DOUBLE CRYSTAL MONOCHROMATOR CONTROL SYSTEM FOR ENERGY MATERIALS IN-SITU LABORATORY BERLIN (EMIL)

A. Balzer, P. Sreelatha Devi, A. Ziegler
Helmholtz-Zentrum Berlin, Germany

Abstract

The control system for the *Double Crystal Monochromator* (DCM) at the *Energy Materials In-Situ Laboratory* (*EMIL*) is discussed in this paper. The DCM feeding the U17 hard X-ray beamlines was designed and optimized for stability and resolution. A multi modal set-up provides synchrotron radiation with a broad energy range of 80*eV* - 10*keV* and variable polarization. Two canted undulators, three monochromators, five end stations, more than twenty optical elements and a sample to source distances of more than 60*m* are challenges by its own.

The mechanical concept of the DCM puts high demands on the control software. For on-the-fly synchronization of crystal pitch, crystal translation and the cryogenic cooling system rotation (referred as *cryo* in this paper), a closed-loop feedback is needed to fulfill the control system requirements. Motion programs are used for compensation of the non-linearities of the pitch rotation. Target positions are approached on a well defined path, improving reproducibility and positioning time. A non-linear closed-loop control provides fine positioning.

A setup of the motion controller, based on the tpmac module, provides the abstraction interface to the complex DCM motion control software [1]. This paper discusses the DCM hardware, software model and experimental verification.

INTRODUCTION

EMIL is a joint venture of *Helmholtz-Zentrum Berlin* (HZB) and the *Max Planck Society* (MPG) and is aimed at combining a chest-tool of spectroscopic techniques and deposition tools at BESSY II synchrotron [2]. The EMIL laboratory uses as light source one of the most complex beamlines at *BESSY II*. Two undulators, one providing soft X-rays and one hard X-ray, are shining light into a beamline which contains three monochromators, two *Plane Grating Monochromators* (PGM) and one *Double Crystal Monochrmator* (DCM), ten mirror chambers and four exit slits. The two beams are dispersed and focused into two isolated pathways towards five interaction points of which three of them achieve the overlap of soft and hard x-rays. This is only possible due to selectable monochromators and mirrors. This design which demands a very high mechanical and thermal stability of its optical elements as well as motion reproducibility was built by Bestec.

The DCM monochromator, the subject of the present work, is a development of the aforementioned company and is equipped with three pairs of silicon crystals which are cooled to liquid nitrogen temperature in order to reduce the crystal deformation at high heat loads produced by the impinging beam.

A single crystal rotation stepper motor drive with harmonic drive gear is used to move the cradle of the selectable double crystals. The cryo system connected to the crystals has to be moved in sync with the crystal rotation. The worm gear of the cryo system rotation is driven by a second stepper motor.

The fixed exit beam position is achieved by the adjustment of the crystal height, driven by an in vacuum stepper drive. A piezo stage mounted on top of that drive is used to fine-tune pitch, roll and crystal translation (CT) (see Fig. 1).

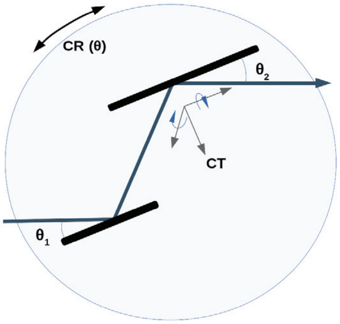

Figure 1: Double crystal positioning using stepper motors for crystal rotation (CR) and crystal translation (CT).

Challenges

Motion control for synchrotron applications is more discerning than ever before. Experimental constructions and prototypes of devices make engineers face various different challenges. None the less, they still have to be cost effective.

Some devices have to follow others on-the-fly, other moving on predefined paths. They have to proceed fast and definite at the same time, to ensure precise positioning of the motors on the endpoint and providing a high stability and robustness regarding vibrations.

