MATHIS SOFTWARE FOR CONTROLLING BCAM-BASED MONITORING AND ALIGNMENT SYSTEMS

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Abstract

The MATHIS Software (Monitoring and Alignment Tracking for HIE-Isolde Software) aims at providing 3D positions of physical components of the HIE-Isolde superconducting modules, accurately and permanently measured by well-designed networks of BCAM devices (Brandeis Camera Angle Monitoring). Although it is originally intended for the HIE-Isolde project, its architecture and its use cases have been extended and optimized for more general setups. Most of the configuration data are stored either within XML-formatted files or within databases. The adaptation of MATHIS for different BCAM monitoring systems therefore does not require any further code rewriting. Moreover, the software is fully cross-platform and can either be run on the specific Linux machines driving the accelerator electronic devices, or be used on independent Windows workstations as a stand-alone software. In the first case, the software mainly relies on FESA (Front End Software Architecture) which is an object-oriented real-time framework that ensures equipment software portability across CERN accelerators. Through this standardized module, MATHIS communicates with dedicated servers networks and publishes in real-time the computed positions to any workstation, and more specifically to the concerned control room operators. This paper describes the main features and explains the modular architecture of the software.

MAIN GOAL AND REQUIREMENTS

MATHIS (Monitoring and Alignment Tracking for HIE-Isolde [1] Software) aims at providing 3D positions of physical objects accurately and permanently measured with well-designed networks of BCAM or HBCAM devices (Brandeis CCD Angle Monitor) [2]. These small-sized instruments can be described as low-cost and very efficient cameras that accurately measure angles on suitable light-sources. They are successfully implemented in several existing alignment systems seeking to monitor the geometry of larges structures. Nowadays, a lot of these optical devices have, for instance, been installed on the muon spectrometers of ALICE [3] and ATLAS [4] experiments at CERN. Cameras are delivered with an open-source software called LWDAQ (Long-Wire Data Acquisition) [2], developed by Brandeis University, and performing data acquisition, display and image analysis. Nevertheless, such software is not recommended for non-expert users who ideally need final positioning results of the monitored structures. Furthermore, complex and robust monitoring systems mostly rely on the combination of multiple devices, and the estimation of 3D positions requires statistical approaches like least square adjustments. In addition, in-situ conditions often involve some pre-processing of the optical sensors measurements. Finally, from the computing side, the acquisition and treatment software has to be optimally integrated in the existing IT-infrastructure, especially when interactions are needed with control-room operators or other experts. In the framework of the HIE-Isolde (High Intensity Energy-ISOLDE) new alignment and monitoring project MATHILDE [5] (Monitoring and Alignment Tracking for Hie IsoLDE), special attention is paid to this last concern. One of the main initial requirements was to allow the control software to remotely drive the monitoring system both from any PC-workstation for expert users ("Stand-Alone Mode") and from the control room usual computing interface ("Control-Room Mode"). In the first case, the software runs on any Windows, Mac or Linux workstation, presents its own graphical interface and saves acquired data locally on the machine. In the second working mode of the software, no interface is provided but operators have an access to the monitored positions, as soon as they are delivered by the system, and are able to create their own display in the control room. Persistent data storage is ensured by appropriate links with various CERN databases. Besides these technical specifications, an important concern was also to make MATHIS software as generic as possible in order to make it re-usable for other BCAM-based monitoring systems without additional code development.

MEASUREMENT AND CALCULATION PRINCIPLES

Thanks to integrated laser light-sources, the BCAM devices are able to see each other: the corresponding spots observed on their CCD sensors partially determine their relative positions. The emitted light can also be reflected back by retro-reflective targets (corner cube prisms for example) placed on measured objects: similar spots are hence produced on the sensor and later analysed by the acquisition software. In other words, by placing the devices in adequate geometrical locations around the measured objects and geodetic references, the alignment system should be able to provide, not only relative displacements of the monitored elements, but also their absolute positions with respect to a global reference coordinate-system. In the case of the HIE-Isolde system [5], the external geodetic references are pillars supporting BCAM-type devices, and their positions are well known with respect to the nominal beam line. In this project, monitored elements are successive superconducting accelerating cavities and solenoids. They are all equipped with specific high-index glass ball retro-reflector targets as described in [6].

