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BEAM STEERING: A TEST BENCH FOR GENERIC ALGORITHMS IN ACCELERATOR CONTROLS

B. Autin, M. Arruat, F. di Maio, and M. Martini

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The algorithm has been coded in *Mathematica* and implemented in the CERN PS control system. It is called through the *MathLink* protocol by an application program linked to standard beam position measurement software. With this technique, the development of the algorithm and its linkage to the control system are fully de-coupled. The application will become generic as soon as the magnetic and optical parameters will be loaded in data bases.

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Beam Steering: A Test Bench for Generic Algorithms in Accelerator Controls

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Abstract

The operation of a complex accelerator system such as LEP or the future LHC at CERN demands automatic and standard controls to make it easy to use and reliable in all circumstances. A class of beam manipulations is the steering in the various machines and transfer channels. An algorithm has been devised to satisfy the required condition of genericity. It is based on a least squares method and yields a correction system which is not necessarily well conditioned in a usual operational environment where correctors and monitors may be either missing or redundant.

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1. INTRODUCTION

The main two parameters of a collider are its energy and its luminosity. If it is usually straightforward to reach the design energy, it is much more difficult to obtain the highest luminosity. This requires permanent development work to correct the various imperfections, a deep understanding of the beam behaviour and even the design of new schemes which overcome basic limitations. Besides the machine development, it is crucial that the operation of the machine have a high level of reliability and that all the setting-up be as fast as possible so as to maximise the time for particle physics. In both development and operation activities, the man machine interface through controls has to take advantage of all the progress in software technology to be as efficient as possible and three criteria can be outlined: universality, simplicity and connectivity.

(i) The code developed in the design and development stages should address a large class of problems and be implemented in the controls without having to be re-written for the operation.

(ii) The programming language should be close to the physics concepts. A code is not appraised by its number of lines but rather by its compactness and its clarity. From this standpoint, advanced symbolic languages using functional programming, pattern recognition and list processing are far superior to traditional numeric codes. Text processing and graphics facilities are indispensable tools in the elaboration and test of the code.

(iii) The algorithms are just one aspect of a control system. The other elements are on one hand a relational data base which contains all the relevant information about the components of the machines and on the other hand the communications with the instruments through equipment modules and the user through graphics interfaces. The programming language must thus have a linkage protocol which connects it to the rest of the controls world which has its own standards (UNIX, C, etc.).

An approach to controls fulfilling those requirements has been tested for the steering of a beam in a transfer line (TT2) situated between the PS and SPS machines at CERN. It will be analysed in each of its aspects: machine development with diagnosis of an alignment error, correction algorithm written with *Mathematica* [1] which has list processing, functional programming, graphics facilities and a linkage protocol available, and integration of the algorithm into the PS control system. A generalisation of the method to beam steering in all CERN machines is under development and its general features are presented.

2. BEAM STEERING

2.1. Operational environment

The method devised for beam steering in transfer channels and closed orbit correction in synchrotrons [2] is applicable to arbitrary distributions of beam position monitors and corrector magnets. The devices used for beam position measurements in the CERN PS complex are mainly secondary emission monitors (SEM-grids) and electrostatic pick-up stations. The correction algorithm solves a linear system iteratively using a least squares method. Its purpose is indeed not to find an exact solution which is both irrelevant and dangerous when the various experimental errors are taken into account but to minimise a residual vector; in brief, the algorithm is a minimiser and not a solver. The method has been widely applied because it is robust, flexible, fast and has the very appreciable practical advantage of converging with a small number of correctors.

The dipole corrector fields are provided either by steering dipole magnets or by moving quadrupole magnets transversally, yielding the angular kick

$$\delta\varphi_i = \frac{l\Delta B}{B\rho} \qquad (1)$$

$$\delta\varphi_i = Klu \qquad (2)$$

where l is the corrector length, u the transverse displacement of the quadrupole magnet, K the quadrupole strength, $B\rho$ the beam rigidity, and ΔB the dipole field. The corrections calculated in milliradian are converted either to Amperes for dipole power supply settings or millimetres for quadrupoles displacements.