Not only the end position precision of hardware is important, but also some beamline applications are very sensitive to disturbances and jerk, resulting from discontinuous acceleration profiles during motions as well. A stable and reliable communication is crucial for the experimental setups to take synchronized data.

In order for software engineers and scientists to get a better grasp of the hardware and software, diagnostic tools had to be implemented and improved. These tools help with the optimization of the devices movement or alignment of the beam, as well as commissioning. To further improve running beamline applications, shorter development cycles of software products are an important requirement ensuring that these complex setups run smooth and safe.

An increased usage of low level programs of motion control hardware is required to achieve best performances from the existing hardware. In some cases, code complexity can be decreased with the help of simple motion programs and can avoid some of the most common mistakes of software solutions in general. This low level functionality has to be supported by the higher level control system.

HARDWARE AND SOFTWARE STACK

This section concentrates on the hardware and software stack of the development process. For some applications of the devices at EMIL beamlines, trapezoidal shaped motion profiles are no longer sufficient. In addition to high precision point-to-point moves, the programming of a complex multidimensional path and closed-loop-moves are required. Some experiments demand the generation of trigger signals in order to synchronize experimental data acquisition and monochromator motion.

During the planning phase of the EMIL project, the *Delta Tau Geo Brick Low Voltage Integrated Motion System* (LV IMS II) [3] has been developed into a stable, powerful and well tested product. It is widely used in the *Experimental Physics and Industrial Control System* (EPICS) community, being able to interface the different hardware devices used to control the stepper motor drives of EMIL monochromators, hexapods, apertures and slit units.

The state machine discussed in this paper, closed-loop positioning, filters and safety features are implemented in PLC and motion programs on the motion controller, thereby, achieving a robust and efficient system.

Based on the tpmac module [3], an EPICS support layer for the new functionality of the motion controller has been added. This was done by deriving new C++ classes and adapting tpmac classes to our devices. Interfaces have been added for the control and diagnosis of complex motion profiles and for safety. Code is shared and reused within derived objects like *PGM, DCM, HEXAPOD, Single Axis, Multi Axis* (see Fig. 2).

The resulting devices were integrated into the legacy BESSY II monochromator control software which runs on a *mvme2100 VME-Board*. It communicates via *CAN Open* with the undulator control program [4]. On devices like the hexapods, the expensive and outdated VME-Crates were replaced by virtual PCs running *Debian Linux*.

DM2K is currently used as the standard graphical user interface. While replacements for DM2K are evaluated, a *Phoebus* based user interface [5] has been implemented for diagnostics and the control of the piezo stage.

The integrated Jython and Python plugins effectively reduce the overall number of programming languages required for implementing small tasks and calculations. This framework makes it easier to collaborate and reuse code. Phoebus also provides a modern display manager and uses predefined libraries for configuration and programming. The Geo Brick motion controller performs low-level tasks with higher update rates. Phoebus and the integrated plug-ins work in the higher level, bringing high quality software hierarchies.

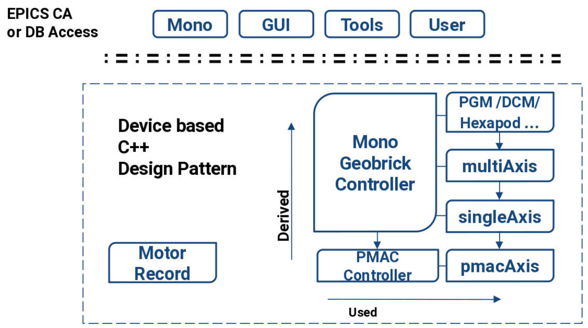

Figure 2: Integration of the low level software written on Geo Bricks into the standard BESSY II monochromator control program.

POSITION MEASUREMENT

In motion control applications at BESSY II, noise from position measurements occurs from a number of sources: vibrations that are generated from devices attached to the monochromator, noise from the position sensor and electromagnetic disturbances or the motion itself. For sufficient positioning, it is critical to remove such disturbances from the measurements with minimum delay. Therefore PLC based filter programs have been implemented, enabling good measurement with minimum delay. These PLC programs are executed with a frequency greater then $1kHz$.

