The Application of Coordination to Magnetic Measurement Automation: An SSW System Example

J.M. Nogiec, P. Akella, J. DiMarco, K. Trombly-Freytag, G. Velev, D. Walbridge

***Abstract*— Magnetic measurements are an integral part of the development cycle of accelerator magnets, a part which provides necessary feedback to drive design and manufacturing improvements and corrections. Automation of these measurements allows for reduction of human errors and reproducibility of measurements. Realization of automation via coordination that is separated at the architectural level from the functional code provides flexibility in defining measurement procedures and substantial extensibility. The described Single Stretched Wire (SSW) system is an implementation of such a solution with the use of a component-based framework designed to build a family of measurement systems.**

***Index Terms*— Magnetic field measurement, Measurement techniques, Automatic testing, Software architecture**

I. Introduction

PARALLEL to the advances in magnet design and technology, new magnet test tools, methods and techniques emerge. Some of them are the result of work on flexible magnetic measurement systems, systems capable of performing multiple types of measurements and easily tailorable to special needs of a particular test.

One such tool is EMMA [4], a framework designed at Fermilab for building magnetic measurement systems using components. Each component provides a specific functionality, such as instrument control, data acquisition, analysis or visualization.

Magnetic measurements are vital and integral part of the accelerator magnet research and development lifecycle; they provide validation of designs and production and uncover areas for improvement or correction. The quality of measurements can be improved by automating the process of measurement, which will reduce human error and guarantee reproducibility.

Measurement systems need to be flexible enough to support several types of measurements as well as different measurement techniques. At the same time, developers face the challenge of producing dependable measurement applications in a short time [1]. In addition, the software for measurement applications should satisfy not only the core functional requirements, but also such non-functional requirements as flexibility, reusability, and maintainability [2].

One way to accomplish these goals is to assemble systems from reusable components and also provide a mechanism for coordinating the work of these components in order to execute measurement procedures. This article describes an example of such a solution: a Single Stretched Wire (SSW) measurement system developed with this technology and capable of executing multiple related measurements.

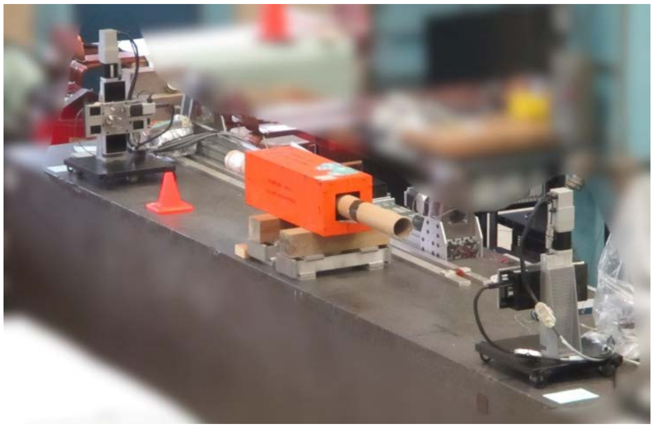

Fig.1. SSW system measuring a quadrupole magnet.

II. SSW System

SSW systems are used in the accelerator domain for alignment of magnets and as a method of determining integrated strengths. The same principle and equipment can be used to perform several different types of measurements.

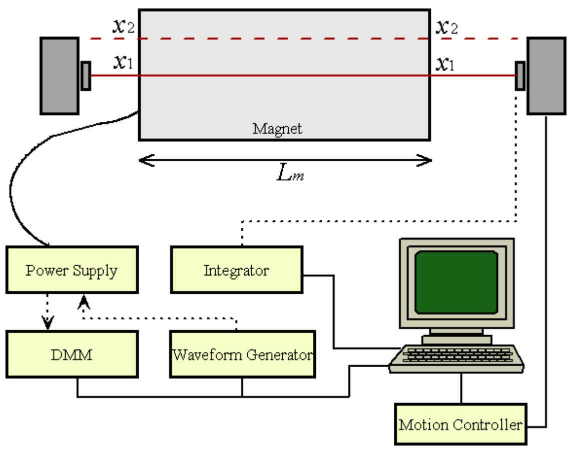

Fig. 2. SSW measurement principle.

