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OPERATION OF GENERAL PURPOSE STEPPING MOTOR CONTROLLERS AT THE NATIONAL SYNCHROTRON LIGHT SOURCE*

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DISCLAIMER

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ABSTRACT

A prototype and four copies of a general purpose subsystem for mechanical positioning of detectors, samples, and beam line optical elements which constitute experiments at the National Synchrotron Light Source facility of Brookhaven National Laboratory have been constructed and placed into operation. Construction of a sixth subsystem is nearing completion. The subsystems effect mechanical positioning by controlling a set of stepping motors and their associated position encoders. The units are general purpose in the sense that they receive commands over a standard 9600 baud asynchronous serial line compatible with the RS-232-C electrical signal standard, generate TTL-compatible streams of stepping pulses which can be used with a wide variety of stepping motors, and read back position values from a number of different types and models of position encoder. The basic structure of the motor controller subsystem will be briefly reviewed. Short descriptions of the positioning apparatus actuated at each of the test and experiment stations employing a motor control unit are given. Additions and enhancements to the subsystem made in response to problems indicated by actual operation of the four installed units are described in more detail.

INTRODUCTION

It was anticipated during planning for experiments to be conducted at the x-ray ring of the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory that many of the experiments would require a method for mechanically positioning beam line optical elements, experiment samples, and x-ray detectors. It was decided that, in many cases, this positioning could be accomplished in "open loop" control mode by a combination of movement effected by stepping motors and position readout provided by various types of position encoders. Moreover, it was believed that most x-ray experiments would require that a large number of position axes be controlled, with perhaps a maximum of 15 axes being reasonable. The exact type and specifications of each and every translator/stepping motor combination and position encoder required for the experiments could not be set far in advance of actual construction and installation of experiment station apparatus, so a controller subsystem with very general interfacing capabilities would be required. Standard interfacing capability would also have to extend to the method used by the experiment control/data acquisition computers to drive the controller since the final manufacturer and type number of these computers also was not known. A device, termed the National Synchrotron Light Source motor control unit and referred to by the letters NSLMCU, has been designed and a prototype constructed.[1,2] The prototype and four copies have been placed into operation. In addition, construction of a sixth unit is nearing completion and this unit will shortly join the other copies in operation at the x-ray ring.

As will be discussed in more detail below, the motor control unit is driven by the computer which has overall control of an x-ray beam line experiment. The method of interfacing the computer with the controller is via a 9600 baud (or slower) asynchronous serial line unit. Motor positioning commands sent over the serial line interface take the form of strings of ASCII characters corresponding to English-language-like command words and arguments. It was recognized during planning for the motor control unit that if most of the units were driven by the same type of computer and if these computers all executed the same type of operating system, a set of motor-positioning subroutines written to be compatible with a single suitable language could be provided to all the motor controller users. It was predicted and has happened that the users all control their experiment with a Digital Equipment Corporation (DEC) computer which executes the DEC RSX-11/M operating system. Thus a package of FORTRAN-language-callable subroutines for driving the motor control unit has been written and provided to the users for incorporation into their experiment control programs. Just as with the motor control unit itself (hardware and software), this software package has undergone modifications and additions in order to solve problems which have arisen during actual beamline operation.

SUBSYSTEM CAPABILITIES

The motor control unit has been designed to be a part or a subsystem of the complete experiment control and data acquisition system present at each x-ray experiment station. The unit interacts with, or must be connected to, the experiment apparatus at both its "front" end and its "back" end. At the front end, defined to be toward the driving computer (or other driving device), the motor control unit accepts experiment element positioning commands via a standard 9600 baud asynchronous serial communication line which obeys the RS-232-C electrical signal standard. The commands are composed of short strings of ASCII-coded characters (bytes) which form English-language-like phrases and readable numbers. Thus, because of this front-end interfacing method, the motor control unit may be driven by almost any type of computer or even ASCII-character-generating terminals.

At its "back" end, the motor control unit is connected to as many as 15 motor-encoder pairs. More precisely, the motor control unit is connected to up to 15 stepping motor translators (or power supplies); the unit generates suitably ramped TTL-compatible pulse streams, one of which causes the translator to move its stepping motor in a clockwise direction, the other causes motion in the counterclockwise direction. The same cables which connect the controller to the translator also carry signals for implementing clockwise and counterclockwise direction position limit switches and a mechanical "home" or fixed reference position switch. This scheme for providing stepping pulses to stepping motor translators is compatible with a large variety of commercially available translator units.

A second set of up to 15 cables connects the "back" end of the motor control unit to the set of position encoders used to read back the current position of each stepping motor actuated axis. More precisely, each of the cables terminates in an encoder readout formatter module, the purpose of which is to

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convert the position reading generated by different types of encoder into a subsystem-standard form, serialize the position value (in order to reduce the number of signal channels which must be returned), and send the value back to the motor control unit in serial line format, obeying the RS-422 electrical signal standard. In practice, this scheme has proved to be very flexible in that a number of different types of encoder have been integrated into the system with a nominal amount of effort. In particular, the following types of encoder are represented in the experiments currently utilizing the motor control unit:

(1) absolute encoders with resolution from 13 to 16 bits;

(2) incremental encoders. The encoder readout formatter module contains an integral up/down counter to handle both the cases of clockwise/counterclockwise-pulse and phase-encoded-pulse encoder output types;

(3) pseudo encoders, in which no physical encoder is present so that the encoder readout formatter module simply counts pulses sent to the stepping motor translator.