The moving average filter averages a specified number of past values. While the moving average filter gives equal weight to each data point, the digital form of the exponential filter will provide an exponential weighted moving average, leading to a shorter digital delay. This filter is used for all closed-loop movements in motion programs. The incremental computation of the position average and the standard deviation can be used for experimental data acquisition. Additionally, the standard deviation provides a good diagnosis in case of vibrations or other disturbances.

MOTION CONTROL

For on-the-fly applications with *trapezoidal* motion profiles, the old VME-based hardware (VMEX, OMS) needs simple velocity and acceleration commands via the VME-Bus. Acceleration of trapezoidal motion profiles is discontinuous, leading to unwanted disturbances during the movement. Discontinuous acceleration results in discontinuous force on the device and will excite vibrational modes of the monochromator. This can be observed at beamlines with very high demands on reproducibility during continuous mode operation [4].

In order to avoid these disturbances, a move profile, which is continuous in the second derivative, had to be developed. Acceleration has to carefully be adjusted and the jerk has to be controlled and limited to an optimal value. The higher the jerk, the bigger the amplitude of the disturbances in a broader frequency spectrum. The vibration energy created will be higher as well [6] [7]. Thus, it is very important that motion profiles are as smooth as possible. The trajectory can be predicted through calculations for the near future points and some applications rely on these predictions.

Geo Bricks offer various options to program linear blended moves with *sigmoid* motion profiles. The planning of movement has to be done in advance, starting at the beginning of the motion. This results in a trade off between acceleration rate and delay time due to pre-calculated moves. The acceleration is remarkably high, if higher velocities are required during a movement.

Algorithm for Smooth on-fly Velocity Profile Generation

As a solution for the challenges of fast high precision point-to-point movements and highly flexible closed-loop on-the-fly moves, an algorithm has been developed to provide smooth trajectories on-the-fly with end-point prediction at any time during the motion.

In general, the different spline move modes of the Geo Bricks (*PVT, SPLINE1, SPLINE2*) are able to generate a smooth profile. However, the limitation of the jerk and the precise move planning are the responsibilities of the programmer. Splines have the disadvantage to easily oscillate if the incorrect values for positioning are used. The planning of the closed-loop moves in general relies on measurements of a noisy input signal. Quantization effects also have to be put into account. Those facts make the generation of on-the-fly spline moves a difficult task.

To eliminate this problem, the motion profiles have been divided in different phases of acceleration, deceleration and constant velocity. A set of smooth predefined profiles are used to construct a gentle and safe path for the motion (see Fig. 3). A sigmoid acceleration profile can be generated by assembling spline building blocks 1 and 2. For a longer acceleration, phase 1 followed by variable lengths of phase 3 ending with phase 2 can be implemented (see Fig. 3).

A state machine is used to quickly generate a sequence of such move phases in real time (see Fig. 4). The current version of the algorithm uses spline segments of $20ms$. It builds either *blocks of 48/12/6/4 spline segments* or a *single spline segment* for constant velocity or acceleration. Those blocks are directly stored in a data array on the Geo Brick controller.

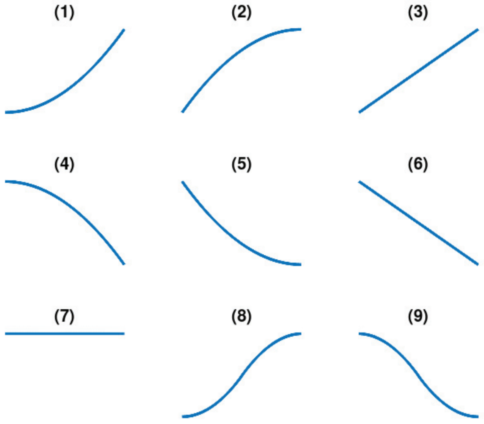

Figure 3: Building blocks or spline move cases for spline control algorithm.