Each observed spot, measured by two image coordinates on the sensor, defines a spatial line that can be mathematically represented by a unit vector and an origin point, for instance the centre of the corresponding BCAM thin optical lens (also called pivot point of the camera in the Brandeis literature). Geometrically, we assume that the measured point lies somewhere along that observation line. The analytic calculations take into account internal calibration parameters of the device, provided by the manufacturer. They also deal with possible optical deviations due to transparent windows (i.e. *viewports*) crossing. The observation line is thus primarily located with respect to a local coordinate-system conventionally attached to the kinematic BCAM mount, based on cone, slot and flat depressions that allow the mount to precisely sit on three hard ceramic balls.

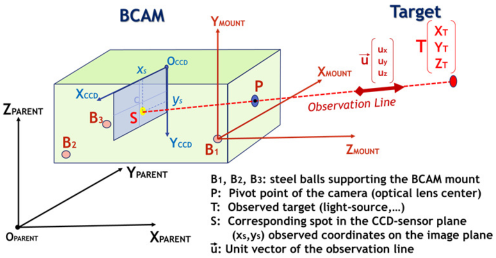


Figure 1: Converting observed spot image coordinates into spatial line parameters.

The positions of the supporting ceramic balls themselves are generally defined in another coordinate-system (i.e. *frame*) that can directly be the global one of the geodetic area, or some intermediate local frame, for example, attached to a mechanical support. In this last case, which corresponds to the most common situation, the BCAM observation line has to be recalculated with respect to the parent-frame by a six-parameter based Helmert transformation (three rotations and three translations). These parameters can be known a priori, or partially unknown and thus part of the global adjustment estimation. Transformations are repeated from one frame to the other, following the ascending hierarchy of the parent frames, up to the global top-level frame.

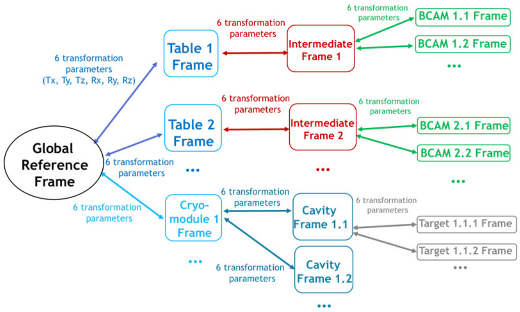


Figure 2: Example of frames hierarchy with their successive transformation parameters.

Unknown transformation parameters are estimated within a global calculation based on least square adjustment method. For that statistical process, MATHIS relies on an external software called LGC (Logiciel General de Compensation) that is the main adjustment module used for geodetic purposes at CERN [7]. The new version (LGC2) available since end of 2015 includes definition of multiple frames, not necessary linked to the gravity. It also handles new types of measurements like unit vector components defining BCAM observation lines.

Indeed, the error minimizing process converges towards a unique solution only if there are enough geometrical constraints between frames, and enough consistent observations determining unknown parameters.

MODULAR ARCHITECTURE

The MATHIS software has been built around four main computing modules achieving different tasks:

- *MathisLIB*: Main data acquisition and pre-processing library.
- *MathisGUI*: Graphical User Interface of the software "stand-alone" version.
- *MathisRT*: Real-time data publication component.
- *MathisCOM*: Communication module with databases for long-term data storage.

