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COLLISION AVOIDANCE SYSTEMS IN SYNCHROTRON SOLEIL

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Abstract

Beamlines at Synchrotron SOLEIL are finding that their experimental setups (in respect to their respective sample environments, mechanical systems, and detectors) are getting more constrained when it comes to motorized manoeuvrability - an increasing number of mechanical instruments are being actuated within the same workspace hence increasing the risk of collision. We will in this paper outline setups with two types of Collision Avoidance Systems (CAS): (1) Static-CAS applications, currently being employed at the PUMA and NANOSCOPIUM beamlines, that use physical or contactless sensors coupled with PLC- and motion control- systems; (2) Dynamic-CAS applications, that use dynamic anti-collision algorithms combining encoder feedback and 3D-models of the system environment, implemented at the ANTARES and MARS beamlines but applied using two different strategies.

INTRODUCTION

System actuation in small or limited workspaces can be a delicate matter when taking the risk of collision into consideration. Synchrotron multi-techniques experimental environments are becoming more difficult in this matter as they combine complex beam-focusing setups, sample stages, and detectors – each section often actuated in many Degrees-Of-Freedom (DOF), sometimes with overlapping workspaces, and each section often very fragile and expensive/time-consuming to repair.

The traditional (and most direct) approach to this problem is to introduce workspace limitations (with mechanical hard-stops and/or limit switches to the various actuators) to different subsections, hence assuring non-overlapping workspaces and thus eliminating the risk of collision. This method is however only limited to static (e.g. unchanging) and less constrained environments in the sense that the setup is set in a fixed configuration and no additional systems should be introduced into the workspaces, nor that the different workspaces should ever overlap.

This paper will outline four motorised Collision-Avoidance-Systems (CAS) at SOLEIL that have been adapted to *dynamic or complex workspaces*, particularly where overlapping workspaces are being used. The CAS applications are here classified as:

1. **Static-CAS**: Systems that use proximity- or touch-based sensors coupled with PLC- and motion control-systems.
2. **Dynamic-CAS**: Systems that use motion controllers with integrated dynamic anti-collision algorithms combining encoder feedback and 3D-models of the system environment to avoid collisions.

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STATIC-CAS AT THE PUMA BEAMLINE

PUMA [1] is an ancient materials analysis beamline optimised for 2D- imaging with hard X-rays in the 4-23 keV range. The beamline offers its users a range of analytical tools in the form of X-Ray fluorescence (XRF), absorption spectroscopy (XANES), and powder diffraction (XRD). A second experimental stage will be added in the future for 3D imaging with up to 60 keV X-ray beam energy.

This section will focus on the setup situated in the CX-hutch where its beam-focusing section, sample-stage, and detector-support all move in collision-range of each other.

PUMA Experimental Station Overview

The PUMA CX Environment system consists of two motorised table platforms: one holds the Kirkpatrick–Baez (KB) mirror subsystem, its sample goniometer stage, microscope and XRF detectors, while the other table supports the 2D X-ray camera detector. Figure 1 illustrates the overall setup, here each subsystem annotated with the DOF used in the CAS. In total, the complete system holds 41 motorised axes - with overlapping workspaces over 16 DOF for the mirror-chamber, sample stage, and detectors.

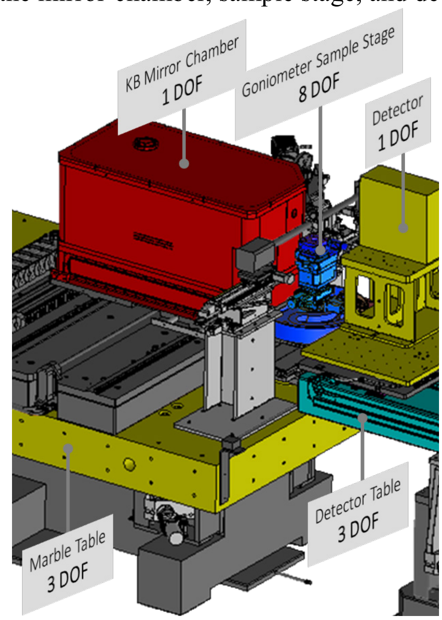

Figure 1: PUMA CX environment overview to be controlled with a CAS, here portraying the five subsystems with a total of 16 degrees of freedom (DOF) used in the CAS.