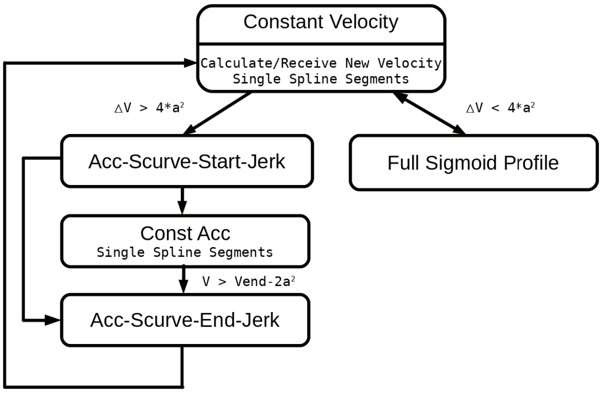

Figure 4: State set of the profile generation algorithm.

The algorithm has been successfully tested on real hardware of PGM- and DCM-monochromators and passed acceptance tests with random input of critical step sizes and profiles. It is presently used for closed-loop control of the DCM cryo drive with various update rates up to $12.5Hz$. Figure 5 shows a long range move, using short spline building blocks every $60ms$ compared to long building blocks at a control-loop update every $960ms$. The size of the spline building block can be adapted to the magnitude of the velocity change. The same state machine can be reused for different applications, for example the improvement of existing implementations like the continuous mode.

In general, the complete trajectory of motion for this algorithm can be predicted in advance at any point of the movement. Figure 6 shows the experimental verification of a full stop at maximum velocity during a closed-loop movement. Those calculations, if done with very high precision, would have to take many factors into account.

The already known static non-linearities of the system make this kind of calculation on motion program level very complicated and difficult to implement. Nevertheless, knowing the magnitude of all deviations should make it easier to extend the existing algorithm with a safe closed-loop deceleration phase, in order to reach the desired end position without big programming effort. Further extension could be the provision of trigger signals for experimental data taking synchronized with the motion.

Algorithm for Exponential Curve Generation for Closed-loop End Positioning

At BESSY II closed-loop point-to-point positioning of the stepper motors is being done, using a series of incremental

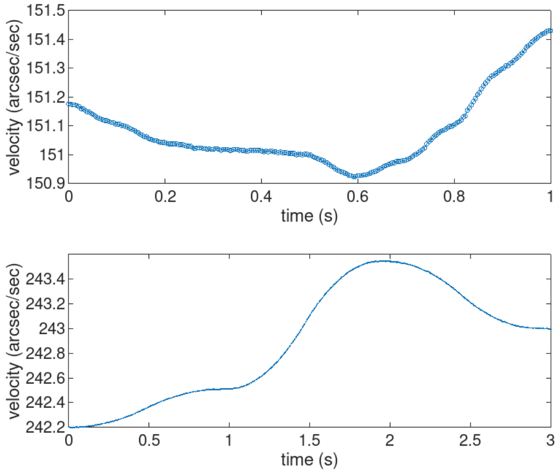

Figure 5: Small velocity changes, controller output during a long range move.

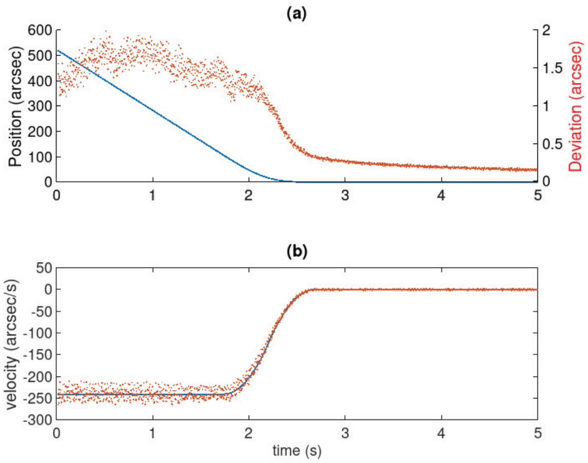

Figure 6: Deceleration phase and stop at predicted end position. Deviation from calculated position (a) and measured velocity and step velocity output (b).