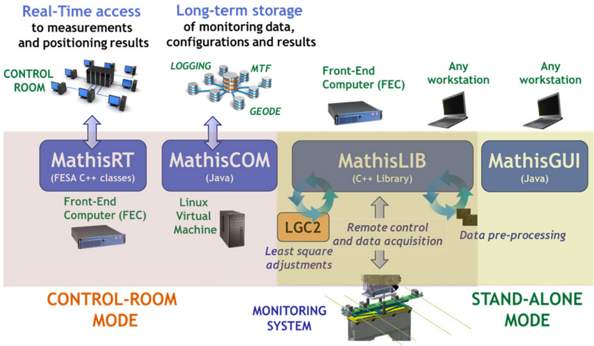


Figure 3: Main modules of the MATHIS software.

MATHIS code has been entirely written in standard C++ (ISO C++98) and Java (Java 8) languages using the open-source Integrated Development Environment (IDE) Eclipse commonly used at CERN, especially by the Control Software developers. This environment highly helped to compile, test and deploy the solution on all available platforms (Windows/Mac/Linux). It also offers specific plugins or frameworks developed at CERN to ease real-time data publication over the network and IT-infrastructure.

MATHIS CORE LIBRARY

The C++ MathisLIB library represents the main core of the application. It drives the low-level equipment (BCAM sensors), pre-processes the acquired data and calculates the monitored positions via the LGC2 software. All other MATHIS modules communicate with it.

Reading XML-formatted configuration files

The widely-used XML standard [8] plays a key role in making MATHIS straightforward and re-usable for other monitoring systems or other conditions. The library parses several XML-formatted configuration files describing different aspects of the connected monitoring system. The geometry of the system is fully described by structured textual data representing the object positions with respect to a parent-frame. Objects can be BCAM mounts, different types of punctual light-sources or fictive points (fiducial marks on monitored elements for instance), viewports (glass windows with specified thickness and optical index) or any other physical support. Frames themselves are defined with respect to a parent one, and transformation parameters can be declared as fixed or unknown in the global calculation. Note that the XML nodes structure does not limit the number of embedded levels of objects and frames: very complex monitoring systems can thus easily be described by the geometrical configuration file. In the case of the MATHILDE system, 237 frames are described into 5 embedded layer levels.

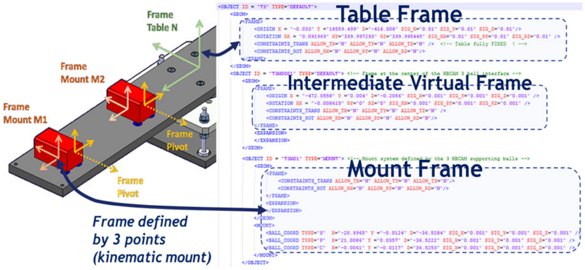


Figure 4: Example of XML data describing a BCAM supporting table of the HIE-Isolde monitoring system.

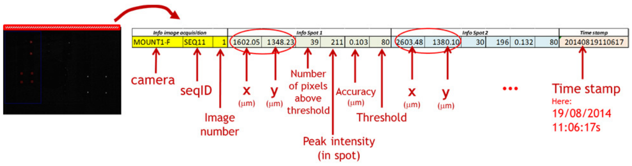
The dynamic behaviour of the monitoring system is also defined in another configuration file. The lowest level of the XML description corresponds to a BCAM sequence of observations, i.e. a set of images iteratively acquired with a same sensor and with identical acquisition and analysis parameters. Each sequence description contains the parameters needed by the underlying LWDAQ server to control the hardware and detect spots in the images. The number of sequences per device is not limited. This is very useful in situations where distinctions have to be done between targets observed in the same camera field of view. When active light-sources or passive reflecting targets are placed at different distances from the camera, it becomes straightforward to measure separately targets –or groups of targets- with appropriate acquisition parameters and focus the spot detection on specified image areas.

In practice, the MATHIS software automatically translates the XML configuration file describing the successive observation sequences into one or several TCL script files [9] that will be interpreted by the LWDAQ server. In other words, neither specific knowledge of this computing language nor any comprehension of the underlying LWDAQ structures and commands is finally needed when starting a new monitoring project and forming the XML files.

