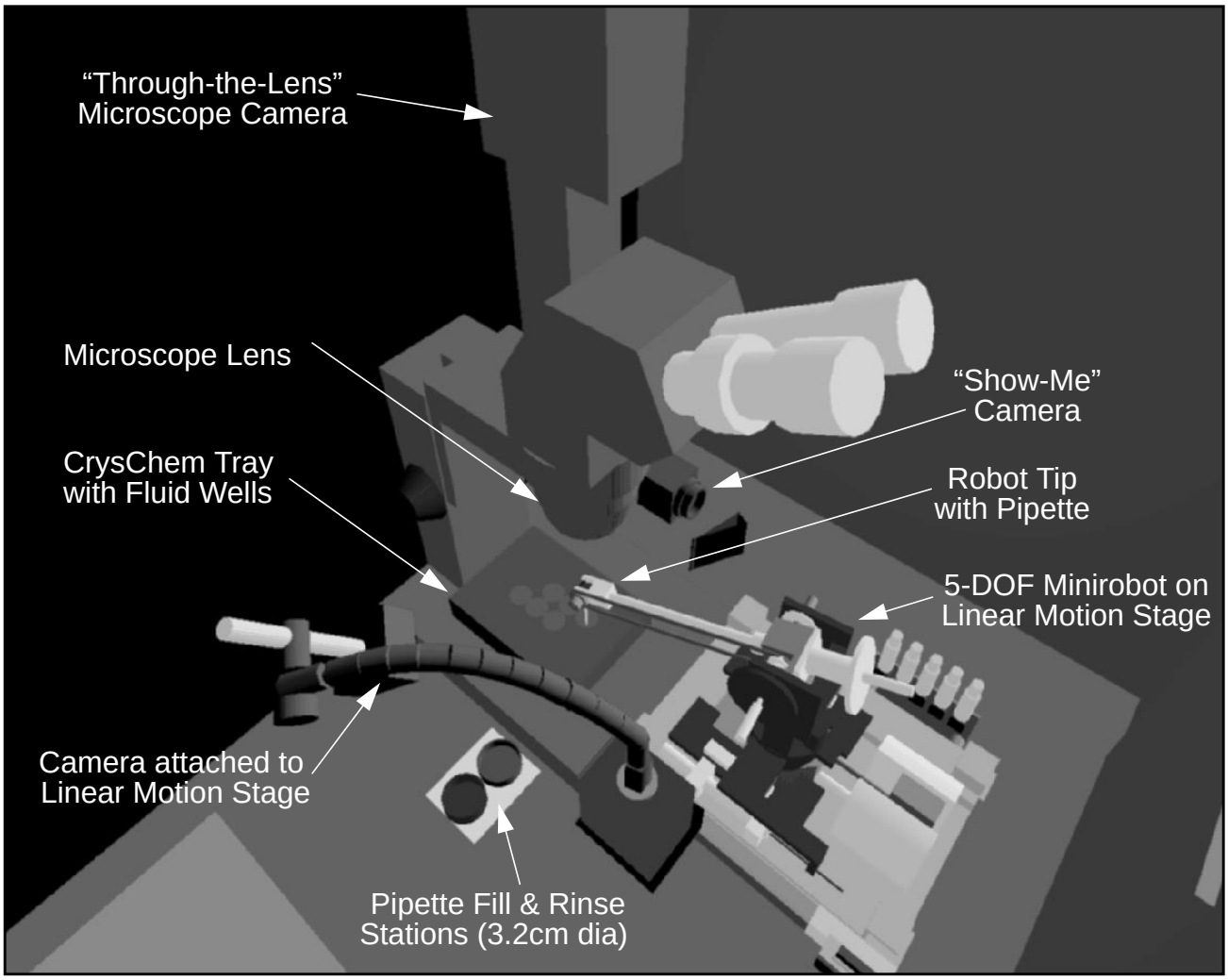

Figure 4: Glovebox Workcell Configuration

Cu-SeeMe sends each signal as a small (160 x 120 pixels), low-bandwidth (90kbps) color video stream over the internet link to a computer running CU-SeeMe reflector software.

At the user control station, a laptop PC running CU-SeeMe provides video feedback to the operator from the three remote video sources. A separate PC running Linux and X-windows is used to maintain a menu-based user interface program. A web-based user interface client is currently under development. Remote display of this interface on the laptop PC allows both user interface controls and video feedback to be displayed on a single portable computer screen. Details of the user interface implementation, communications protocol, and remote server are described in Hannaford, et al., 1997.