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PUMA Experimental Station Control & CAS Architecture

Figure 2 shows the control architecture for the complete system implemented in the CAS: low-level control is applied via a SOLEIL-standardised 4-controller(ControlBox)-driver(DriverBox) setup [2] and a PLC system, and high-level control is done via the TANGO framework [3].

The CAS framework is introduced at the low-level, with proximity-sensors and a safety light curtain sensor strategically installed at collision risk-zones. A PLC continually monitor and filter these sensor states and blocks (via dedicated PLC-controller TTL signals, here marked 'Inhibition' in Fig. 2) specific axis movements if it deems a collision is imminent. All controllers contain application-specific microcode to take the appropriate action based on these PLC-signals. To 'unblock' motors, the user can apply an 'Acknowledge'-command to the PLC via the TANGO framework, which then transfers it to the controllers via TTL-signals and hence unblocks the motor movements in the appropriate direction. The *Inhibition* and *Acknowledge* signals have been made active so that if connectivity or power-loss issue arise, the motors are blocked by their controller.

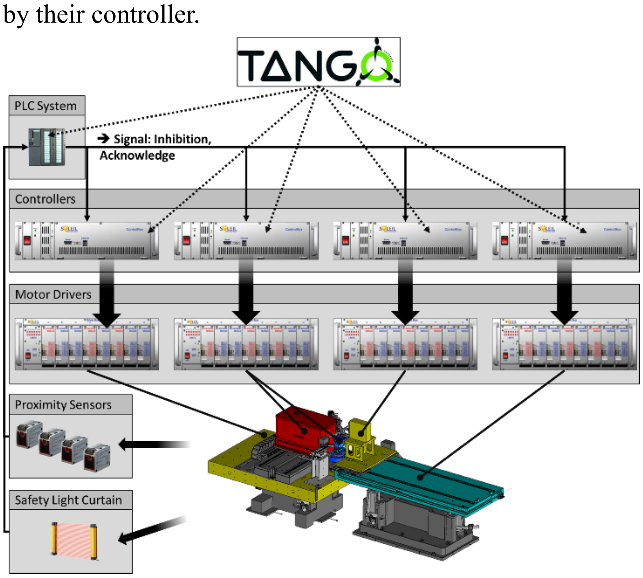

Figure 2: PUMA CX CAS control architecture, the SOLEIL standard controllers (ControlBox [1]) here complemented with PLC-treated signals from proximity- and safety light curtain sensors.

Each anti-collision sensor outputs two states (collision/no-collision) to the PLC system: the safety light curtain sensor simply does this by detecting laser-breaks in the visible path, the proximity sensors must however be preconfigured to output their collision-states if the measured distance falls within certain thresholds. The output from the proximity sensors can however give off false activations (in the form of ON/OFF flickering) and are therefore filtered in the PLC system for more robust use. The PLC then blocks/unblocks specific axis movements using the combined sensor data using pre-filled table-data for reference.

The whole CAS can be disactivated via the TANGO device server with a password protection.

STATIC-CAS AT THE NANOSCOPIUM BEAMLINE

The NANOSCOPIUM beamline [4] is dedicated to hard X-rays (5-20 keV) fast scanning multimodal and multiscale (35 nm to 1 µm) 2D- and 3D imaging with high spatial resolution (nanometric). The beamline offers cutting-edge X-ray nanoprobe imaging and tomography techniques. It provides a wide range of complementary imaging and spectroscopy modalities, to which coherent diffraction imaging is associated.