A block diagram showing the position of the motor control unit among its associated experiment apparatus constitutes Fig. 1.

SUBSYSTEM STRUCTURE

The major function of controlling a set of stepping motor-encoder pairs has been partitioned into three subfunctions which bear a more-or-less hierarchical relationship to each other. Each of these three subfunctions has been confined to its own computer processor, a Digital Equipment Corporation LSI-11/2. Each processor has a local memory array of 64K bytes and the "peripheral devices" required to carry out its specific function. These peripheral devices include in each case at least one video display generator for producing CRT displays of character text which detail in real time the status of the subfunction being performed. The three major subfunctions are the following, in descending hierarchical order:

(1) Protocol Handler. This processor is responsible for communicating with the driving device, interpreting the received command character strings, converting position values to internal binary representation, and formatting appropriate responses to received commands. This processor also checks the commands for errors and generates appropriate error messages;

(2) Motor Driver. The motor driver processor computes the number of motor pulses required to reach a specified target position and generates a suitably ramped stream of stepping pulses on the correct directional channel. This processor also interprets the limit and home position switch signals;

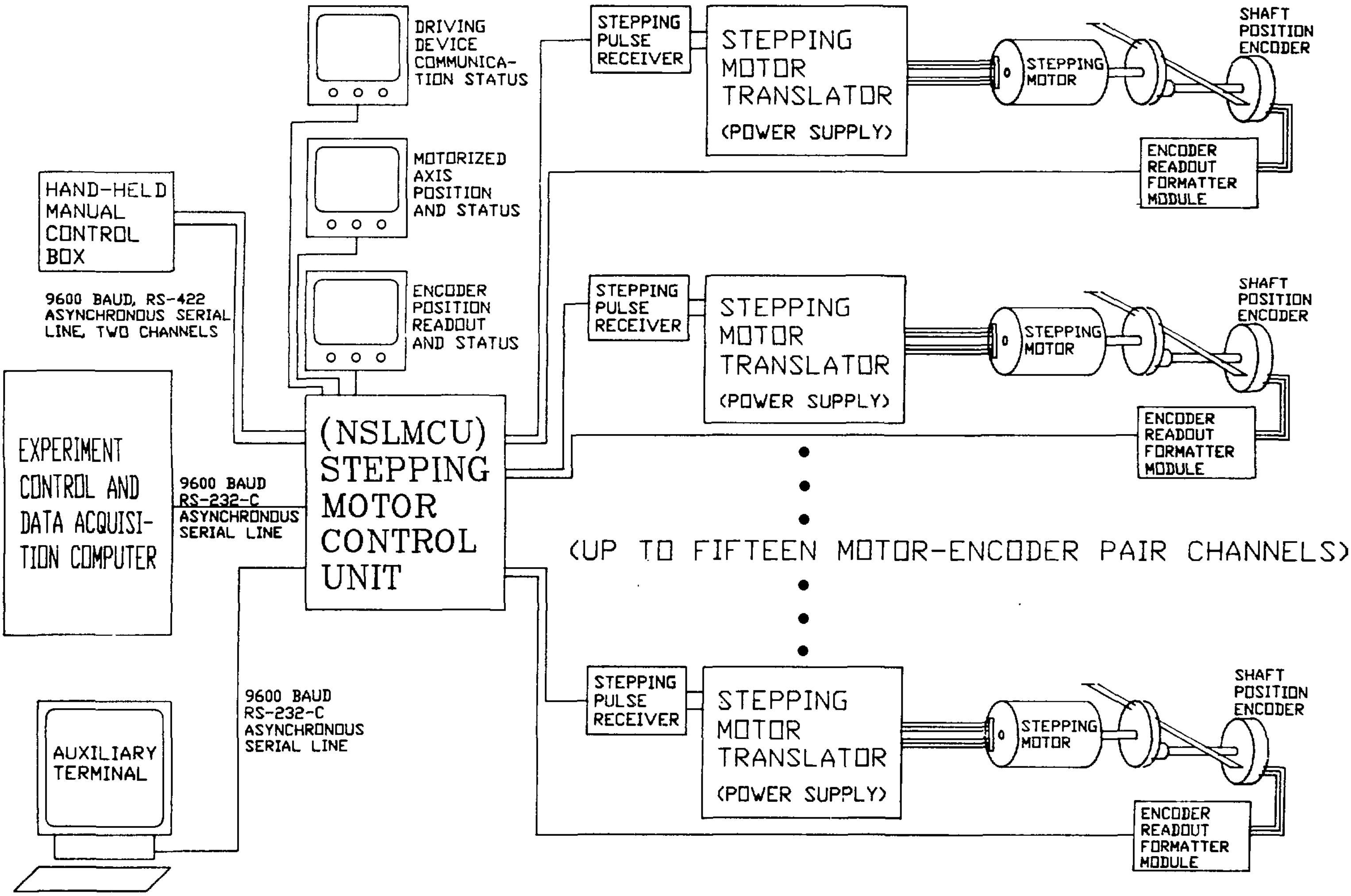

Fig. 1. Block diagram of motor control unit interconnections with experiment apparatus.