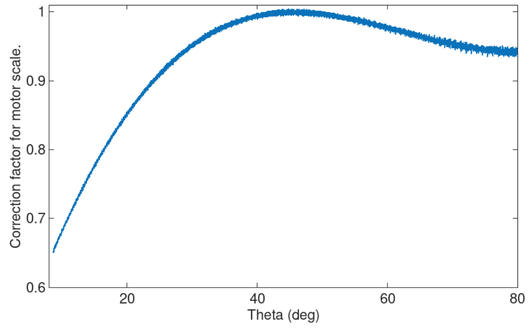

Figure 7: Measured relation between actuator position and rotation angle theta.

moves, proportional to the distance from the start point to the end-point. By modifying the proportional gain depending on different ranges to the target position, a good performance for both *high-precision-short-moves* and *long-moves* could be obtained.

Based on this work, a *continuous closed-loop motion profile* has been created that exponentially reduces the velocity according to the distance of the target position, using a proportional gain as a function to the end position (see Fig. 8 a).

In the first phase of this move, the velocity ramps up with defined acceleration up to a maximum fine positioning speed and then smoothly reduces it according to the output of the proportional gain (see Fig. 8 c). The move will stop after reaching an in-position-band of the target position and at the same time it allows no inversion of the move direction. The result is a very smooth approach move with no vibrations induced due to discontinuous changes of acceleration. Figure 8 shows the encoder signal and the step motor output for a step scan.

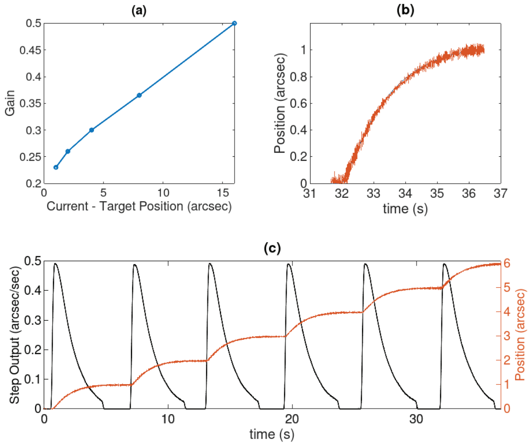

Figure 8: Non linear proportional gain for end positioning.

Close Loop Control of the Cryo Drive

The operation of the cryo drive attached to a gear box that is connected via worm gear to the rotation axis is very critical. The system has a backlash of more then 1000*arcsec*, but the motion has to be synchronized with the crystal rotation axis within 1000*arcsec* in order to avoid a twist of the cryo pipes and bellows attached to the crystal stage of the DCM.

The crystal rotation drive, which uses a sine bar mechanism, moves on a smooth predefined path (see Fig. 15 and Fig. 7). As a result, the cryo drive moves approximately with constant speed while following the motion of the crystal rotation (see Fig. 9 and Fig. 5).

After linearizing the step output scale (see Fig. 7), the target velocity of the cryo drive can be calculated, using a simple PID velocity feed forward controller (see eq. 1).

$$V_{cryo} = K_p\,(e(t)\,K_d\frac{de(t)}{dt}\,K_i\int e(t)dt\,K_{vff}\,V_{theta}) \tag{1}$$

Where $e(t) = P_{theta} - P_{cryo}$ is the difference of the position measurement from the cryo drive and the crystal

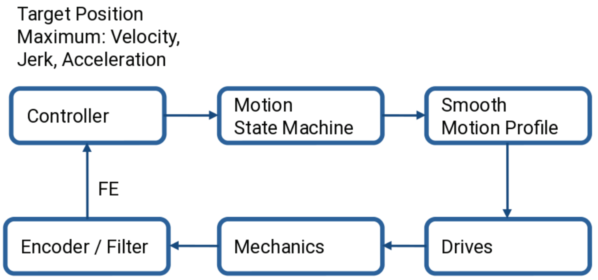

Figure 9: Closed-loop move of CR2.

rotation, V_{theta} is the current velocity of the theta drive in $\frac{arcsec}{sec}$.