Acquiring data via TCP-IP based communication layers

The data acquisition essentially relies on the LWDAQ server running on either the same or a remote machine. This server usually reads TCL scripted files containing the sequences of measurements and LWDAQ commands to be executed. It then communicates via the basic TCP-IP protocol with the hardware driver that in turn controls the connected low-level equipment. Raw images acquired by the camera are sent back to the driver EEPROM (Electrically-Erasable Programmable Read-Only Memory) and to the LWDAQ server software which provides Pascal-encoded analysis routines that automatically detect the positions of the observed spots.

As previously explained, the MathisLIB library automatically generates the script files required by the LWDAQ server. These files contain successive commands and parameter settings for the acquisition. They jointly ask the LWDAQ server to do MATHIS specific low-level tasks at the end of the acquisitions. The server inserts thus textual information in each image content by substituting first pixels data. Note that the replaced rows at the very top of the image should never affect the observed spots or their neighbourhood. The inserted header contains information about the device source (BCAM name), the observation sequence (MATHIS identifier), the image index, the acquisition timestamp and the main results of the LWDAQ analysis routines (image-coordinates of the various detected spots).



Info image acquisition			Info Spot 1						Info Spot 2						Time stamp
MOUNT1-F	SEQ11	1	1602.05	1348.23	39	211	0.103	80	2603.48	1380.10	30	196	0.132	80	20140819110617

Figure 5: Information data header inserted in each BCAM acquired image.

Note that the image information header only contains image coordinates of the detected spots, not any target name or identifier. Relationship between spots and real targets of the monitoring system is done by comparing the received image coordinates with the theoretical expected values declared in the XML configuration file. The LWDAQ server is also asked to initiate a TCP-IP communication process with the MathisLIB library and to send modified images. The library receives incoming Ethernet data packets (limited by the protocol to a maximum of 1’500 bytes) and decodes the information headers of the successive arriving images.

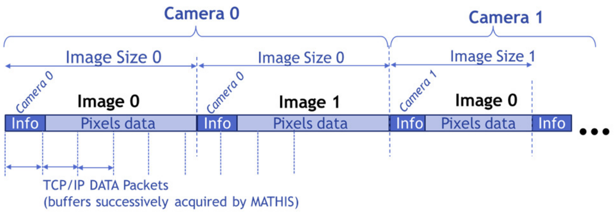


Figure 6: MathisLIB decodes streaming data packets sent by the LWDAQ server with specific scripts.

Hence, the order of the incoming images has no importance in this on-line process. The library is also able to handle the dataflow produced by different BCAM types with mixed image sizes. Another major benefit of this solution is that images stored by the library can always be linked to their original device and sequence, even if files have been misplaced by mistake.

Saving acquired data

In the stand-alone mode of the software, acquired data are locally saved on the machine hard drive. One directory is created per new acquisition session. It contains a raw data file storing all measurements of that run, without any pre-processing, and duplicated XML configuration files describing the monitoring system. This storage allows to re-load acquisition sequences of a former run, and re-do calculations. The raw data file itself keeps either the complete image contents or the information headers only. In the second case, the total storage size needed per run can be drastically reduced (about 600 Kbytes for the HIE-Isolde system based on two cryomodules, against approximately 128 Mbytes when storing also image contents). The main drawback is the impossibility for the user to visualize past acquired images: only resulting spot image coordinates remain accessible.

In the control-room mode of MATHIS, data are published on various CERN databases depending on their type.

Pre-processing data

The software includes several data pre-processing steps described in [5]: averaging measured spot coordinates for each sequence, correcting observation lines crossing optical *viewports* (i.e. thick transparent windows) and retrieving theoretical centres corresponding to observations on high-index (~2) glass ball targets. Indeed, this last kind of retro-reflective target is systematically flashed twice, i.e. once per device laser source, and gives rise to two distinct spots on the sensor. According to the BCAM symmetrical geometry and the small diameter of the ball, it has been demonstrated that a fictive punctual light source at the exact centre of the ball would produce a spot that is nearly at mid-distance from both observed laser diode spots [5]. A simple average of pairs of observed spot positions is therefore done and is considered precise enough at this level of the data pre-processing.

