SYNCHRONIZED NONLINEAR MOTION TRAJECTORIES AT MAX IV BEAMLINES

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Abstract

The motions at beamlines sometimes require components to move along non-trivial and non-linear paths. This type of motion can be achieved by combining several simple axes, typically linear and rotation actuators, and controlling them to perform synchronized motions along individual non-linear paths. A good example is the 10 meter spectrometer at MAX IV Veritas beamline, operating under the Rowland condition. The system consists of 6 linked axes that must maintain the position of detectors while avoiding causing any damage to the mechanical structure. The non-linear motions are constructed as a trajectory through energy or focus space. The trajectory changes whenever any parameter changes or when moving through focus space at fixed energy instead of through energy space. Such changes result in automated generation and uploading of new trajectories. The motion control is based on parametric trajectory functionality provided by IcePAP. Scanning and data acquisition are orchestrated through Tango and Sardana to ensure full motion synchronization and that triggers are issued correctly.

Keywords:trajectory, motion, spectrometer, control system, linked axes

INTRODUCTION

Motion of devices is a fundamental requirement on beamlines in order to position samples, detectors, optics and other items precisely and in a timely manner [1–5]. The requirements vary vastly from being a simple on/off beam motion, continuous energy scans through linear approximation [6,7] to even more complex ones where several axes are linked together to perform a non-linear motion where each position is dependent on others positions and where those motions should be conducted correctly in time. At MAX IV a concept of trajectories is used where each motor in a system is given a unique trajectory table to follow. Motion trajectories are used, with clear benefits, in, e.g., the SCANIA spectrometer at Balder beamline, the flight tube at CoSAXS beamline, and the monochromators at FlexPES and FinEstBeAMS beamlines but here, we focus on the solution for Veritas Rowland spectrometer.

The 250 to 1500 eV soft x-ray beamline Veritas and its 10-meter spectrometer arm (Fig. 1) has a detector wagon that is allowed to move roughly 2.5 meters along a linear path (1.2 meters vertically) suspended on a truss of beams. Inside the truss, the vacuum system is suspended that also needs to move. In the detector wagon, the detector is suspended in three linear motors. In the near future, a second detector will be added orthogonal to the first one and a multilayer mirror inserted to allow polarization measurements. All the involved motors have to be in a certain position described by the equations derived and described in [8] to ensure that the beam path is correct through the system.

SPECTROMETER CONCEPT

Rowland Circle

From a conceptual point of view the detector follows a Rowland circle [9] to maintain the focus of the detector Fig. 2. In order to maintain the Rowland circle criteria, the detector motion should follow the circle arc determined by the curved grating surface. This is achieved by using two linear motions together with a rotation. By combining the motion of two linear actuators, the detector moves along the desired circle arc. As the entire beam path must be under vacuum, a set of vacuum pipes, interconnected by bellows, are installed between the gratings and the detector, whereas the last bellow allows for a 2.5-meter displacement of the detector. This vacuum system is too heavy to passively follow the motion of the detector. Instead, it is driven by three linear actuators. It is essential to avoid mechanical stress on the system, especially the bellows, as these might be damaged. Therefore, any displacement of the detector requires all six axes to move in a synchronized manner, which keeps the vacuum system straight and stress-free, not only at the target position but also during the entire motion. Directions and strokes of the 6-axes motion system are depicted in Fig. 3, where the trajectories should place the red circles and the detectors (D1 and D2) on the red beam path, by performing linear motions marked with blue circles. The beam path differs depending on gratings used and desired energy and focus. One motion will affect other motions causing at least one red dot to move away from the correct path.

Mechanical Limitation

Each motor is equipped with limit switches to prevent overtravel. This is however not sufficient to prevent damage to the system. One example is the mirror chamber (denoted MC in Fig. 3) in front of the detector chamber. Both of these components need to be able to move vertically, to align them correctly with respect to the beam. These motions allow much larger relative displacements than the bellow connecting the two chambers can accommodate. Thus any larger detector motion must be compensated for by also moving the mirror chamber. Another example is the two motors that move the detector horizontally and vertically. In the middle of the horizontal motion, the detector needs to pass over a part of the support structure. Around this position, the detector must be in the upper half of its vertical