The constants K_p and K_{vff} were calculated from the system kinematics. Fine tuning all constants of equation 1 leads to slightly better performance, the cryo axis stays in sync with the crystal rotation within a few *arcsec*.

DIAGNOSTIC TOOLS

Upgrading the motion control software in the storage ring hall is a critical process. To ensure high quality upgrades at the beamline, python scripts for acceptance and tool based tests have been used. Motion profiles are tuned by *trial and error methods*, since modelling is not accurate enough, not possible or not required. Additionally, conditions and use-cases may change over time.

For the diagnosis of spline motion profiles during regular operation, a continuous data stream with data acquisition rates of about 200-400 Hz is required.

To achieve these rates, simple flexible PLCC (see Fig. 10) and RT PLC programs were implemented to calculate and store the data inside the Geo Brick user buffer. The tpmac module has been extended to continuously poll these data packages and pass it to a EPICS waveform record support module. It has originally been developed for diagnosis of the continuous mode and for other optimization procedures [8] [4] and belongs to the BESSY II standard monochromator control software interface. Six channels of data up to a data acquisition rate of about 300Hz are provided in the current configuration.

In addition, a complete set of EPICS Process Variables (PVs) which describes the state of the monochromator, is correlated to that feedback data, using EPICS time stamps. A spike detection PLC program, triggered when noisy measurements suddenly changes by a large amount and the fatal following error feature of the Geo Bricks is used for machine protection in case of errors in the programmed splines.

PIEZO STAGE

Maintaining of the parallelism of the crystals is important for the functioning of the double crystal monochromators. Piezo motors are the best choices when it comes to µm precision due to high resolution, small size, high torque to weight ratio and fast response because of low inertia. At BESSY II, a closed-loop piezo motor stage is used for precise corrections of pitch, roll and crystal translation (height), along with a stepper stage for larger crystal translations. This system consists of three piezo motors, one stepper motor and three Renishaw encoders. The crystal translation can be adjusted using the stepper motors and the piezo motor.

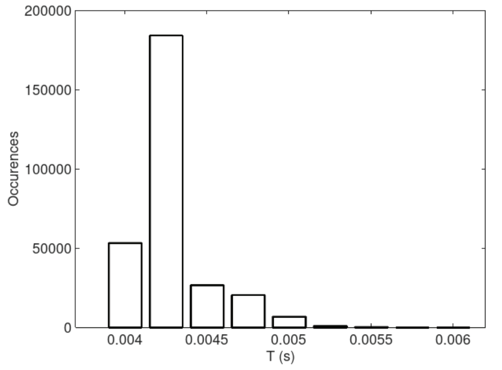

Figure 10: Jitter of periodic data acquisition using a background PLC task on Geo Bricks during regular operation.

The state space model of the open-loop system is described by equations 2 and 3:

$$\left[\ \dot{X}\ \right] = \left[\ A\ \right]\left[\ X\ \right] + \left[\ B\ \right]\left[\ u\ \right] \tag{2}$$

$$\left[\ Y\ \right] = \left[\ C\ \right]\left[\ X\ \right] + \left[\ D\ \right]\left[\ u\ \right] \tag{3}$$

Figure 11 shows the inter connected two-area closed-loop system.