This work was supported in part by the Fermi Research Alliance under DOE Contract DE-AC02-07CH11359.

J.M. Nogiec (e-mail: nogiec@fnal.gov), P. Akella, J. DiMarco, K. Trombly-Freytag, G. Velev, D. Walbridge, are with Fermi National, Accelerator Laboratory, Batavia, IL 605010 USA.

A. Principle of Measurement

The SSW system (Fig. 2) uses a long wire with high strength-to-weight ratio (CuBe, $TiAl_6V_4$, etc.) stretched through a magnet bore between two precision X-Y stages offering 1µm accuracy. The wire forms a loop with the return wire typically fixed at the bottom of the beam pipe. The wire ends are connected to an integrator which measures the magnetic flux change caused by the wire position change. The change in flux depends only on the start and end positions of the wire. The wire tension and magnet current are also measured.

B. DC Measurements

For magnets with large field, measurements are made at a fixed (DC) magnet current. Let us adopt a notation for the flux, Φ, where + and – denote respectively a move in the positive and negative direction, and V and H vertical and horizontal moves. A sequence of motion steps performed from the center of the wire frame will find the offsets to the average quadrupole center, x_0, y_0 to be:

$$x_0 = -\left(\frac{D}{2}\right)\left(\frac{\Phi_H^+ - \Phi_H^-}{\Phi_H^+ + \Phi_H^-}\right), \qquad (2)$$

$$y_0 = -\left(\frac{D}{2}\right)\left(\frac{\Phi_V^+ - \Phi_V^-}{\Phi_V^+ + \Phi_V^-}\right). \qquad (3)$$

When the wire is placed in the average magnet center, the following is true:

$$\Phi_H^+ = \Phi_H^- \text{ and } \Phi_V^+ = \Phi_V^- . \qquad (4)$$

The average magnet center is parallel to the wire axis. Using counter-directional movements, where one stage is moving +D and the other -D, one can measure yaw and pitch, and thus obtain a "true" magnet axis [6]. Counter-directional movements can also be used to locate the axial center of the magnet [7].

The integral gradient, ∫ Gdl, can be obtained from:

$$\int_0^{L_m} Gdl = \frac{\Phi_H^+ + \Phi_H^-}{\cos(2\alpha)\, D^2} = \frac{\Phi_V^+ + \Phi_V^-}{\cos(2\alpha)\, D^2} \qquad (5)$$

where L_m is a magnet magnetic length, G is a field gradient, and α is a roll angle.

The roll angle, α, can be obtained by measuring x_0 as described by (2) for varying vertical positions and then fitting a line to the data. The slope of this line yields -2α.

C. AC Measurements

For magnets with low field strength (e.g. superconducting magnets at room temperature) the magnet can be powered with AC current to improve sensitivity. AC powering typically chooses a frequency which provides an integer number of cycles every 128ms, which addresses the problem of the current being asynchronous to the data acquisition and allows use of a FFT. The Fourier component of the flux corresponding to the AC magnet frequency gives the AC flux, serving as a 'lock-in' technique. The difference between the flux amplitude measured at positions separated by a distance D determines the change in flux, and these results are combined for positive (+D) and negative (-D) moves in the same way as for DC alignment and strength calculations. Counter-directional and roll angle measurements can also be made in this mode as for the DC case.

D. Wire Sagitta

SSW measurements require corrections for wire sagitta and susceptibility. These effects can be compensated by repeating measurements at several tensions (or equivalently several wire resonant frequencies) and extrapolating the results to infinite tension [6][7].

III. Measurement Framework

The cost and time to market for building a new measurement system or a new version of an existing system depend on the flexibility and reusability of the software. One approach characterized by high flexibility and reusability is to build a family of measurement systems reusing components and the mechanism for their collaboration [9].

EMMA, a software framework, has been developed at Fermilab based on these premises [4]. It offers component-based development of measurement systems by assembling new applications from reusable components according to a given configuration. EMMA components execute concurrently and communicate via a publish-subscribe software bus that offers homogenous support for exchanging messages between local and remote components (Fig. 3).