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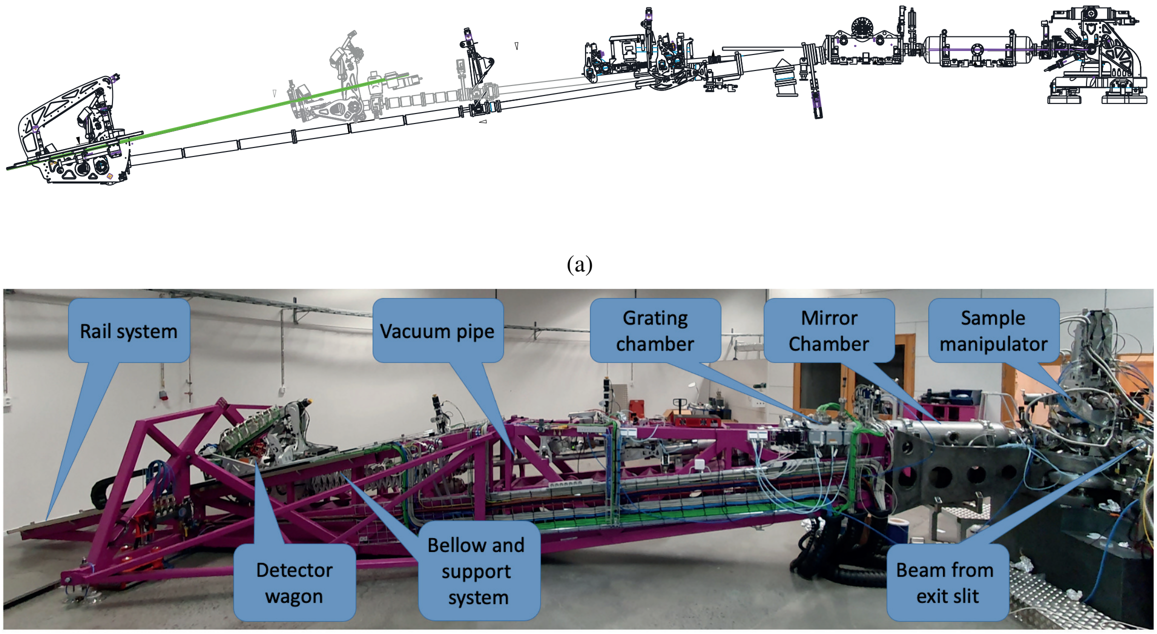

(a)

(b)

Figure 1: Veritas spectrometer with the detector table to the left and sample to the right as a) a CAD model and b) the complete system after installation and commissioning.

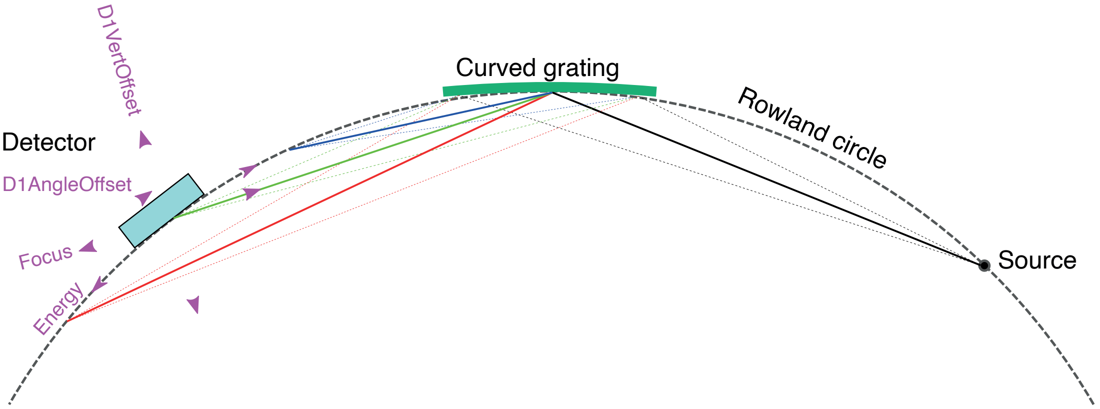

Figure 2: With a Rowland circle configuration the detector images a picture in focus if it stays on the diameter of the curved gratings radius.