2.2. Correction algorithm

The matrix A of the linear system is made of as many columns as possible correctors. Each component of a column is the position of the particle trajectory when the corrector has a unit excitation, all the other correctors being set to 0. The errors to be corrected are collected in a vector U. The unknown corrections are the components of a vector $\delta\varphi$ and calculated in such a way that the norm of the residual vector $A\delta\varphi + U$ is minimised in an iterative manner. That correction magnet which yields the lowest residual r.m.s. distortion at monitor positions is first selected. Then, the residual distortion is re-analysed and the next best magnet selected. Keeping all correctors from the previous iterations but recalculating their strengths, the method proceeds until the residual r.m.s. distortion is comparable with measurement errors.

The trajectory deviations at the i-th monitor due to a unit kick at the j-th thin lens corrector for a transfer channel and a ring are

$$a_{ij} = \sqrt{\beta_i\beta_j}\,\sin(\mu_i - \mu_j) \qquad (3)$$

$$a_{ij} = \frac{\sqrt{\beta_i\beta_j}}{2\sin\pi Q}\cos(|\mu_i - \mu_j| - \pi Q) \qquad (4)$$

respectively where β and μ are related to the amplitude and phase of the betatron oscillation and Q is the machine tune [3]. In matrix notation $A = (a_{ij})_{j=1...m}^{i=1...n}$ denotes the full correction matrix.

The various steps of the calculation at the k-th iteration are:

(i) Compute the corrector strengths from the measured trajectory distortion as

$$\Delta\varphi^{(k)} = -(A_i^{(k)T} A_i^{(k)})^{-1} A_i^{(k)T} U \qquad (5)$$

for $i = 1...m$, with $i \neq i_1, ... i \neq i_{k-1}$, where the matrix $A_i^{(k)}$ is formed by concatenation of $A_{i_{k-1}}^{(k-1)}$ with the i-th column of A ($A_i^{(1)}$ being the i-th column of A), and $\Delta\varphi^{(k)} = (\delta\varphi_i)_{i\in\{i_1..i_k\}}$ is the vector kick. The letter T denotes the transpose of a matrix.

(ii) Compute the norm of the residual vector $R_i^{(k)}$ as

$$|R_i^{(k)}|^2 = U^T U + \Delta\varphi_i^{(k)T} A_i^{(k)T} U \qquad (6)$$

(iii) The k-th best corrector is the one which minimises the norm of the m-k+1 residual vectors

$$|R_{i_k}^{(k)}| = \min_i(|R_i^{(k)}|) \qquad (7)$$

The re-distribution of the columns of the correction matrix is well suited to list processing. In addition, the generalised inverse $(A^T A)^{-1} A$ is a built-in function of *Mathematica*. As a result, the total code does not exceed one hundred lines and has been written and tested in a few days. It is called through the *MathLink* protocol by a control application written in C and linked to the standard emittance measurement software installed in the PS control system [4]. In the case of very large machines, the computing time can be substantially reduced by resorting to Householder's transformations [5] which have not yet been implemented.

3. PROTOTYPE FOR A BEAM CORRECTION SYSTEM

3.1. PS to SPS transport line trajectory correction

With the new and more stringent requirements of beam emittance for LHC, the beam profile has to be measured with an enhanced precision. This is done in the transfer line TT2 using high resolution SEM-grid monitors (0.35 mm wire step size, appropriate for minimum transverse beam size of, say 3 mm, for the LHC). The measurement necessitates a good centring of the beams which is carried out first by means of low resolution SEM-grid devices (2.5 mm ribbon step size), then by a finer beam centring using the high resolution SEM-grid devices. The correction algorithm did not converge at the beginning of the tests in the vertical plane and an absence of convergence is the symptom of anomalous measurement errors. The alignment of the SEM-grids on the axis of the adjacent quadrupoles has thus been checked and it turned out that one grid had indeed an excessive offset which was eventually taken into account so that a complete correction could be done.

