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USING ARUCO CODES FOR BEAM SPOT ANALYSIS WITH A CAMERA AT AN UNKNOWN POSITION

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Abstract

Measuring the focus size and position of an X-ray beam at the interaction point in a synchrotron beamline is a critical parameter that is used when planning experiments and optimizing beamline performance. Commonly this is performed using a dedicated ultra-high vacuum (UHV) "focus chamber" comprising a fluorescent screen at an adjustable calibrated distance from the mounting flange and a camera on the same plane as the beam. Having to install a large piece of hardware makes regular checks prohibitively time consuming, particularly on beamlines with permanently installed endstations. A fluorescent screen can be mounted to a sample holder and moved using a manipulator in the existing end-station and a camera pointed at this to show a warped version of the beam spot at the interaction point. The warping of the image is an effect of perspective related to the relative positions of the camera and the screen, which is difficult to determine and can change and come out of camera focus as the manipulator is moved. This paper proposes a solution to this problem using a fluorescent screen printed with ArUco codes which provide a reference in the image [1]. Reference points from the ArUco codes are recovered from an image and used to remove perspective and provide a calibration in real time using an EPICS AreaDetector plugin using OpenCV [2, 3]. This analysis is presently in commissioning and aims to characterize the beam spots at the two-color beamline of the EMIL laboratory at the BESSY II light source.

THE ENDSTATION

The SISSY-1 endstation is located at one of the focus points of the two-color EMIL beamline at BESSY II [4]. X-ray light from either soft or hard X-ray beamline can be focused on the same interaction point, allowing the continuous variation of the photon energy between 80 and 10,000 eV at one spot. The endstation comprises an UHV chamber with several fluorescence detectors, an electron analyzer, and an X-ray emission spectrometer. Samples can be brought into the chamber from the UHV backbone that connects the endstation with a variation of deposition tools, other characterization setups, and an inert-gas glovebox [5] – most prominently battery, catalyst, and solar cell related layer stacks are studied (see Fig. 1). The chamber has a 5-axis manipulator and several spare view ports. One is equipped with a wide-angle lens to monitor the sample transfer, the others have zoom macro lenses which are used for looking at the sample for sample positioning/monitoring. The connection of the SISSY-1 endstation to the UHV backbone and to a beamline section leading to a second focus point via "pass through" geometry makes temporary replacement of the endstation with a focus chamber a practical impossibility.

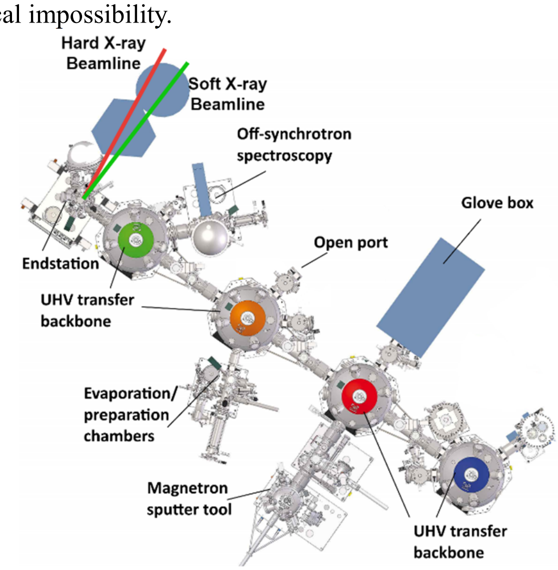

Figure 1: SISSY-1 endstation connected to UHV backbone at the focus point of the two-color EMIL beamlines.

The samples that are measured in the end station can be inhomogeneous. Sometimes they can also be located inside a cell that allows the sample to be in ambient pressure conditions while the UHV conditions in the beamline and the analysis chamber can be maintained. These cells comprise X-ray transparent windows through which the X-rays must pass to reach the sample. This means that the size and shape of the X-ray beam is an important factor in the design of these cells, alignment procedures, and planning of measurement routines. In addition, knowing the size and shape of the soft and hard X-ray beams at the interaction point is critical to the verification of the beamline setup and optimization, and a crucial prerequisite for overlapping the two beam spots. Viewing these parameters in real time while adjusting the position of beamline optical elements is essential for beamline commissioning and for researchers to

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fully exploit the capabilities of the two-color beamline for their experiments.