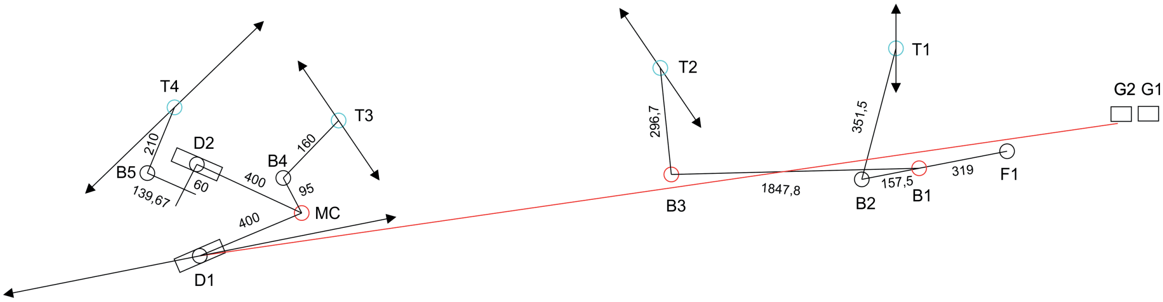

Figure 3: The motion of the axis as illustrated with nodes.

motion to avoid colliding. However, towards both ends of the horizontal motion, the detector needs to be in the lower half, to catch the Rowland circle. Thus, any larger horizontal motion of the detector must follow an arc. These rules are very difficult to enforce with physical limit switches. The many degrees of freedom mean that such a system would either need to be very complicated, or severely limit the allowed motion ranges.

ICEPAP TREATING TRAJECTORIES, POSSIBILITIES AND LIMITATIONS

IcePAP [10], originally developed at the ESRF, is the MAX IV Laboratory standard motion controller system. The controller system may contain up to 8 chassis, each with its own controller unit, sharing a single CAN bus for communication, data exchange and synchronization. Each chassis can host up to 8 drivers, which allows the system to accommodate up to 128 drivers. Besides the power electronics, each driver hosts 1-MB memory that can be configured for different purposes. In addition to the default trapezoidal profile of the driver's internal indexer, the driver's firmware features parameter-based motion mode as well. In this mode, a look-up table combining a parameter to internal indexer is downloaded to the driver and then trapezoidal profile movements can be executed with regard to the parameter. Besides, from the master it is possible to synchronize the parametric motion of several drivers, allowing to potentially move a whole system on the same parameter. In this case, an event causing a single motor to stop (limit switches, position closed loop errors,...), will cause all involved drivers to stop.

Tables up to 10k points can be uploaded, and an internal interpolation mechanism based on linear or spline polynomials allows to reduce the amount of data to transfer. As an example, a 3rd order splines between two consecutive points are calculated from the positions and the slopes in those points (slopes will be estimated if not supplied). An example of a (truncated) table with energy as the trajectory parameter and 2 motors in user units, this case mm, are shown in (List. 1). The header states "active trajectory" indicating that this trajectory is loaded in IcePAP. The rest of the header contains information for the user to verify on what the trajectory calculations were based upon, such as grating line density and source angle.

Listing 1: IcePAP energy trajectory (truncated) for two motors.

```
"ActiveTrajectory": {
"_description":
    "Normal trajectory ,
    240.0-960.0,
    1350.0-1350.0,
    0.03054-0.03054, ",
    "_table": [
        [
            240.0,
            240.72072072072072,
            ...
            959.2792792792792,
            960.0
        ],
        [
            -166.95959306707357,
            -166.42171860494807,
            ...
            7.352565954100715,
            7.414482558850775
        ],
        [
            15.587070375275488,
            15.5674055524307,
            ...
            9.221481607237592,
            9.219223341264524
        ],
    ],
"_time":
"2023-09-27T01:14:24.841193+02:00"
}
```

The first column is energy (in this particular table). The first motion will be to enter the trajectory and this is done with the normal axis trapezoidal movement profiles for each individual axis. A motion command with target energy is send and position corresponding to that row sets the motion for the individual motors. Subsequent motion commands to another energy will be following the loaded tables.

CONTROL SYSTEM INTEGRATION

The control software is implemented as Sardana [11] motor controller using Tango Control System [12] together with the MAX IV control system and therefor integrated seamlessly from the beginning. The spectrometer is presented as a single motor axis, that moves in energy space. Motions are performed at a fixed velocity measured in eV/second.

The Sardana controller exposes a number of parameters for adjusting the trajectory. This includes offsets in height and angle of the detector. There is also a focus parameter. Setting this to a non-zero value moves the detector along the beam by the given number of millimeters. This is used while adjusting the system, in order to find the optimum focus. All trajectory parameters are also exposed as Sardana motor controllers.