Applying thermal corrections on frame positions

MathisLIB also takes into account thermal expansions of the equipment in the final calculation. Indeed, temperature conditions can significantly change and affect the dimensions of the objects during the measurements, especially when monitored elements, like HIE-Isolde cavities, are cooled down to cryogenic conditions. Corresponding frame positions are constantly corrected with respect to locally measured temperatures. The XML configuration file describing the system geometry allows to associate thermal expansion coefficients to each defined frame: they characterize via a simple mathematical model (cubic function) the variations of the object's dimensions along the three spatial directions with respect to the currently measured temperatures.

MATHIS USER INTERFACE

The graphical user interface is intended for experts and has been exclusively developed for the stand-alone mode of the MATHIS software. This Java-coded module, called MathisGUI, directly interacts with the C++ MathisLIB core library through the JNA (Java Native Access) standardized interface [10].

MathisGUI includes several simple features as starting remotely new monitoring sessions and saving data locally on the machine, or re-loading and re-processing previously acquired data. It also offers a graphical editor simplifying the preparation of the various XML configuration files describing the monitoring system (geometry and observation sequences).

The interface also comprises an interactive 3D-viewer representing devices, targets, physical supports and observation lines in space with typical zooming and rotating graphical features. By clicking on the chosen device, a separate window displays the acquired sequences and the user can easily navigate through image series and read the detected spot positions.

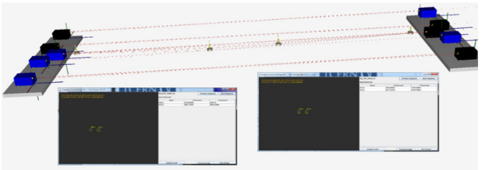


Figure 7: MathisGUI 3D Viewer.

Finally, MathisGUI offers advanced possibilities to implement, in Java code, more specific image treatment algorithms on the BCAM acquired images.

MATHIS PUBLICATION MODULE

The CERN Controls Middleware

For the HIE-Isolde alignment system, a complete set of measurements is acquired every 15 to 30 minutes, depending on the monitoring periods: more frequent acquisitions are required during cool-down or warm-up phases of the cryomodules. Whatever the chosen frequency is, estimated positions of the physics components, i.e. vertical and radial offsets of the cavities with respect to the nominal beam line, have to be presented to control-room operators as soon as available. Therefore, MATHIS uses the real-time communication layers of the CERN IT-Infrastructure. The CMW (Controls Middleware) framework provides communication infrastructure for all CERN accelerators, enabling client applications to connect, control and acquire data from all kind of equipment.

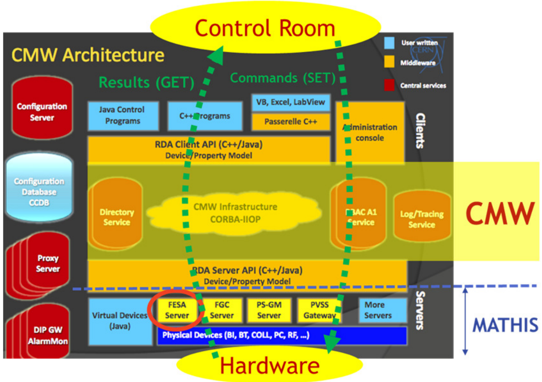


Figure 8: Common software communication infrastructure for the CERN accelerator controls.

Device-property model

The control system globally relies on a device-property model consisting of named devices that have one or more properties. These properties can be private or publicly shared: in this last configuration, their content (internal set of valued items) can be accessed from any CERN workstation by invoking setting and getting methods through high-level applications or dedicated API (Application Programming Interface). The various CMW clients and servers ensure safe and real-time data transmissions from the equipment lowest level to the control room top-level.