(3) Encoder Reader. The current position reading of the encoder on each axis controlled by the motor control unit is read back by the encoder reader processor and converted to internal standard form.

The processors communicate via a small shared memory module.[3,4] The shared memory module is also used to store the programs and operating system images required by the processors and contains the database of current and default axis parameters. The internal structure of the motor control unit is illustrated in Fig. 2.

SUBSYSTEM OPERATION

A prototype and four copies of the motor control unit have been used successfully to position mechanical apparatus. The prototype unit, in very primitive form, was originally placed into operation in May of 1981. The unit is still in operation and is used routinely to test updated versions of the software which executes on the three motor control unit processors. The prototype system is equipped with two axes of motor-encoder pairs. One axis employs a Superior Electric SLO-SYN[5] TBM105-6309 translator to drive a SLO-SYN M063-FC09 motor. The axis is coordinated with a BEI[6] 5V241 12-bit absolute encoder. The other axis utilizes a SLO-SYN STM1800 translator logic card with external power supplies, a SLO-SYN SS25-1002 motor and a BEI 5V270BZ incremental encoder. The prototype unit serves as a very convenient test facility for components which were built in-house during the motor controller project, i.e., motor driver boards, translator pulse receiver cards, and encoder readout formatter modules. The test capability was used to great advantage when the operational motor control units were being installed at their beam lines. Most of the additional in-house components required for bringing all operational units up to their full complement of 15 motor-encoder pairs have already been tested for correct operation. It is expected that the test facility will next see heavy use when the fifth copy of the subsystem, currently used for spare parts, is placed into operation (probably within the next six months).

The four operational motor control units were installed at x-ray beam lines at the NSLS and connected to their driving computers and motor-encoder pairs during the past two years. The number of axes currently under the control of each unit varies from 6 to 15. Stepping motors and encoders are being added, albeit sporadically, to those stations which have less than the full complement; the plan is for each motor control unit to control the maximum allowable number of axes. Actual experiments have been performed at three of the stations. Experiments at the fourth station await completion of other parts of its data acquisition system.[7] However, the fifteen axes of the fourth station have been actuated extensively by driving its motor control unit with both an ASCII terminal and the station experiment control computer and experiment apparatus alignment measurements have been made. Brief discussions of the mechanical actuation equipment and experiments performed at each x-ray beam station with an operational motor control unit follow.

Unit 1, X-ray crystallography, BNL Chemistry Department, beam line X-13B. This unit drives six axes of a Huber goniostat by means of six Superior Electric SLO-SYN translators and motors. All translators are 5000 step/second open chassis type, series TBM105. The motors are types M062-FC09 and M092-FD310, and M093-FD301. No encoders are used; the encoder readout formatter modules act as pseudo-encoders by counting motor step pulses.

The crystallography station motor control subsystem has been fully operational for approximately