THE EXISTING FOCUS CHAMBER

To determine the focus position and size at the interaction point of a beamline a dedicated UHV focus chamber has been in use at the BESSY II facility for decades. It comprises a fluorescent screen at an adjustable calibrated distance from the mounting flange and a camera on the same axis as the beam (see Fig. 2). There is only one focus chamber available at BESSY II and mounting it for regular checks requires removing the end station. In the case of SISSY-1 this is prohibitively difficult once the end station has been installed.

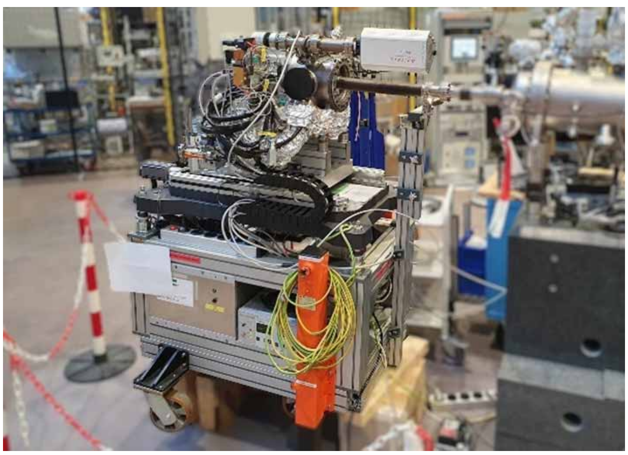

Figure 2: Existing focus chamber at the interaction point of a beamline in commissioning at BESSY II.

THE WARPED IMAGE

In an initial attempt to determine the beam focus size that is the order of 100 µm and position without the need to use the dedicated focus chamber at SISSY-1, a fluorescent screen was attached to a sample holder and brought into the end station chamber (see Fig. 3).

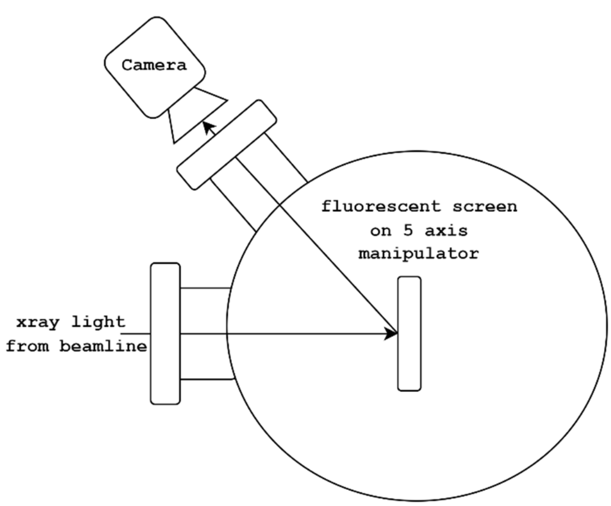

Figure 3: Configuration of the fluorescent screen in the endstation chamber.

When the X-ray beam hits the fluorescent screen, it produces a bright spot which can be recorded with one of the cameras pointing into the chamber. The screen can be positioned using the 5-axis manipulator and the focus position can be determined. However, it is not possible to determine how many µm each pixel in the image represents because there is no reference in the image. The camera cannot look directly at the screen since this is the same position that the X-ray light comes from. The perspective of the captured image results in a warped version of the beam spot. This warping also likely leads to inaccuracies in the determining of the focus position.

SYSTEM REQUIREMENTS

Measuring the size of objects on the screen requires a reference to remove distortion or warping and at the same time provide a size reference to measure features down to 1 µm resolution.

The focus position of the X-ray beam is to be determined by scanning the position of the screen along the beam direction and observing the point at which the beam profile full width half maximum (FWHM) in x and y is minimized. The screen should be scanned over +/- 5 mm along the beam axis only, due to the short focal distance of the last two soft and hard X-ray refocusing mirrors of the beamline at SISSY-1. The camera system should be able to focus on the screen over this range. In the case of SISSY-1, the center of the chamber is ≈ 350 mm from the flange where the lens can be mounted.