By using these communication layers, the positions estimated by the MATHIS software are finally published through adequate properties and existing setting/getting mechanisms. In other words, the control room operators can follow the displacements of the monitored elements, as soon as they are available, through their usual computing interface. The way the final results are graphically displayed in their interface (numerical tables, plots, etc.) is independent of MATHIS and can be freely designed by controls developers.

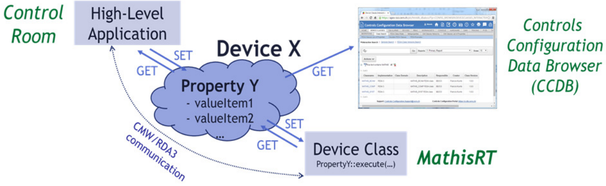


Figure 9: Device-Property model of the CERN control-system

The control room operators can transmit data, such as configuration parameters or commands, to the instrumentation level. Typically, they can choose the frequency of the measurement cycles, or simply start/stop the monitoring system at any time. The access rights have to be discussed.

FESA framework and Front-End Computers

The MATHIS software is permanently able to bi-directionally interact with remote users in the control room. From a technical point of view, it relies on the Front-End Software Architecture (FESA), which is a complete environment developed at CERN for the equipment experts in order to facilitate design, development, testing and deployment of real-time control software for front-end computers (FEC). These specific computers directly control the equipment at the accelerator level: they are, in practice, CERN fully standardized Linux machines, connected to a restricted-access IT-network, and having no graphical terminal and no hard drive. They communicate with devices via appropriate software, libraries and drivers (MathisLIB and LWDAQ server running on the FEC machine in our case).

MATHIS COMMUNICATION MODULE WITH DATABASES

The lifetime of the published data accessible from the control room is limited to a few measurements cycles only. Consequently, the long-term storage has to be done through CERN databases, and the MATHIS software has to communicate with them via existing computing mechanisms. Java Database Connectivity (JDBC) is one of those technologies [11]. It is an API for the computing language Java, which defines how a client may access a database. It is part of the Java Standard Edition platform, from Oracle Corporation. It provides methods to query and update data in a database, and is oriented towards relational databases. The MathisCOM communication module relies on JDBC for accessing the SURVEY Database at CERN. This database is the source for the theoretical positions of the accelerator beamlines at CERN, and all the measurements and calculation results related to them. MathisCOM logically uses it to store the calculated accelerator element positions and retrieve all configuration parameters of the monitoring system (various XML structured data described before).

Note that links can be established between the SURVEY database and any other CERN Oracle database, to centralize MathisCOM queries on a single database. The Oracle materialized view concept is used to replicate subsets of data from the Manufacturing and Test Folder (MTF) database that provides traceability of large quantities of manufactured equipment in the CERN geographically distributed environment. This materialized view mechanism also guarantees that equipment data needed for MATHIS software are always available on-line, since MTF database is not meant to assure such permanent services.

Finally, the central database at CERN called LOGGING plays a key role for the long-term data storage of the monitoring measurements. The LOGGING service persists data of close to 1 million pre-defined signals coming from heterogeneous sources (electricity, industrial data such as cryogenics and vacuum, beam positions, etc.). The crucial point is that the LOGGING service is also able to connect to the CERN Controls Middleware devices and properties described above: subscriptions mechanisms have been developed at CERN to automatically update database variables with respect to properties changes. The complete raw measurements of the monitoring sessions (image information headers previously described) are continuously stored in the LOGGING database through this automated mechanism.

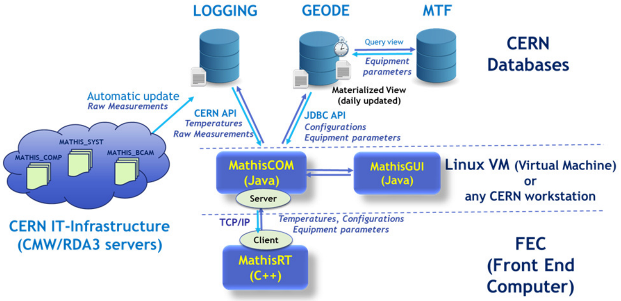


Figure 10: MathisCOM links with the CERN databases and the Controls Middleware infrastructure.