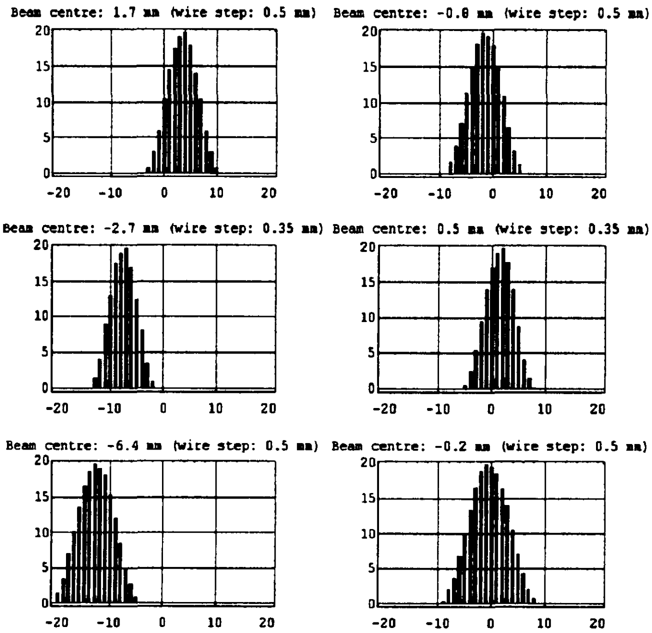

Fig. 1: SEM-grid signals before (left) and after (right) centring.

The beam is centred on the monitors using two steering dipoles selected out of a set of three; the r.m.s. trajectory distortion and the peak-to-peak value decreased from 2.4 mm to 0.3 mm and from 8.1 mm to 1.3 mm in the horizontal (Fig. 1) and vertical plane respectively.

3.2. AA and AC closed orbit correction

Corrections of closed orbits are important to increase the machine aperture. The vertical closed orbits have been corrected in the CERN Antiproton Collector (AC) and Antiproton Accumulator (AA) rings which are equipped with the same number of correctors and monitors: 28 in AC and 12 in AA. These machines have no on line control of the closed orbit and the corrections performed off-line took less than one hour.

In both rings the correction has been accomplished using 3 correctors. In AA, the r.m.s. distortion and the peak-to-peak value decreased from 0.7 mm to 0.2 mm and from 6.6 mm to 2.2 mm respectively and the vertical machine acceptance increased after correction from 15 π mm.mrad to 24 π mm.mrad. In AC, the r.m.s. distortion and the peak-to-peak value were reduced by a factor 2 thus enlarging the transverse acceptance from 183 π mm.mrad to 196 π mm.mrad [6] (Fig. 2).

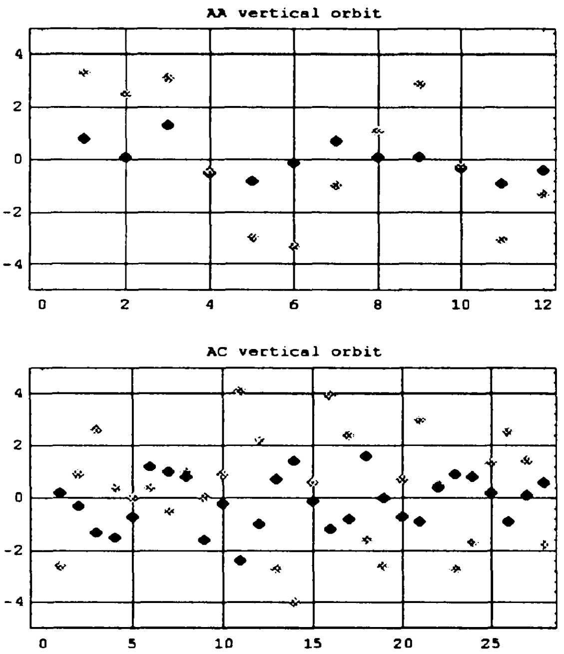

Fig. 2: Closed orbits before (grey dots) and after (black dots) correction.

3.3 On-line operation of the trajectory correction prototype

The trajectory correction in TT2 has been implemented in a prototype application program, using the CERN PS control system. This program has been extensively used on-line, during machine development sessions dedicated to LHC type beam (Fig. 3).

The correction algorithm implemented with *Mathematica*, which was developed and tested off-line, has been directly integrated into the program with only minimal interface adaptations. The beam trajectory is acquired through SEM-grids instruments and the corrections are applied through the power-supplies of the horizontal and vertical dipoles.