The NANOSCOPIUM CX2 and CX3 nanoprobe stations are in exploitation in sequential mode: CX2 is based on FZP and CX3 is based on KB nanofocusing optics. CX2 offers Ptychography with highest spatial resolution down to 35 nm and full field X-ray microtomography in absorption and phase contrast modes. For which many different types of motorized detectors and optical elements are installed in a very compact space, each can be inserted or extracted to build a specified station environment according to the experimental requirements. However, the risk of collision between different elements is increasing and needs to be treated for its safe operation.

NANOSCOPIUM CX2 Overview

The general setup of the CX2 environment is shown in Fig. 3, where the sample stage and most of the detector sections are installed in close proximity to each other. In addition, the Fresnel Zone Plate (FZP) and Central-Stop (CS) optical stages may also approach the same area and possibly collide with the vertical support marble during their displacement, which complicates the issue even further.

The risk of collision doesn't only present itself from the motorised elements: users should be able to manually displace certain sections (e.g.: the XRF stations along a circular rail) and possibly install/uninstall beam transfer tubes that approach the sample environment.

The first CAS control has been implemented to take care the collision risks between the optics stage, 3 detector stages, the support marble and the CX3 beam transfer tube. It will be completed by an evolution study in the future to take account collision risks with the sample stage and XRF detector stages.

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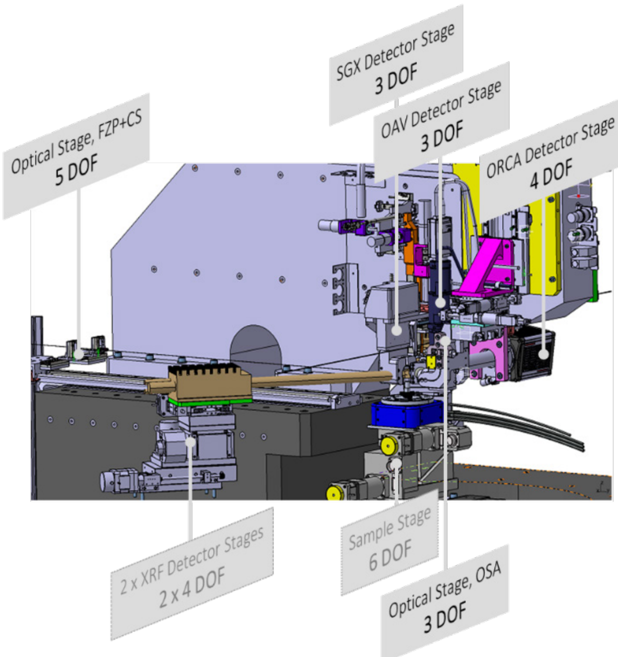

Figure 3: NANOSCOPIUM CX2 environment overview to be controlled with a CAS system, here portraying the five subsystems with a total of 18 degrees of freedom (DOF). Note that the two XRF-stations and Sample Stage are not yet included in the CAS.

NANOSCOPIUM CX2 Control & CAS Architecture

Figure 4 shows the general architecture that is currently in place: low-level control is using a high-performing SOLEIL-standardised 4–controller (Powerbrick LV [2][5] & Controller+Piezo driver) setup [2] and a PLC system. All the controllers (1 master and 3 slaves) are synchronized by a fibre-optic ring network (MACRO ring). High-level control is exerted via the TANGO framework [3].

The NANOSCOPIUM-CAS operates primarily in the PLC system and continually receives: the states of all the CAS-limit switches, each controller state (ex: running/not-running), and the general locations of the subsystems (based on encoder feedback). The PLC system also relies on user-specified (via TANGO devices) experimental configurations – where each configuration defines a set of optical stages and detectors to be used in the workspace. The PLC then authorizes/refuse stage movements depending on the combined sensor- and user-configuration- data with pre-filled reference tables.