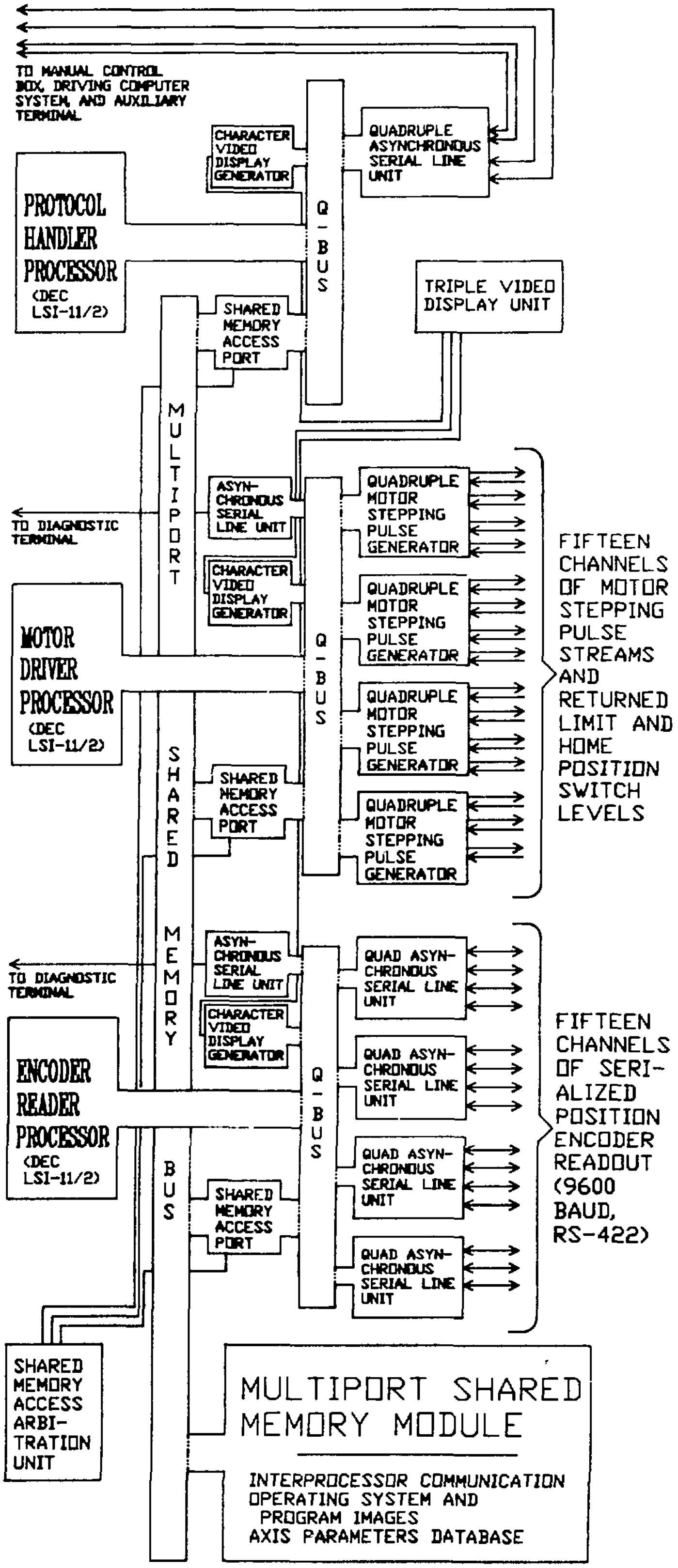

Fig. 2. Motor control unit internal structure.

two years. The subsystem has been used extensively for measuring parameters of the incident x-ray beam and aligning experimental equipment with respect to this beam. Crystals have been mounted on the sample spindle of the goniostat and diffraction peaks sufficient to determine orientation matrices for the crystals have been detected with film and a sodium iodide detector.

Soon after the x-ray monochromator in this beam line became fully operational, several full-fledged structure determinations, requiring tens of hours of data acquisition time each, were made.

Unit 2, Materials analysis using EXAFS, BNL Department of Applied Science, beam line X-11A. The motor control unit at the DAS EXAFS line is connected to nine MESUR-MATIC[8] series 340 motors, three of which actuate a four-crystal monochromator, three position a subsystem of input beam ion chamber, sample holder, and output (transmitted) beam ion chamber with respect to the incident beam, and two control the x,y position of the sample with respect to the ion chamber table (and, hence, the fine sample position with respect to the incident beam). The last motor positions a user-specified axis which varies in function from experiment to experiment. No encoders are present in this system; the encoder readout formatter modules act as pseudo-encoders.

Originally the two monochromator crystal orientation axes were equipped with BEI model 3733CZS-3 ruggedized incremental encoders. The crystal pairs also have an adjustment of their relative orientation accomplished by piezoelectric actuators operating in closed loop mode independently of the motor control subsystem. The incident x-ray flux (incident on the sample, transmitted through the monochromator) is used as the feedback variable for relative adjustment of the monochromator crystal pairs. When the absolute crystal orientation with respect to the incident beam is changed (i.e., a new x-ray wavelength is selected), it is possible for the relative adjustment apparatus to go out of "lock", i.e., for the crystal pairs' absolute angular difference to exceed its maximum allowed value, if the absolute motions are not sufficiently synchronized. (Note that an original specification of the motor control unit was that motion on each axis is completely independent of the other axes.) The combination of insufficient resolution on the original incremental encoders and normal motor backlash had the result that the monochromator crystal pairs would occasionally (∿ once every few hours) lose their relative orientation. This problem was corrected by removing the incremental encoders and simply counting motor pulses. The problem of insufficient synchronization of the individual crystal motions during an absolute orientation adjustment has been partially solved by adding gear reducers between the motors and crystal angle axes, so that the relative angle between the crystal pair faces does not change as much during the delay period when only one of the crystal pairs has started to move toward its new absolute position. An effort is underway to improve the synchronization between multiple axis moves by precomputing the total travel (number of stepping pulses) involved in each move, preloading the stepping pulse stream generators with all parameters of the moves, and then starting the moves with the simplest possible subroutine (written in machine language) executing in the motor driver processor. It is believed that this technique can be used to start two axes in motion within <100 μsec of each other (at present the delay is several milliseconds).