DESIGN OF REFERENCE SCREEN

The primary purpose of the screen is to provide a surface which will fluoresce when exposed to X-ray light. Additionally, the screen should provide reference points which can be easily determined. These reference points will later be used to calculate the transform from the acquired image to a reference image, a homography. The reference image will be of known dimensions. This homography matrix can then be used to warp the perspective of the input image so that it appears that the camera is pointing straight at the screen. Additionally, the size of every pixel in the resulting image is known. To determine the homography a minimum of four reference points in the reference image and the input image are required.

ArUco codes are patterns which are easily discernible within an image and from each other. When arranged in a checkerboard, finding one pattern allows us to determine the position of corners to sub-pixel precision. It also gives an additional set of points to use as a reference. This is called a ChArUco board [6].

At the interaction point the X-ray beam of the soft branch has a theoretical size of 44 µm horizontally by 7 µm vertically (800 l/mm, 100 µm exit slit, 80 eV). The X-ray beam of the hard branch is 93 µm horizontally and 5 µm vertically (Si (111), 2 keV). It should be possible to zoom in on this to maximize the precision with which we can measure the beam footprint. Opposing this requirement, the screen must be possible to manufacture. This limits the minimum

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feature size that can be reliably achieved. In this initial study UV lithography was used.

The screen material therefore has the following design requirements:

- The screen should fluoresce when exposed to light from the X-ray beam.
- The screen should be made of a material which is homogenous and does not add additional structure to the image of the beam when exposed to light.
- The screen should provide a light surface in visible light that provides high contrast against the titanium oxide that is left on the screen after the lithographic process.
- The screen should be no larger than 25.4 mm in diameter to fit on the standard sample holder that is used in the SISSY-1 end station.

The pattern design had the following design requirements:

- The pattern should be sufficiently small that a minimum of four reference points are visible when the lens is zoomed in around the beam.
- The pattern should be possible to manufacture in the lithography setup that is available.
- The pattern should provide enough empty space that the beam can fit inside without being masked by edges of the pattern.
- The pattern should fit on the 25.4 mm diameter screen.

Taking all these constraints and requirements into account a 200 µm thick YAG:Ce crystal was purchased from Crytur which was polished on both sides [7]. Onto this screen a ChArUco pattern was printed in titanium oxide using UV lithography. The pattern was designed using the OpenCV library with the parameters shown in Table 1. An additional border was added to help with alignment during manufacturing.

Table 1: Pattern Parameters

Attribute	Value
ArUco Dict	DICT_4X4_250
Square Size	20 px
Marker Size	14 px
ChArUco Pattern	5 x 5
Board Size	650 px (16.25 mm)
Inverted	True

REFERENCE SCREEN CONSTRUCTION

After the screen had been manufactured it was mounted on a piece of unpolished silicon to provide a matte background giving light contrast to the darker titanium oxide pattern. This was all mounted on a SISSY-1 standard sample holder using carbon tape and mounting clips.

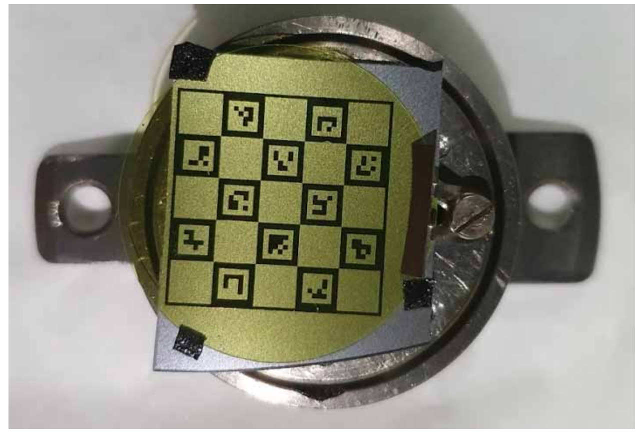

Figure 4: ChArUco reference pattern on YAG:Ce screen mounted on a SISSY-1 sample holder.