Load Mechanisms

The tables loaded to the motor drivers describe a trajectory in energy space. Whenever a parameter other than energy is changed, the system must move from its position on the current trajectory to a position on a new trajectory. The position on the new trajectory is chosen using one of two methods, depending on which parameter is changed. For most parameters, the target position is the same energy as the current one. For the parameters that are expected to change rarely, and that may result in large motions, the target position is instead chosen as the point on the new trajectory physically closest to the current position. This process is done in several steps shortly described in the enumerated list as they are evaluated:

1. calculate the new trajectory using current parameters
2. determine which position on the new trajectory to move to, using one of the two methods described above
3. calculate and generate a temporary linear trajectory leading from the current to the new position
4. load the temporary trajectory to the motor drivers
5. move to the new position along the temporary trajectory
6. load the new trajectory

Loading of a new trajectory takes a fraction of a second, and since the motions are generally gentle, the loading does not result in a significant delay. The main contribution to latency is found in the calculation and safety mechanisms.

Visualization

It is possible to have a view of loaded theoretical trajectory as shown in Fig. 4 where the predicted trajectory is blue and framed by red limit switches. It is also possible to calculate and visualize the theoretical trajectories for a set of parameters in order to evaluate how parameters affect the individual trajectories.

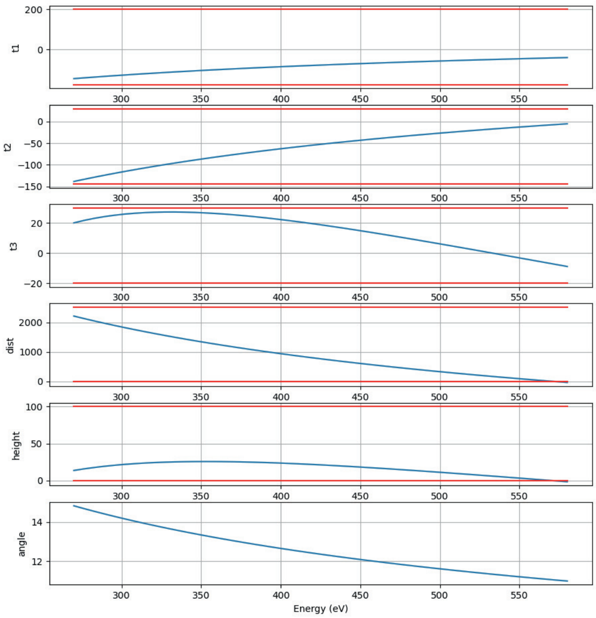

Figure 4: Expected trajectory for a particular grating as visualized by viewer for different energies.

The visualization tool is also used to highlight, as in Fig. 5, when a trajectory will be interrupted as one motion is outside its boundary. The entire set of motors will stop simultaneously and the system has to be brought back to an allowed trajectory.

The theoretical trajectories should be followed in space by real motion and be reliable. A prerequisite is operating motors under closed loop condition. It is important to compare theoretical calculations with actual motion as in Fig. 6 where the solid line is the theoretically calculated positions prior being uploaded into the IcePAP as a trajectory. The dots are the actually measured positions as tango attributes from the control system, i.e. encoder positions as the motion is progressing through its scan.

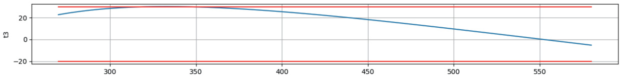

Figure 5: When trajectories (blue) are predicted to violate boundaries such as limit switches (red), the motion should not be started and the situation can be visualized.

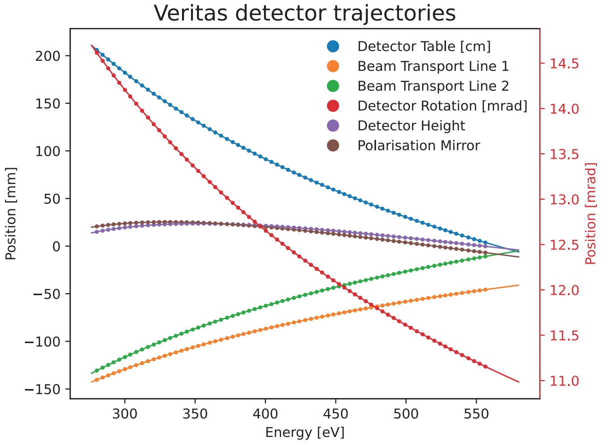

Figure 6: Theoretical calculated position (line) and measured positions with encoder(dots) are compared. The motion is closely following the precalculated motion.