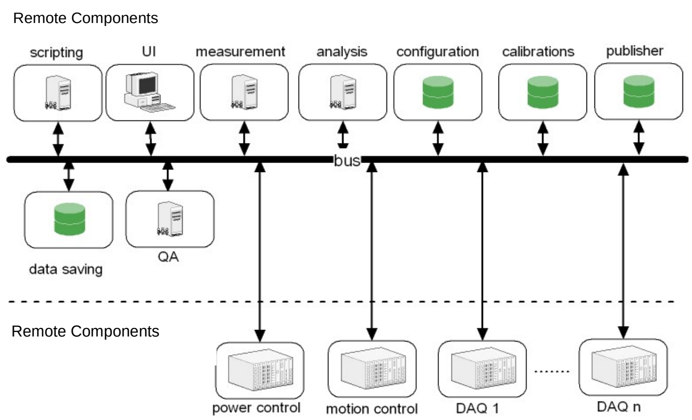

Fig. 3. EMMA architecture with a software bus and components.

The software bus offers broadcasting, multicasting and unicasting communication patterns and two-level addressing of the form *topic.event*, where a topic is *control*, *property* or *data* and an *event* is a unique identifier of information carried in the message.

The framework provides support for assembling applications from components and coordinating their execution.

IV. Automation and Coordination

When discussing measurement systems, "automation" means completing a measurement task without human intervention. Automation makes measurement processes more efficient, reproducible and dependable.

The implementation of measurement system automation requires executing a sequence of steps comprising the intended measurement. These steps include functionality to control the conditions of the test and acquire data from various transducers and instruments. Then the acquired data can be processed (analyzed) and visualized on-line, off-line or both.

A crucial element of any automated system is the software. Current industry trends favor software architectures based on concurrent, loosely coupled components with flexible communication middleware. These systems require coordinating the actions of several components to provide harmonious parallel execution of components according to the measurement protocol/procedures.

One of the fundamental principles in software engineering is the Separation of Concerns principle coined by Dijkstra. This states that separate abstractions should be handled in separate entities, and it can be successfully applied at the architectural level to the concept of coordination thru the use of orchestration.

Orchestration is a centralized solution, where the coordination of components is separated from other concerns [11]. The central coordinating element performs a similar role to the conductor of an orchestra. A "conductor" module directs other separate elements (musicians) to execute (play) their parts following a desired workflow, without participating in actual execution (producing sounds).

Implementing coordination via orchestration allows for the inclusion of error-handling and transaction-type behavior as well as allowing for easily changing the measurement processes and component composition.

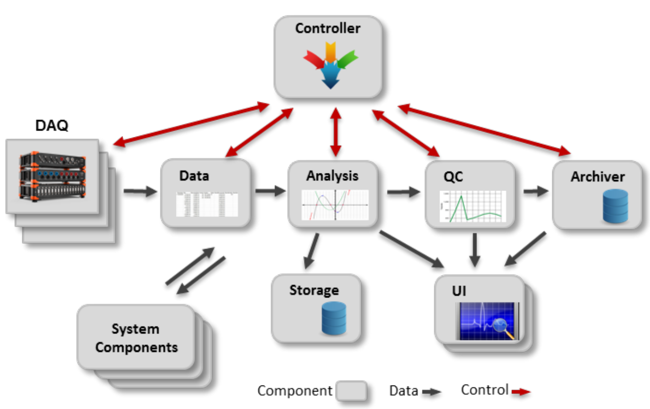

Fig. 4. Separation of data and control flow in the SSW system.

V. Coordination in SSW

Following separation of concerns at the architectural level suggested in [10], the SSW system can be viewed as a layered system with the coordinator component as part of the supervisory level, and the system components supplied with the framework as the system layer, with the rest of components forming the functional layer.

A. *Data and Control Flows*

The functional layer of the SSW system is configured from components that are set up to produce the desired dataflow in the system (Fig. 4).

Data is generated by a set of DAQ components, which acquire signals and read instruments. The data created at the data acquisition stage is assembled together and sent to be analyzed. Both the raw data and the analysis results are visualized in the user interface windows. They are also examined, by applying several on-line quality control checks, to validate the measurement or its part. The quality control process can produce warning or error events. Error events necessitate repetition of the measurement and inspection of the problem, whereas a warning may focus the operator or analyst's attention to lower than typical quality of the data. Finally, the raw and processed data are archived separately. Selected crucial results and values are stored in a persistent storage to facilitate sharing of data between different measurements.