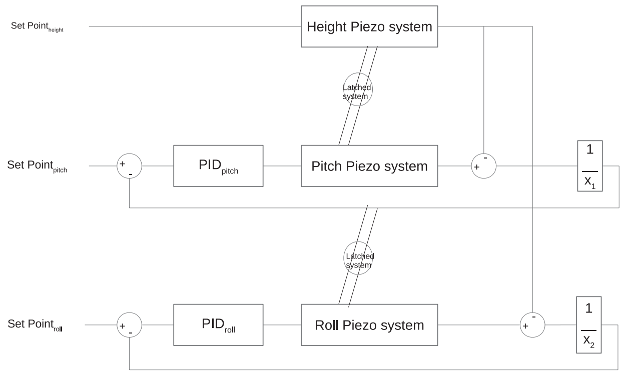

Figure 11: Piezo stage as a closed-loop MIMO system.

Figure 1 shows the ray diagram and the degrees of motion of the piezo stage. The open-loop piezo stage (see Fig. 12) consists of a digital to analog converter, a piezo amplifier, a piezo motor and an encoder.

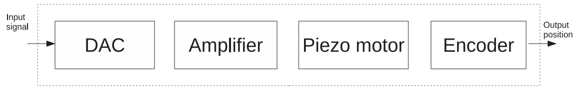

Figure 12: Open-loop piezo motor stages for pitch, roll and height.

Due to the geometry of the construction, a motion in one of the motors affects the position of all other motors as well and results in changed encoder positions for all of them. Hence the system is a *Multiple Input Multiple Output* (MIMO) system. A system identification [9] [10] [11] was conducted on the open-loop system and the state space model of the open-loop system is computed accordingly with 90.3% curve fit (see Fig. 13).

In the closed-loop system, the unit for set points and feedbacks is µrad. The new output vector is calculated as seen below:

$$y_2' = \frac{(y_2 - y_1)\mathrm{mm}}{64.75\mathrm{mm}} \mu\mathrm{rad} \qquad (4)$$

$$y_3' = \frac{(y_3 - y_1)\mathrm{mm}}{127.75\mathrm{mm}} \mu\mathrm{rad} \qquad (5)$$

Where, $x_1 = 64.75mm$ is distance between pitch and height encoders, $x_2 = 127.75mm$ is the distance between roll and height encoders.

The stability is analyzed using the *Nyquist stability criterion* [12] and a suitable controller is designed [13] [14]. The model stability was analyzed and a PID compensator was designed and tuned to obtain a robust and fast responsive system (see Fig. 13a).

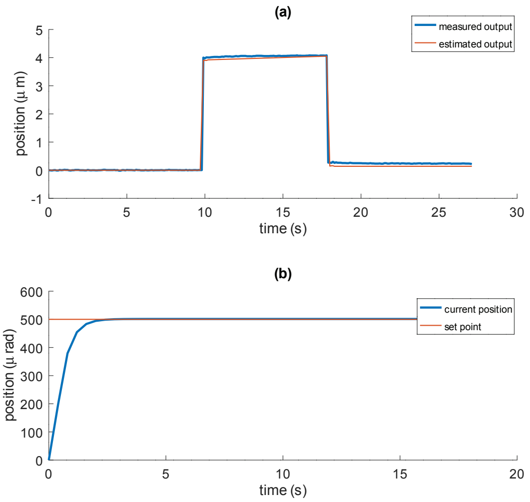

Figure 13: Estimated system and the closed-loop performance.

The system identification, controller design and closed-loop system tuning had been done in the following steps:

1) Open-loop system identification
2) Estimation of MIMO system-state space model
3) Stability analysis
4) Pole Zero placement design
5) Closed-loop tuning of the interconnected system
6) Implementation and testing

The tuned closed-loop performance of the actual system can be seen in Figure 13 b.

DCM MOVE PROGRAM LOGIC

Figure 14 illustrates the motion program logic used for the DCM. Because of the excessive backlash of the cryo axis, a safe algorithm at the start of the movement is needed. Before the motors start with the actual motion both axis have to be moved in a way that ensures parallelism during the acceleration phase of the actual planned move.