The LOGGING database data extraction is performed using a Java API, and optionally a generic Graphical User Interface (called TIMBER) to visualize the data. The entire Java infrastructure is based on the Spring framework, and pure JDBC for database interactions. MathisCOM directly uses this Java API in order to re-load past monitoring measurements, or extract data measured by other accelerator devices. More specifically, this MATHIS communication module periodically checks temperatures measured by multiple sensors installed inside the HIE-Isolde cryomodules, in order to apply the thermal corrections on frames parameters in the final adjustment calculations.

The link with the lower level acquisition and calculation modules is done via an integrated TCP-IP based client-server communication.

CONCLUSION

The stand-alone version of the MATHIS software runs since June 2015 and has been more intensively used during installation phases of the two first HIE-Isolde cryomodules. Over 6’000 acquisition and calculation cycles have been more specifically operated during the cool-down and the warm-up periods of both cryomodules. About 800 measurement cycles have been jointly done with the control-room version of MATHIS software that is still under evaluation, and that will be fully accessible for the operators during autumn 2016. Only few non-converging adjustment calculations have been noticed during those periods, mainly due to some non-detected targets on the imaging sensors and missing redundant observations. Although they are rare in practice, these situations will be more efficiently handled by the general LGC2 software after better understanding the instabilities and limit-cases due to numerical algorithms and computations.

Above all, thanks to its modular architecture and its cross-platform implementation, MATHIS has proven to be very flexible and easy to integrate in various environments. It operates not only on the restricted Linux environment of the CERN Front-End Computers, but runs also in a stand-alone mode on Windows or MacOS workstations with a straightforward 2D/3D graphical interface. Furthermore, no additional code has finally been written when passing from one practical monitoring configuration to another (different test mock-ups, HIE-Isolde monitoring system for one and then two cryomodules). The XML-based architecture has proven to be flexible enough to externally describe all of these situation changes. The MATHIS software is thus a promising solution for future monitoring systems based on BCAM devices, especially when integration is needed in constraining IT-infrastructures.

REFERENCES

[1] M. Lindroos, P. A. Butler, M. Huyse and K. Riisager, “HIE-ISOLDE,” *Nuclear Instruments and Methods in Physics Research B 266,* pp. 4687-4691, 2008.

[2] K. Hashemi, “BCAM/LWDAQ User Manual,” 2004-2016. [Online]. Available: http://alignment.hep.brandeis.edu.

[3] F. Lackner, P. Osanna, W. Riegler and H. Kopetz, “A novel solution for various monitoring applications at CERN,” ALICE Collaboration, 2004.

[4] C. Amelung, “The Optical Alignment System of the ATLAS Muon Spectrometer Endcaps,” ATLAS, 2008.

[5] G. Kautzmann, J.-C. Gayde, F. Klumb and Y. Kadi, “HIE-ISOLDE - General presentation of Mathilde,” in *IWAA2014*, Beijing, 2014.

[6] G. Kautzmann and J.-C. Gayde, “The HIE-ISOLDE Alignment and Monitoring System Software and Test Mock-up,” in *IWAA2012*, Chicago, 2012.

[7] M. Barbier, Q. Dorleat and M. Jones, “LGC: A new revised version,” in *IWAA*, Grenoble, 2016.

[8] T. Bray, “Extensible Markup Language (XML) 1.0 (Fifth Edition),” W3C Working Group, 2008.

[9] J. K. Ousterhout, Tcl-Tk Toolkit, Addison-Wesley, 1994.

[10] J. Friesen, “Java Native Access:An easier way to access native code,” 02 05 2008. [Online]. Available: http://www.javaworld.com/article/2077828.

[11] L. Andersen, “JDBC™ 4.1 Specification,” Oracle, 07 2011. [Online].