All controllers contain specifically written microcode to transfer its running state to the PLC – only the master controller has additional CAS programs to take the appropriate action based on commands from the PLC. In addition, the master controller also holds automated scripts to safely insert/extract the subsystems into use.

Currently under investigation, the PLC-Controller-GPIO communication could be replaced by a serial communication bus (ex: EtherCAT) – which would significatively simplify the communication architecture.

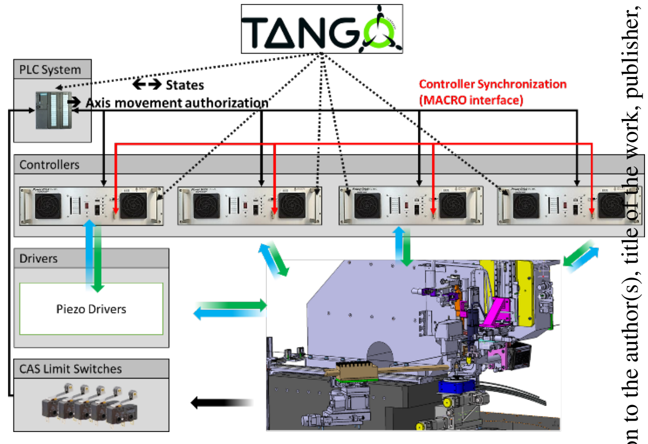

Figure 4: NANOSCOPIUM beamline CAS control architecture, the SOLEIL standard high-performance controllers (Powerbrick LV [2][5]) here complemented with a PLC-system and CAS limit switches (green arrows indicate control signals, blue arrows are encoder feedback signals, black are state/command data).

DYNAMIC-CAS AT THE MARS BEAMLINE

The MARS beamline [6] seeks to research radioactive matter in the fields of biology, chemistry, and physics. The beamline provides users amongst other things with characterizations with transmission and high-resolution X-ray powder-diffraction (XRD), Wide Angle X-ray Scattering (WAXS), and Small Angle X-ray scattering (SAXS).

The MARS Detector Support was installed in 2020 in the CX3 experimental station to actuate heavy detectors (<~ 50kg) for SAXS experiments and would be doing so using relatively large movements in the sample stage vicinity (and would therefore induce risk of system-collisions).

MARS Detector Support: Overview, Control- and CAS Architecture

Figure 5 shows the overall system overview annotated with its DOF. The system only contains 5 motorised axes, of which the three axes (*TS*, *TX*, *RX*) are the ones running the risk of system-collision with its surrounding environment. As is seen in the same figure, the control- & CAS architecture is relatively simple and direct; a single high-performing SOLEIL controller [2][5] is used which is connected to a high-powered (> 1 kW) motor amplifier for the rotational axis. The CAS algorithm here is generated from the system 3D-models and is entirely implemented in the controller which will dynamically calculate the (*TS*, *TX*, *RX*) motor *software limits* in function of their respective encoder values to prevent their entries in collision areas. This constant re-calculation of the motor software limits allows for a more complex and detailed workspace - assuring that movements on the (*TS*, *TX*, *RX*)-axes would never cause a system-collision with a perceived virtual object in its vicinity.

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These virtual objects are the core of the MARS dynamic-CAS algorithm and it is essential that they mirror the real environment.