The motor controller at the DAS EXAFS station is the unit which has logged the most actual data collection time. Many tens of samples have been examined in EXAFS experiment scans, where a scan involves computing the ratio of the x-ray flux transmitted through the sample to the x-ray flux incident on the sample while the energy of the incident x-rays is changed by small increments. Motor control by computer is used to initially position a sample in the incident beam and then the two axes which determine the monochromator energy are scanned through a long series of values. The general layout of the DAS EXAFS beam line is shown in Figs. 3-5.

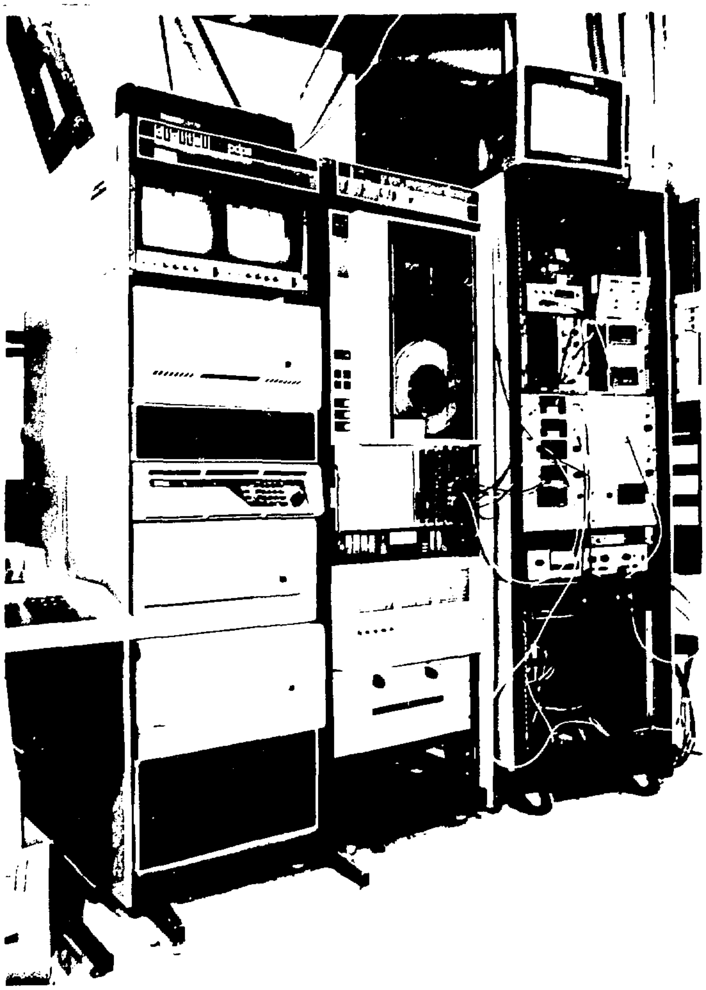

Fig. 3. Experiment control and data acquisition computer at BNL Department of Applied Science EXAFS station, beam line X-11A. Motor control unit chassis box is located near bottom of center rack. CRT units for displays of motor-encoder pair current and target positions are at top of left rack.

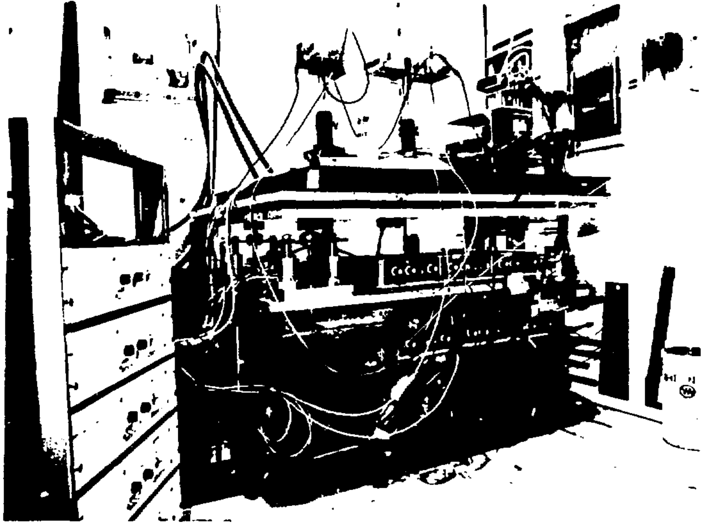

Fig. 4. View inside DAS EXAFS station beam line hutch. Stepping motor translators are visible at left. Table supporting ion chambers is positioned by three motors driven by the motor control unit. Two motors just under upstream beam chamber (right side) adjust for fine position of sample with respect to input beam-defining slits.