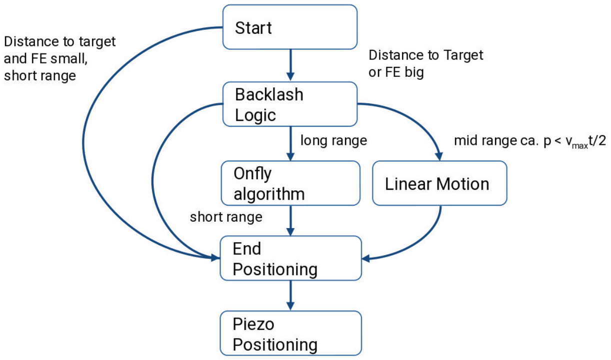

Figure 14: Move program logic for various point-to-point move step sizes.

Following the standard building blocks that were described above, the rest of the program logic can be distinguished within these three different cases:

1. Long range moves where the crystal rotation trajectory is done in a way that results in almost constant velocity for the cryo drive (see Fig. 15 a) while at the same time the cryo axis is following the crystal rotation.
2. Mid range moves that are executed in a linear move sequence where the axis would spend the whole time in the acceleration phase without reaching the maximum velocity (see Fig. 15 b, c).
3. Short high accuracy moves with exponential move profile (see Fig. 8).

By configuring the different in-position bands of each move type the program structure is very flexible and can be adapted to the needs of the user.

For safety, a PLC program is running which monitors the difference between the cryo drive and the crystal rotation and will stop all motions in the case of a fatal following error. Only when all stepper motion has stopped, the controller of the piezo stage can be started. Especially the crystal translation axis has to be set to a fixed position, since this motion would interfere with the MIMO system of the piezo stage.

CONCLUSION

Device specific low-level features relevant to the users at EMIL have been made accessible and directly configurable by the users. The user interface can easily be extended.

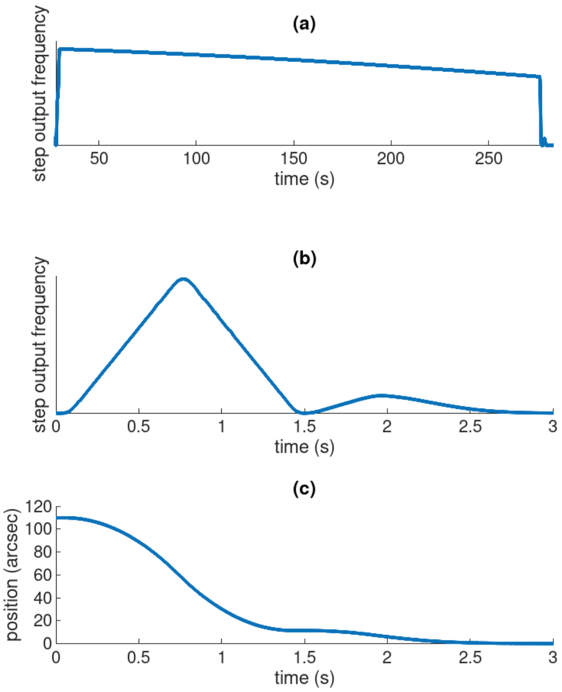

Figure 15: Long range move profile of crystal rotation (a) and mid range move profile (b,c)

Low-level safety features ensure safe operation of the devices. Diagnostic tools for motion trajectories have been implemented, they have been proven to be helpful for software development.

In addition, similar features have been requested for post-mortem correction of experimental data on several beamlines at BESSY II. Trigger signal generation in sync with movements or from PLC are also one of the requirements for future developments at BESSY II.

The proposed algorithms have been tested and experimentally verified. Especially the tests with the algorithm for smooth on-fly velocity generation turned out to be very promising. This algorithm will be further developed for end positioning, resulting in a simple but very flexible motion program structure for high-speed and high-accuracy applications. Another application is the continuous mode on PGM, SGM and DCM monochromators.

A stable closed-loop system has been implemented for the MIMO system of the piezo stage for fine tuning pitch, roll and yaw of the DCM. However, a redesign of the hardware setup is needed for faster servo update rates, proper system identification and tuning.

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