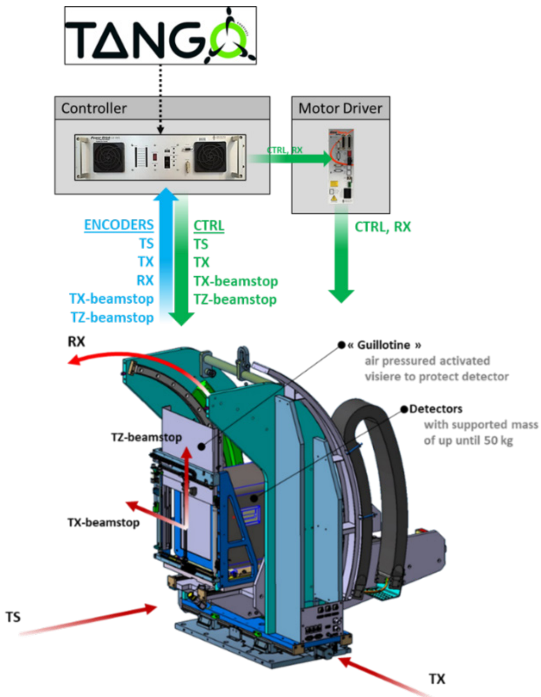

Figure 5: MARS Detector Support overview and control architecture - here using a SOLEIL standard high-performance controller (Powerbrick LV [2][5]) matched with a high-powered driver for the rotational axis.

MARS Detector Support: dynamic-CAS algorithm

Figure 6 illustrates the five-step approach in which the MARS dynamic-CAS was implemented – starting here with system 3D-models (and its environment), extracting the necessary kinematic- & spatial data, identifying collision points (using MatLab simulations), and then generating and implementing the CAS-algorithm. We will in this paper focus on the second and third point: *Simulations & Collision Detections*, and *Anticollision equation generation*.

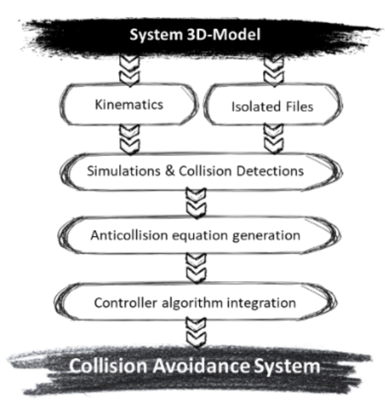

Figure 6: The five-step approach used in implementing the MARS Detector Support dynamic-CAS.

Dynamic-CAS: Finding Collision Points & Generating the Algorithm

Figure 7 shows the approach taken to generate the CAS algorithm. The 3D-models of the Detector Support system and its environment were implemented (with the system kinematics) into Matlab where a batch of simulations would move the system axes to find all collision points with its environment. These simulation-movements would virtually test all points (and map them) in the (*TS*, *TX*, *RX*)-space (with pre-defined small step increments) for collisions.

To further condense the collision point data (which is in this case 3-dimensional), and make it more suitable for controller implementations, linear collision boundaries were calculated - thus grouping together collision data-points using linear equations.

The line equations (depicting the collision boundaries) could then all be transformed into a set of geometrical closed half-space equations (see Fig. 7). This set of equations (each equation stretching over n dimensions, where n is the number of actuators used), would essentially contain as many equations as there were boundaries – making it scalable and simple enough to implement in the controller.

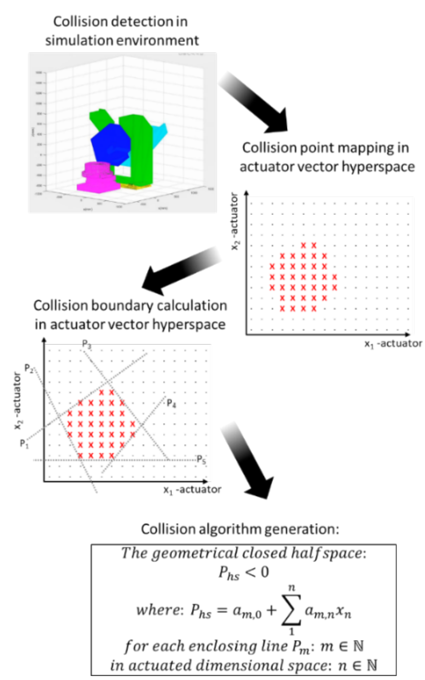

Figure 7: Finding collision point data and generating the dynamic-CAS algorithm on the MARS beamline.