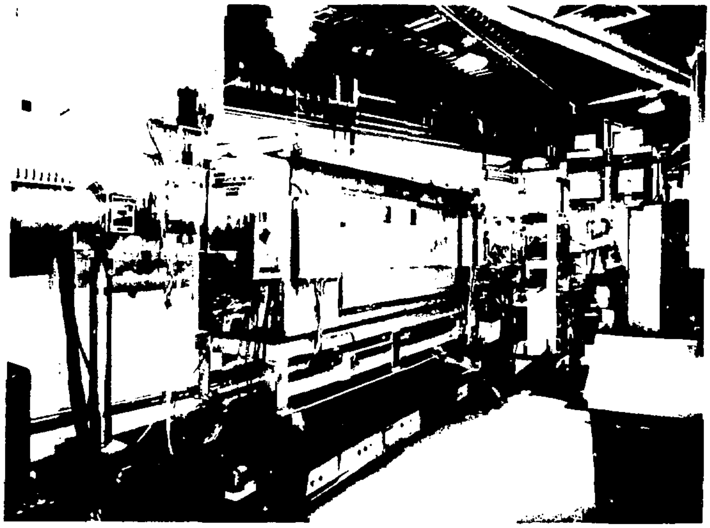

Fig. 5. Four-crystal x-ray monochromator in DAS EXAFS beam line, X-11A. Two crystal angle motions and separation of crystal pair goniometers are under control of motor control unit. Motor translators are visible under monochromator.

Unit 3, X-ray topography, NSLS and State University of New York at Stony Brook, beam line X-19C. Motor control unit number 3 drives a full complement of 15 motor-encoder pairs. The 15 encoders are all identical; the associated encoder readout formatter boxes convert and count phase-encoded output streams from BEI 5792 encoders. The station contains equipment necessary to support x-ray topography experiments and includes a white-beam camera and a multiple crystal camera.[9] Table I lists the labels of the axes controlled and their associated translators and motors, and provides a brief description of each motion. Presently, connection of all motor-encoder pairs to their actuated experiment components is nearing completion. The motor control unit has been used to perform two experiments requiring actuation of all nine axes of the white-beam camera.

Unit 4, Small-angle x-ray scattering, BNL Biology Department, beam line X-12B. The Small-Angle X-ray Scattering Station being constructed by the BNL Biology Department at beam line X-12B incorporates a motor control unit to position a total of 15 axes, with one axis determining the x-ray wavelength transmitted by the station monochromator and 14 axes controlling the positions of a large mobile spectrometer. The axes are encoded by a varied mix of absolute, incremental, and pseudo-encoder type encoders; the translators and stepping motors are all of the same manufacturer's brand, Superior Electric SLO-SYN, but are of many different power ratings and sizes. A list of the spectrometer motions, translators, motors and encoders has been published before.[2] As mentioned above, all axes controlled by this motor control unit have been moved successfully with corresponding read back of encoded position. Also, automated control provided by the unit has been used to make equipment alignment measurements.

UPGRADES AND MODIFICATIONS

Experience gained by operation of the motor control units under experiment conditions has led to three significant modifications to the subsystem. All three modifications have been implemented by upgrading the software which executes in the three processors which constitute each unit. A discussion of each modification follows.

Additional Motor Control Functions

The set of motor control functions which the motor control unit performs has been expanded. Some of the new functions represent consolidations of sets of functions which previously had to be requested individually and sequentially by the driving device. The more important of the new functions are listed below:

(1) compensation for backlash takeup. A new function starts a motor axis moving toward its target position under the constraint that the final approach to the target position will always be made in a predetermined direction. In this manner, the motor control unit automatically compensates for the effects of backlash in the motor-encoder gear trains. The disadvantage of this mode of translation is that it can be substantially slower than direct, uncompensated translation if the direction of travel is opposite to the direction of backlash takeup travel. The backlash takeup algorithm is programmed into the microprocessors (INTEL 8085A's) on the stepping-pulse-generation printed circuit boards.

(2) translation with no iterations. In the normal mode of translating toward a target value, the motor driver processor checks that the target value has been reached, exactly or within a predetermined number of steps, at the end of a move. If the motor position does not satisfy this condition, a new translation distance is calculated and a second translation toward the target is begun. As many as four attempts to reach the target may be made. The new motor control function has the motor control unit calculate and carry out only one translation operation. Some users prefer to operate in this mode, collecting data at axis positions not exactly equal to their preplanned values by simply reading back and recording the actual position value with its corresponding data value. The actual data collection points rarely differ from their target points by more than 1-2 motor steps. This mode of translating is useful when one or two axes are scanned through a long series of position values.

(3) redefinition of coordinate system parameters. The motor control unit generates video displays of axis current and target positions in three coordinate systems, two of which are with respect to a physical scale on the actuated instrument or a logical coordinate system which has meaning only in the context of the experiment being performed. These coordinate systems are derived from the absolute, or encoder reading, coordinate system by a linear transformation of the form $y = mx + b$, where x is the encoder reading. The transformed coordinate value is then truncated to within a predefined valid range. Motor control functions have been added to allow the user to redefine the higher level coordinate systems by modifying the parameters m and b. All internal parameters which must be adjusted to be consistent with the new coordinate system are automatically updated.

(4) automatic setting of limit switch position estimates. Estimates of the current limit switch positions are required when the motor control unit determines which direction to take during computation of the amount of travel required to reach a target value. The unit may now be commanded to move all motors to their clockwise and counterclockwise limits in turn and record the positions of the limit switches in its internal database of axis parameters.