The trajectories are used in all motion, not just individual scans. This behavior is illustrated in Fig. 7 where a typical investigation is conducted on a sample. An energyscan is followed by a change of grating in the spectrometer and then a new energyscan, and finally, a scan in focus for a fixed energy. During all those motions the trajectories keep the mechanics under control.

Recovering After a Problem

The IcePAP drivers stay in parametric trajectory mode as long as corresponding motors are only moved using the parametric motion commands. A normal move command, or an issue such as an error in the closed loop control, will make the motor drop out of parametric mode. If this happens, the parametric mode must be recovered before any larger motions can be done safely. For this purpose, the Sardana controller exposes a read-only attribute telling which energy the system currently is closest to. It also exposes an array that gives the distance that each motor needs to move in order to reach the desired position. The recovery is done by a special move command, that moves the system to the desired trajectory position and re-initiates the parametric mode. For safety, this command only accepts a target position that is close to the current position.

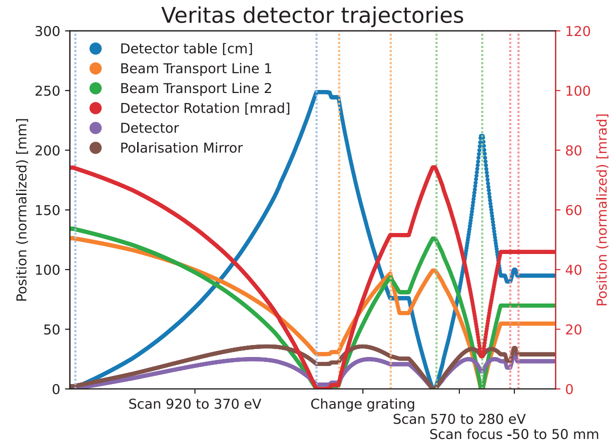

Figure 7: Position plotted as a set of motions are run. Sections indicated with vertical lines shows energy scans, grating changes and focus scans. In each motion new trajectories needs to be created and uploaded.

Limitations and Challenges

The parametric trajectory functionality of the IcePAP system supports one-dimensional trajectories only, meaning it's not possible to have a combined trajectory with for example energy and focus. This can be worked around by dynamically generating and loading new trajectories to support motions along other dimensions. Parametric trajectories offer much more functionality than normal pseudo motors, which inherently makes them more complex to use. For example it is more difficult to recover from problems such as hitting a limit switch. It is the responsibility of the control system software to hide as much as possible of the complexity, and present a user friendly interface giving access to the required functionality.

User Parameters, Fitting Routine

The Sardana controller exposes a number of parameters for adjusting the detector trajectory and it is possible to scan those users parameters for calibration, if needed. These are:

- detector height offset
- detector rotation offset
- detector focus offset
- grating line density
- grating curvature

The exact trajectory of the Rowland geometry is very sensitive to parameters such as grating radius and line density. By finding a few known points along the energy scale, by using samples with well-known emission, it's possible to fit the parameters. For this purpose, a fitting routine has been developed. Given the recorded detector positions at these known points, the routine optimizes the Rowland parameters in order to generate a trajectory that gets as close as possible to these positions, at the correct energies. The output is a set of adjusted parameters that can be entered in the Sardana motor controller.

TRAJECTORIES' FUTURE AT MAX IV

Parametric trajectories can be used to perform synchronized motions that can be difficult or even impossible to achieve by mechanical solutions. The fact that the trajectory is defined in software, rather than by a mechanical system, also means that the trajectory can be changed freely. These properties mean that new instruments often are designed to be controlled using parametric trajectories. This allows future instruments to be very flexible.

Driving for example monochromators with trajectories is also useful for performing continuous scans. This is already implemented at a few beamlines, but is potentially useful on several more. This can be further improved by designing monochromators with continuous scans in mind, for example by minimizing vibrations caused by moving motors.

CONCLUSION

With the introduction of trajectories, the possibilities in the mechanical design and in the measurement methodology is increased as the parameter to follow can be arbitrarily chosen as e.g. energy or a curvature in space. A large set of motors can be treated as one unit and the complex motion is solved without the need of interference from the user, hence faster and safer motion is ensured. Based on the scan the user wants, recalculated and uploaded trajectories, unique for every motion, makes the user experience as a whole much improved.

ACKNOWLEDGEMENTS

The soft x-ray beamline projects Veritas at MAX IV is funded by Knut and Alice Wallenbergs foundation and Vetenskapsrådet. Also SSF, Stiftelsen för strategisk forskning, have through RIF14-0064 provided funding for this work.

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