DYNAMIC-CAS AT THE ANTARES BEAMLINE

The ANTARES beamline offers its users a spectroscopic non-destructive nanoprobe (k-space nanoscope) that is used to study materials using Angle Resolved PhotoEmission Spectroscopy with nanoscale lateral resolution (nanoARPES) [7].

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The ANTARES experimental station (see Fig. 8) is set in a vacuum chamber and contain several piezo-driven stages. Three of these stages: the Order-Sorting-Aperture (OSA), the Fresnel-Zone-Plate (FZP), and the Sample Stage have their workspaces overlap and run the risk of collision when in use.

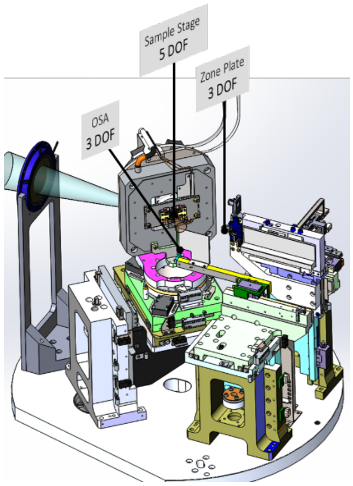

Figure 8: ANTARES Experimental Station overview, here showing the 11DOF that are used in the CAS.

ANTARES Experimental Station: Overview, Control- and CAS Architecture

The experimental station makes use of a two-controller configuration (see Fig. 9): two synchronized Delta Tau Controllers [2], both using Piezo- and stepper-drivers to interface with the motors and actuators. The control-CAS system controls 11 DOF in total.

The ANTARES beamline makes use of a dynamic-CAS – here essentially blocking\unblocking motor axes in function of the system encoders. It does this by identifying what specific region each subsection finds itself and blocks other stages from entering the same space.

CONCLUSION

The trend towards multi-techniques & multimodal beamlines makes for more densely packed experimental stations with overlapping (or more complex) workspaces – this makes Collision Avoidance Systems a more pertinent addition to control-systems. As is shown in this paper, the CAS-architecture and approach differ somewhat between applications but the common thread in CAS would indicate a closer collaboration between metrology, mechanical design, and electronics- & control- architecture.

Advanced-CAS development is a part of the roadmap for the SOLEIL electronics group to address future synchrotron beamline needs in respect to: workspace limitations, and experiment automatization (in particular integrating industrial arm robots in the mechatronic architecture).

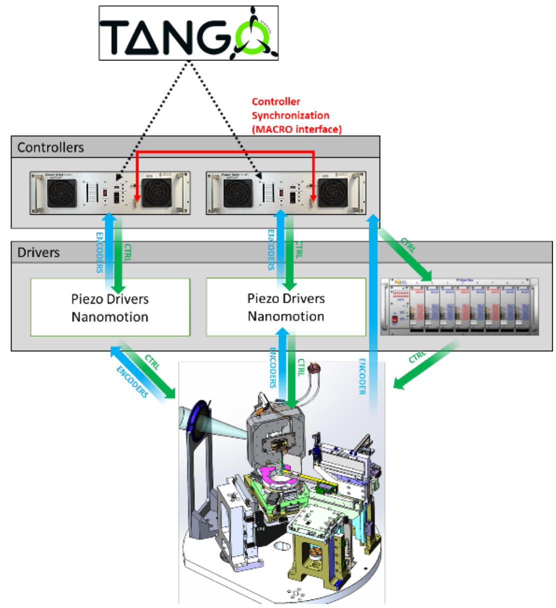

Figure 9: ANTARES Experimental Station Control- & CAS architecture, here with two synchronized SOLEIL standard high-performance controllers (Powerbrick LV [2][5]) using piezo- & stepper- drivers to control the 11 DOF. The Controllers contain the anti-collision algorithm.

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