(5) continuous reading of motor positions. An additional motor control command places the unit in a

MOTION LABEL	MOTION DESCRIPTION	TRANSLATOR TYPE†	MOTOR TYPE†	RESOLUTION, RANGE
(Following Six Axes Correspond to Motions of the White Beam Camera (WBC))				
CAMPOS	Rotation of TV camera/detector arm in vertical plane, revolution of TV camera/detector about sample in vertical plane	ST103	M092-FC09-C2	2000 steps/deg 0↔360 deg
CAMTRK	Linear drive adjustment of TV camera/detector to sample distance (motion along detector arm)	ST103	M062-FC09-C2	2000 steps/in 0↔7 in
THETA	Rotation of Eulerian cradle (χ motion) together with sample rotation assembly (ϕ motion) in horizontal plane, sample Eulerian θ motion	ST103	M092-FC09-C2	200 steps/deg 0↔360 deg
CHI	Revolution of sample rotation assembly around Eulerian cradle, sample Eulerian χ motion	ST103	M091-FD09	4000 steps/deg 0↔360 deg
2THETA	Rotation of sample θ,ϕ,χ goniometers together with TV camera/detector arm assembly in horizontal plane, sample-detector 2θ motion	ST103	M092-FC09-C2	200 steps/deg 0↔360 deg
PHI	Rotation of sample mount, sample Eulerian ϕ motion	ST105	M062-FC09-C2	4000 steps/deg 0↔360 deg
(Following Nine Axes Correspond to Motions of the Multiple Crystal Camera (MCC))				
MTHETA	Rotation of specimen upper arc and lower arc actuating apparatus, i.e., MCC χ and ϕ goniometers, in horizontal plane, specimen Eulerian θ motion, coarse movement	ST103	M092-FC09-C2	200 steps/deg 0↔360 deg
MCCPOS	Rotation of TV camera/detector arm in horizontal plane, revolution of TV camera/detector about specimen in horizontal plane	ST103	M092-FC09-C2	200 steps/deg 0↔360 deg
LARC	Revolution of upper arc Eulerian cradle portion together with specimen spindle mount around lower arc Eulerian cradle portion, specimen Eulerian ϕ motion	ST103	M062-FC09-C2	4000 steps/deg -20↔ +20 deg
UARC	Revolution of specimen mount spindle around upper arc Eulerian cradle portion, specimen Eulerian χ motion	ST103	M062-FC09-C2	4000 steps/deg -20↔ +20 deg
TRDXTL	Rotation of "third" or asymmetric crystal, downstream of monochromator, about an axis in vertical plane, "third" crystal θ motion	ST103	M062-FC09-C2	4000 steps/deg 0↔360 deg
TRDTRK	Linear drive adjustment of "third" crystal position along track downstream of monochromator and parallel to incident beam, indirectly adjusts <u>range</u> of specimen 2θ motion	ST105	M062-FC09	2000 steps/mm 0↔100 mm
MCCTRK	Linear drive adjustment of specimen to TV camera/detector distance (along track on TV camera/detector arm)	ST103	M092-FC09-C2	200 steps/mm -127↔ +127 mm
MCCHGT	Linear drive adjustment of TV camera/detector height above plane of rotation of detector arm, motion on track vertically perpendicular to detector arm	ST103	M092-FC09-C2	200 steps/mm -127↔ +127 mm
MCSCAN	Rotation of upper arc and lower arc, i.e., MCC χ and ϕ goniometers, in horizontal plane, specimen Eulerian θ motion, fine movement (fine adjustment of MTHETA motion)	ST103	M062-FC09-C2	4000 steps/deg -180↔ +180 deg

TABLE I. Axis Actuation Equipment for Cameras at State University of New York at Stony Brook and BNL NSLS Department X-ray Topography Station, X-19C

†All translators and motors are Superior Electric SLO-SYN models. All encoders are ruggedized phase-encoded, incremental BEI models, built integrally into their associated stepping motors as motor option "-C2", except for axes CHI and TRDTRK which have electrically equivalent Datametrics[10] Model KD15DM-200-5SE-6B encoders. The output from all encoders is phase decoded to produce 200 pulses per revolution.

mode in which it continuously reads back and displays the current position of every controlled axis. This display also includes a count of the number of errors obtained while reading back the encoder position values, i.e., while interrogating the encoder readout formatter modules. This command is very useful during initial installation of a motor control unit or diagnosis of a unit malfunction.

"Binary" Mode Communication Protocol

A new motor control unit mode or communication protocol has been implemented in order to speed up execution of a most-used subset of motor controller commands. In normal operation, commands are submitted to the motor control unit as strings of ASCII characters representing English-language-like command words, motor names, and readable position values. When the driving computer sets up a command, it must look up the ASCII characters specifying the function, convert the motor number from internal binary representation to an ASCII label, and convert the position specification (if the command requires one) from internal binary representation to ASCII-coded form. When the command is received by the motor controller, essentially the inverse of these conversions must be performed. In order to speed up the overall communication process, a new "binary" mode of encoding transmitted parameters, in which command information is not converted from internal binary representation to ASCII characters, has been implemented. In "binary" mode, command parameters are converted into character equivalents simply by treating portions of their internal binary representation bit set (bytes or words) as "characters" for transmission over a serial line. The new "binary" communication protocol may be used for only a limited "most-used" subset of the motor control commands.