In first attempts, the screen was mounted with the pattern on the top side, but this led to shadowing effects caused by the 200 µm thick screen. Better results were obtained when screen was flipped round. Carbon tape was laid over the edge of the screen instead of between the silicon and the screen so that there was no gap between the screen and the silicon backing material, to avoid the creation of shadows (see Fig. 4 and Fig. 5).

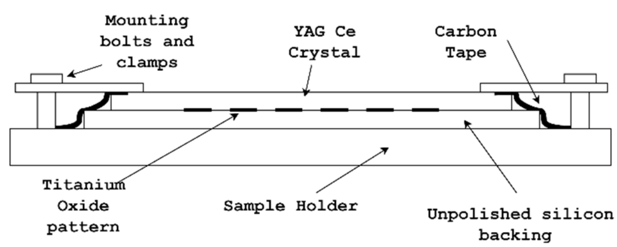

Figure 5: Mounting of screen on standard SISSY-1 sample holder.

DESIGN OF IMAGING SYSTEM

The camera was chosen to give a small pixel size, had the ability to control the gamma correction, and to be provided with a EPICS AreaDetector interface. A FLIR BFLY-PGE-13H2M-CS was chosen [8]. It is connected directly to a 1 Gb ethernet port of a host machine.

The lens was chosen to provide ×12 magnification at a focal distance of between 250 and 350 mm. It was not possible to find a motorized version of a lens which matched these requirements, so a set of stepper motors was attached which move the barrels of the lens using belts. The motors are controlled by a Phytron Motion Controller through an EPICS interface using the EPICS motorRecord [9]. Zoom and focus are both motorized. The lens and motors are held in position using a frame manufactured from 3D printed parts.

A bright light is shone through another flange window. This can be turned on and off through an EPICS interface so that the screen can be well illuminated to find reference points while also allowing for the chamber to be made dark when observing the spot from the X-ray beam. This

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increases the signal to noise ratio when measuring the X-ray beam spot. Controlling it with EPICS allows the process to be automated.

IMAGE PROCESSING

The open source OpenCV library is used to implement the following steps [3]:

1. Search for ArUco codes; then identify ChArUco corners.
2. Find the subset of points that appear in both the acquired image and the reference image.
3. Determine the homography transform between the two sets of points. (See Fig. 6)

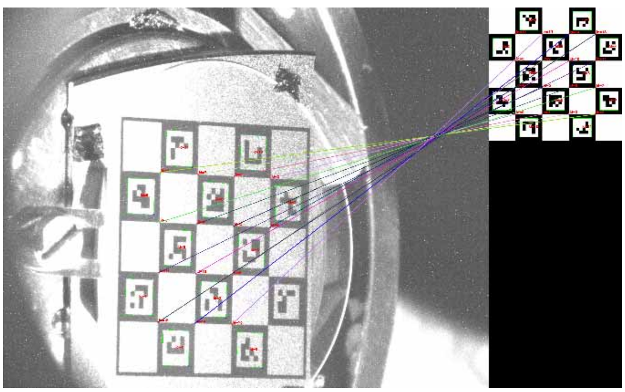

Figure 6: Mapping between the ChArUco points in the acquired and reference image.

The resulting transform can then be applied to all new images provided neither the screen nor lens is moved.

4. Use the homography transform matrix to remove perspective of input image and apply scaling.
5. Estimate of beam spot parameters.

All these steps are performed in EPICS areaDetector plugins [2,10]. This allows images to be processed and for clients to wait on that processing, guaranteeing that results are from a particular trigger. This is important for automating the process.

PROCESS TO DETERMINE BEAM FOCUS POSITION AND SIZE

Having constructed a system comprising of the remotely operated lens, chamber light, camera system, and image processing system, a measurement plan was created using the python package Bluesky [11]. The combination of the Bluesky plan and the processing in the AreaDetector plugins achieved the following:

1. Move screen to desired position.
2. Turn on chamber light to illuminate the pattern.
3. Set the camera gamma and exposure settings to maximize contrast.
4. Scan lens focus motor to maximize image sigma and bring the image into the camera focus.
5. Acquire an image and perform search for reference points. Determine homography transform.
6. Turn off chamber light to minimise background illumination
7. Configure camera to use gamma = 1 and set exposure to maximize use of dynamic range of camera.
8. Acquire images and apply previously determined homography transform to remove warping and apply scaling.
9. Find the beam spot then determine the beam spot parameters.
10. Repeat steps 1 through 9 for different positions of the screen in the chamber to determine the size of the beam at different positions and thus determine the focus point of the beam.