The user interface provides two distinct methods for controlling equipment at the remote site. The primary control method involves the use of pre-determined "macros" which encode sequences of low-level commands such as "move robot along a trajectory to position 'X', move linear rail to position 'Y', and dispense 'Z' microliters of fluid from the fluid pump." These macros are assigned to individual buttons on the graphical user interface, allowing the operator to quickly accomplish tasks by pressing a sequence of macro buttons.

The user interface also allows low-level control of robot joints, linear rail position, fluid pump parameters, etc. via sliders and buttons in pop-up dialog boxes. This low-level control capability is intended only as a secondary or backup control method and is used for performing unplanned or experimental procedures as well as for generating new macro definitions.

1. See http://cu-seeme.cornell.edu and http://www.wpine.com/cu-seeme.html.

System Operation

The glovebox workcell is currently configured to demonstrate the capability to capture simulated protein crystals under interactive operator control using a series of macro commands. The workcell is arranged as shown in Figure 4. This demonstration task involves the following operations:

1. Initialization
2. Moving the robot-held pipette tip to the CrysChem cell under the microscope.
3. Hunting down and capturing the protein "crystal"
4. Moving the pipette to a close-up camera station to verify that the capture was completed successfully.

To begin, the operator (in Huntsville, AL) first starts up the user interface software, connects to the remote 'server' computer over the internet, and commands it to begin power-up sequencing of the glovebox workcell equipment (in Seattle, WA). This turns on lights, powers up the control systems and power amplifiers for the robot, linear motion rail, and syringe pump, and activates the small video cameras within the workcell.

Immediately following the power-up sequence, the state of glovebox devices are not known. The minirobot uses incremental analog quadrature encoders for position sensing and must be calibrated to a known position after power-up. The linear motion rail and syringe pump both use open-loop stepper motors for position control so that they too must be initialized to a known position. A single macro allows the operator to completely initialize these devices to a known state.

The hydraulic tubing between the syringe pump and the pipette tip tends to develop large pockets of air in the line, due either to evaporation out of the pipette tip or the emergence of dissolved gasses in the water. A single macro allows the user to initialize the fluid system by moving to a rinse station and flushing the entire line with fresh fluid.

Once all initialization is completed, the operator uses a "GotoCell" macro to safely move the pipette tip into the CrysChem cell that is being viewed under the microscope. With both the simulated protein crystal and the pipette tip visible in the microscope view (see Figure 2), the operator can then guide the pipette tip down and over the protein "crystal" using macro buttons that generate incremental ~250um motions along any of 6 directions relative to the camera view (up, down, left, right, in, and out).

Once the operator feels that the pipette is correctly positioned to capture the crystal, a "Capture" macro is used to command the syringe pump to withdraw a controlled amount of fluid which will cause the crystal to enter the pipette. A "ShowMe" macro then moves the robot and linear motion rail along a collision-free trajectory which safely positions the pipette tip in front of a video camera that displays the 0.5mm crystal within the pipette.

If the crystal capture operation failed (which happens more often during initial operator training), the operator can use additional macro commands to move the pipette tip back to the CrysChem cell and re-attempt the capture.

Performance

We have not yet conducted a formal performance evaluation of the system. However, a few measurements can be reported to give a sense of what it is like to operate the system. We have implemented the demonstration using macros which command movement times in the range of 0.5 - 2.0 seconds. When the user clicks a macro button on the client user interface, the motion is initiated within one second or less. The delay most apparent to the user is the 1-30 seconds needed for completion of the Cu-SeeMe video update at full resolution. The update is faster for a viewer at the remote site. We noticed little or no degradation in response time when we switched between our private T1 link and the open internet.

The mini robot is theoretically capable of moving from one joint extreme to the other in under 200 ms (Hannaford, et al., 1994). We did not demand movements this fast, but robot motion appeared smooth, stable, and coordinated at all times. This was also true for very small and slow movements observed under the microscope. For example, a 1.0 mm movement of the pipette tip planned for 10 seconds duration was observed under high magnification of the pipette tip. This movement appeared smooth, stable, and of the correct amplitude without overshoot. Periods of acceleration and deceleration consistent with the 3rd order polynomial trajectory generation algorithm were clearly observed.

In our initial demonstrations, a 0.5 mm plastic cube was substituted for the protein crystal. In one set of experimental operations in which the robot in Seattle was controlled from Huntsville Alabama, the crystal was successfully captured in 3 out of 4 attempts. Each protein capture took about 3 minutes.

Conclusions

Our demonstration system has produced encouraging results which suggest that handling of protein crystals by telerobotics is a viable alternative to the use of scarce astronaut crewtime. In addition to the space station application, a remotely operated ground system could allow technicians to avoid difficult micromanipulation tasks performed in cold environments.