Communication between components necessary to control the measurement procedure is separate from the data flow. The coordinator component communicates directly with the other components and orchestrates the measurement by requesting a component to perform particular actions and by the setting of their control parameters. The coordination flow and data flows, although using the same message-oriented communication bus, are separated by using different topics: "data" for value flow and "control" for all communication. Some control messages, such as "initialize", "begin- and "end of a measurement step" and "terminate", are broadcast to all components.

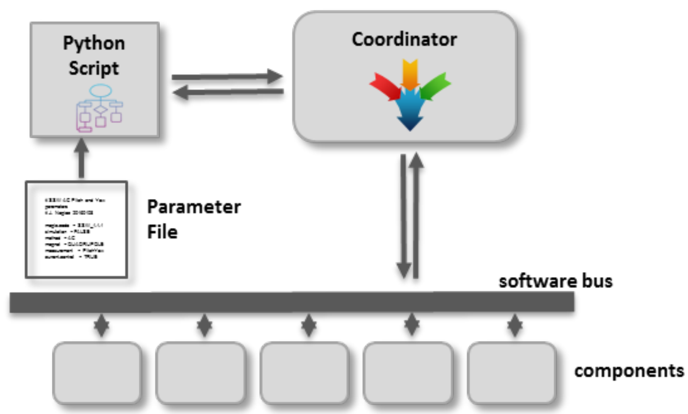

Fig. 5. Python script-driven coordination.

B. *Implementation of Coordination*

The central role in orchestrating the measurement is played by the coordinator component. This component is a *de facto* proxy component that translates TCP/IP messages exchanged with the program executing the coordination script, to EMMA events suitable for sending on the software bus (Fig. 5).

Python, a popular programming language, has been chosen for writing coordination scripts because of its high-level language constructs, high expressiveness and the availability of exception handling.

The coordinator component starts the execution of the selected Python script, which then runs asynchronously to the coordinator. The coordination Python script and its proxy component send and receive only events in the control topic and do not participate in data flow in the system.

C. *Coordination Primitives and Protocol*

Measurement coordination scripts are written with the use of the EMMA API, which provides message-oriented communication primitives (Table I).

TABLE I
COMMUNICATION PRIMITIVES

sendCmd (topic, event, par1, par2, ...)	Send command with parameters.
awaitEvent (topic, event, sender, timeout)	Await an event from a specific component.
rpc (topic, event, replyTopic, replyEvent, replySender, timeout)	Send an event and await a reply event.
setProperty (topic, event, propertyName, propertyValue)	Set property on the component using its property topic.

The EMMA API has a layered design and also provides lower level communication primitives to allow for building communication primitives with different semantics [4].

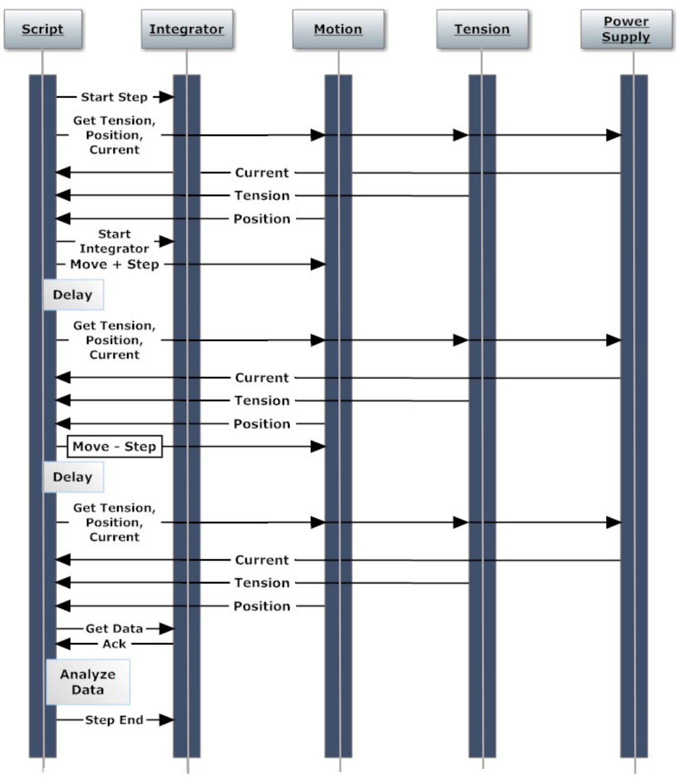

Fig. 6. Measurement step coordination.