Note that the number of bytes or character-equivalents which must be transmitted and returned in order to process and execute a command depends on the number-of-data-bits parameter for the serial line connecting the motor control unit with its driving device. A list of the binary mode commands and the format of their required byte transmissions is presented in Table II, for both 7-data-bit and 8-data-bit serial lines.

It is estimated that the binary mode of operation reduces the total command execution time by ∿ 200 msec (from a previous total of ∿ 900 msec) for commands which involve the transmission of a position value, and by ∿ 50 msec for other commands. Note that a disadvantage of the binary communication mode is that display of the "characters" received over the serial communication line, a display generated by the protocol handler processor, is no longer intelligible. As a consequence, this mode is used only by experienced users who have a definite requirement for the maximum processing speed obtainable from the motor control unit.

"Wait" Intercommand Processing Mode

Another additional motor controller command places the unit in a state such that it simply waits for the next command to be received during the interval between processing successive commands. In normal or "display" intercommand processing mode, the motor controller loops over all controlled axes and reads, converts, and displays their current position values. The problem with this procedure is that one or more of the processors may have to load an overlay program (into processor-local memory from the shared memory module) if it is caught in its display loop upon receipt of the next command. The overlay load process can consume ∿ 100 msec in some cases. Placing the motor control unit in "wait" intercommand processing mode eliminates this overhead. The disadvantage of employing this mode is that real-time displays of current motor position are no longer generated. The usual motor control technique is to leave the motor controller in display mode while setting up all axes except one "scan" axis and then entering "wait" mode just prior to initiating a long scan over one position variable.

Additional Serial Line Input Port

The protocol handler processor is responsible for receiving and decoding commands received from the device which drives the motor control unit. This processor has a DEC DLV-11J quadruple asynchronous serial line interface on its Q-Bus and thus may communicate via up to four serial line ports. Originally only three of these serial line ports were used, one for the driving device and two for a "local" controller, or manual control box. Now the software executing in the processor has been modified to support a third driving device interacting at the fourth or "auxiliary" controller port. The motor control unit may be driven by either its normal experiment control computer or a terminal device without having to disturb the cabling at the unit input ports. A major source of operational confusion and error has been eliminated. The software upgrade required to multiplex the communication handling routines between these two ports was not trivial.

MOTOR CONTROL FUNCTION	SUBMITTED CHARACTER EQUIVALENTS (8-Data-Bit Serial Line, Hexadecimal Digit Pairs)	SUBMITTED CHARACTERS (7-Data-Bit Serial Line, ASCII Numeric Characters)	RETURNED CHARACTER EQUIVALENTS (8-Data-Bit Serial Line, Hexadecimal Digit Pairs)	RETURNED CHARACTERS (7-Data-Bit Serial Line, ASCII Numeric Characters)
Stop All Motors	00	0	FF	?,?
Stop Motor	M1	M,1	FF	?,?
Set Target Value	PP,PP,PP,PP,M2	,P,P,P,P,M,2 P,P,P,P	FF	?,?
Start All Motors Toward Target Values	03	3	FF	?,?
Start Motor Toward Target Value	M4	M,4	FF	?,?
Obtain Status of All Motors	05	5	FF,SS,SS	?,?,S,S,S,S
Obtain Status of Motor	M6	M,6	FF,SS,SS	?,?,S,S,S,S
Obtain Motor Position Value	M7	M,7	FF,PP,PP,PP,PP	,P,P,P,P,P,P ?,?,P,P
Exit Binary Communication Mode	08	8	FF	?,?

TABLE II. Binary Communication Mode Motor Control Commands and Transmission Format of Associated Character-Equivalents
(M,P, and S are hexadecimal digits in the case of 8-data-bit serial lines and numeric ASCII characters in the case of 7-data-bit serial lines. M represents a motor number, P represents four bits of an internal-binary-coded motor position value, and S represents four bits of an internal-binary-coded motor status value. Digit or character to extreme right (and on first line) is transmitted first. Commas appear as digit-pair or character separators only, they are not transmitted.)

ACKNOWLEDGEMENTS

The Light Source motor controller project benefitted from many suggestions and comments due to the experimenters who had primary responsibility for actual construction of the experiment stations which include a motor control unit. The DAS EXAFS station, X-11A, was the first to use the unit in an experiment, hence S. Heald and J. A. Tranquada probably suffered the most frustration associated with initial operation of a unit. The contributions of Å. Kvick (X-13B), A. B. Hmelo, J. Babb, and H.-Y. Liu (X-19C), and D. Wise and E. J. Desmond (X-12B) are acknowledged. The draft and final version of this manuscript were prepared by B. D. Gaer

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