INITIAL RESULTS

During initial tests it was shown that the reference screen allowed for ArUco codes and ChArUco corners to be located in the acquired image and, using the described process, it was possible to remove the warping of the image and determine the true (i.e., perspective corrected) beam size in µm (See Fig. 7). Processing a1024 x 1024 pixel 8-bit image took under100 µs.

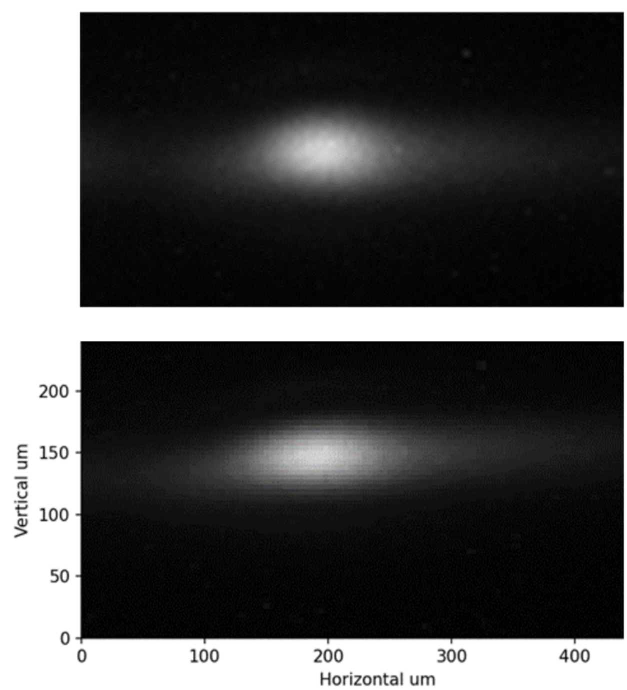

Figure 7: Warped input image (top) and perspective corrected, scaled image (bottom) of the hard X-ray beam at the SISSY-1 interaction point. Input image is 16-bit while corrected image is in 8-bit in this initial study.

It was noted that the ChArUco points provide a more accurate and stable set of reference points than the ArUco codes [6]. As such the AreaDetector plugin allows the user to optionally use only the ChArUco points in the homography.

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It was also found that the illumination of the screen during the ChArUco acquisition was critical. The brighter the chamber could be made, the smaller the aperture of the lens which allowed for a wider depth of field. Since the reference screen is at an angle to the lens, if the depth of field is too narrow then only a small portion of the screen can be in focus. This drastically limits the number of points that can be located. Additionally, a bright chamber light gives better contrast between the codes and the silicon backing material making them easier to locate.

Given the size of the beam, the ChArUco pattern could be made denser, providing more reference corners when the lens is zoomed in. It was easier than anticipated to achieve the required minimum feature size using the lithographic process available.

CONCLUSION

This study has shown that it is possible to make a fluorescent reference screen which can be used in UHV to determine the size and shape of an X-ray beam at the interaction point of a beamline. The mounting and illumination of the screen was found to be very important. The powerful open source OpenCV image processing library coupled with the EPICS AreaDetector framework allowed for this tool to be developed relatively easily.

Further work should investigate making a reference screen with more ChArUco corners with smaller more tightly spaced ArUco codes. The plugin also has several limitations in it's first iteration. Namely only working for 8-bit images and not exposing all the ArUco detection parameters as EPICS process variables.

It is hoped that this tool can continue to be developed and deployed at other beamlines allowing for the beam profile to be characterized more regularly than is possible with the dedicated focused chamber.

ACKNOWLEDGEMENTS

This work would not have been possible without the tireless work of the developers of EPICS, AreaDetector, OpenCV and Bluesky. The authors also thank the other members of the EMIL group for their support and fruitful discussions as well as practical help in the laboratory. In particular, Johannes Frisch who helped mount the screen and beamline scientist Anna Efimenko who set up the hard beam at SISSY-1 for the commissioning test.

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