There are many opportunities to improve the system. We are planning a WWW interface as pioneered by Goldberg (1995). This would allow higher resolution video images. A very useful feature would be a video streaming protocol for the internet which supported a user controlled trade-off between update rate and resolution. In our evaluations, users found some occasions in which they needed high speed video updates and others where they were willing to wait for higher resolution.

Macro programming and end-user control would be aided by the provision of Cartesian trajectory planning for the Mini DD robot. Although we have used this type of control in the UW Mini DD robot (Hwang 1995), we have not yet integrated it into the PCG testbed system.

We are now working on hardware details which will permit the system to run unattended for up to 3 days and which will allow the remote user to power cycle all system elements except the server.

Finally, a more rigorous performance evaluation is desirable. This evaluation should include both task specific and generic experiments. The former will keep development of the system focused on the needs of users and applications, and the latter will provide performance measures which can be compared across systems and applications

References

H. Asada, T. Kanade, “Design of Direct-Drive Mechanical Arms,” ASME J. Vibration, Acoustics, Stress, and Reliability in Design, vol. 105, no. 3, pp. 312-316, 1983,

D. Fetterman, “Videoconferencing On-Line: Enhancing Communication Over the Internet,” Educational Researcher, May 1996

K. Goldberg, M. Mascha, S. Gentner, N. Rothenberg, C. Sutter, J. Wiegley, “Desktop teleoperation via the World Wide Web,” Proceedings IEEE International Conference on Robotics and Automation, vol. 1, pp. 654-9, Nagoya, Japan, 21-27 May, 1995.

B. Hannaford, P.H. Marbot, M. Moreyra, S. Venema, “A 5-Axis Mini Direct Drive Robot for Time Delayed Teleoperation,” Proc. Intelligent Robots and Systems (IROS 94), vol. 1, pp. 555-562, Munich, Sept. 1994.

B. Hannaford, A.K. Bejczy, P. Buttolo, M. Moreyra, S. Venema, “Mini-Teleoperation Technology for Space Research,” Proceedings Micro Systems, Intelligent Materials and Robots (MIMR-95), pp. 524-527, Sendai, Japan, September, 1995.

B. Hannaford, P.H. Marbot, P. Buttolo, M. Moreyra, S. Venema, “Scaling Properties of Direct Drive Serial Arms,” In Press: International Journal of Robotics Research, vol. 15, no. 5, 1996.

B. Hannaford, J. Hewitt, T. Maneewarn, S. Venema, M. Appleby, R. Ehresman, “Telerobotic Remote Handling of Protein Crystals,” Proceedings IEEE International Conference on Robotics and Automation, (in press), 1997.

G. Hirzinger, B. Brunner, J. Dietrich, J. Heindl, “Sensor-Based Robotics -- ROTEX and its Telerobotic Features,” IEEE Transactions on Robotics and Automation, vol. 9, no. 5, pp. 649-663, October 1993.

D.Y. Hwang, “Teleoperation Performance with a Kinematically Redundant Slave Robot,” Ph.D. Dissertation, University of Washington, Department of Electrical Engineering, December 1995.

H. Kazerooni, “Design and Analysis of the Statically Balanced Direct-Drive Manipulator,” IEEE Control Systems Magazine, vol. 9, no. 2, pp. 30-34, Feb. 1989.

W.S. Kim, A.K. Bejczy, “Demonstration of a high-fidelity predictive/preview display technique for telerobotic servicing in space,” IEEE Trans. Robotics and Automation, vol. 9, pp. 698-702, Oct. 1993.

D. Normile, “Search for Better Crystals Explores Inner, Outer Space,” Science, vol. 22, pp. 1921-1922, 22 Dec 1995.

J.K. Ousterhout, “TCL and the TK Toolkit,” Addison-Wesley, 1993.

B.L. Stoddard, R.K. Strong, A. Arrott, G.K. Farber, “Mir for the Crystallographers’ Money,” Nature, vol. 360, pp. 293-4, 26 Nov. 1992.

B.L. Stoddard, G.K. Farber, R.K. Strong, “The Facts and Fancy of Microgravity Protein Crystallization,” Biotechnology and Genetic Engineering Reviews, vol. 11, pp. 57-77, Dec 1993.

J. Sztipanovits, Karsai, G., Franke, H., “Model-Integrated Program Synthesis Environment,” Proc. of the IEEE Symposium on Engineering of Computer Based Systems, Friedrichshafen, Germany, March 11-15, 1996.