All SSW measurements share the same coordination script, which describes the overall measurement process. It implements a measurement model, where a measurement consists of repetitions of sequences of steps. Each step is an acquisition of the flux change and includes a series of interactions between the coordinator component and other components participating in the execution of the step (Fig. 6).

Each measurement type has a dedicated parameter file, which allows for both tailoring the measurement process and providing the measurement parameters, such as a step distance, a number of repetitions, a requested current, a set of tensions, etc.

VI. Conclusion

The majority of measurement systems would benefit from automation, which offers the advantages of a hands-off execution of measurements, measurement repeatability, measurement traceability and operator mistake avoidance leading to improved measurement dependability.

The implementation of automation via coordination allows for separating the measurement procedure from the details concerning the implementation of data acquisition, analysis and data management, including data structures, data processing and data flow.

Coordination in this system is achieved via orchestration implemented by scripting, and, in addition to the above advantages, improves the flexibility of the system and its extensibility. The use of parameterized scripts in the implementation of orchestration further increases maintainability and modifiability of the measurement systems.

The authors' experience with the EMMA framework and several systems built with it shows that this solution provides a powerful technology for building extensible, flexible systems based on a common software platform. A testimony to this is the SSW system built with EMMA, which measures the strength and alignment parameters (axes and angles) of accelerator magnets. This system can be easily extended to other measurement methods, such as rotating wire and vibrating wire. It has been successfully used at KEK for measuring magnetic centers and roll angles of the final focus quadrupole system at the interaction region of SuperKEKB [5].

Acknowledgment

The authors would like to thank Drs. N. Ohuchi and Y. Arimoto from KEK National laboratory for High Energy Physics, Tsukuba, Japan for their collaboration in measurements of quadrupoles for SuperKEKB.

References

[1] J. Bosch, Design of an Object-Oriented Framework for Measurement Systems, Object-Oriented Application Frameworks Conference, 1998.
[2] P. Arpaia, E. De Matteis, V. Inglese, “Software for measurement automation: A review of the state of the art,” Measurement, vol. 66, 2015
[3] P.E. Poirot, S. Ren, J. Nogiec, J. Tsai, “Separating functional and non-functional concerns through coordination an application to reliability,” COMPSAC06
[4] J. Nogiec, K. Trombly-Freytag, “EMMA: A New Paradigm in Configurable Software,” Journal of Physics: Conference Series, vol. 898, IOP Publishing, October 2017
[5] Y. Arimoto , K. Egawa, T. Kawamoto, M. Masuzawa, Y. Ohsawa, N. Ohuchi, R. Ueki, X. Wang, H. Yamaoka, Z. Zong, J. DiMarco, J. Nogiec, and G. Velev,” Magnetic Measurement with Single Stretched Wire Method on SuperKEKB Final Focus Quadrupoles,” IPAC'19, Melbourne, Australia, 19-24 May 2019
[6] J. DiMarco et al., “Field Alignment of Quadrupole Magnets for the LHC Interaction Regions,” MT16, Tallahassee, Florida, 1999
[7] L. Walkiers, “Magnetic measurement with coils and wires,” presented at the CERN Accelerator School CAS 2009, Bruges, 16-25 June 2009
[8] J.M. Nogiec, “Architecture and features of an extensible measurement system framework,” in: IMMW-15, Batavia, USA, 2007.
[9] J.M. Nogiec, J. DiMarco, “Magnetic Field Measurement System as Part of a Software Family,” in IMMW-14, Geneva, Switzerland, 2005
[10] J.M. Nogiec, K. Trombly-Freytag, S. Ren, “Toward an Architecture of a Component-Based System Supporting Separation of Non-Functional Concerns,” International Journal of Computer and Information Science and Engineering, 2007, No 3, ISSN 1307-4164