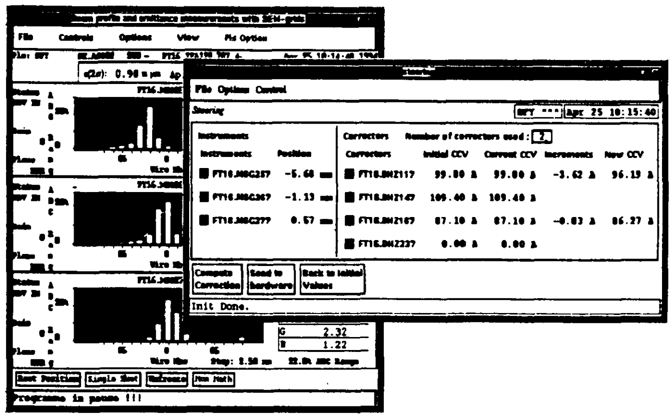

Fig. 3: Display of the interactive windows used for the beam steering programme.

In the control system, the correction function requires three distinct modules which are inter-connected (Fig. 4). An instrumentation application produces the trajectory, the computation module calculates the corrections to be applied and the steering application creates the communications between the instrumentation application, the computation module, the correction equipment and the operator.

Beam trajectories are acquired with SEM-grid equipment. Such an equipment requires a dedicated program which implements the control of the devices as well as the treatment and presentation of the acquisitions. The control of the devices includes commands like: "Put SEM-grid in the beam", "Select gain", etc. The treatment of the acquisitions consists of filtering, interpolation and r.m.s. calculation.

The SEM-grid application is a *X-Window/Motif* program. Through the *X-Window* protocol, it exports beam trajectories to the steering application synchronised with machine events or on operator's request.

The computation module is a *Mathematica* session executing the trajectory correction algorithm. The *Mathematica* session is activated by means of the *MathLink* protocol during the software initialisation. The correction functions are loaded from a file which can be updated without having any program to be re-compiled nor re-linked. Should the syntax of the functions remain unchanged, corrections or extensions of the algorithm can therefore be very quickly implemented.

The correction functions are executed through the *MathLink* protocol. On operation workstation (DEC-MIPS), this does not introduce any user-perceptible delay (i.e. less than 2 seconds between clicking on the button and having results displayed).

The steering application is a *X-Window/Motif* program which integrates the different software modules, implements the user interface with the correction algorithm and controls the correction equipment. It activates the measurement application and the *Mathematica* session, receives data from the instrumentation application and executes the correction calculation through the computation module. The various options of the correction algorithm, like the selection of a sub-set of monitors or correctors, are presented inside a dialogue window. Computed corrections are displayed and can be applied under the operator control.

Each instance of this program is defined in an *Oracle* table. The definition includes the instrumentation application, the set of correction equipment and the *Mathematica* file.

4. ARCHITECTURE OF A GENERAL CORRECTION SYSTEM

In the present status of the beam steering procedure, the optical parameters are included in the code. In fact, the code should contain the correction algorithm only to be applicable to any ring or transfer line and the optical parameters stored in a data base. The de-coupling between algorithm and data is the major improvement to be implemented in the new steering control. As a consequence, the presence of a data base forces the revision of the flow of information between data, algorithm and controls themselves.

4.1 Data base

A relational data base for accelerator physics has already been elaborated for the LEP collider [7] and will eventually be extended to LHC. It will thus be adapted to a general beam steering control. The data concern the characteristics of the magnets and of the beam monitors. A first set contains all information about the type of the elements, their position, length, magnetic field and conversion factors. Those data serve as input to a beam optics program which returns the parameters of the particle beam. That quantities have an intrinsic interest since they reflect the status of the channel and can be used not only for beam steering but also for any other beam manipulation such as the adjustment of the beam spot size at an intersection point or at a target.

4.2 On-line operation of a general correction system

The CERN-PS control system already includes computers which are dedicated to on-line *Oracle* applications (like reference values and sequencer description). However, the two required data-bases have to be set-up with their configuration procedures and tools.

The set of instrumentation equipment integrated into this architecture can be easily extended to the pick-up equipment of the transfer lines which are all controlled through a single instrumentation application in the new CERN-PS control system. Reference trajectories must also be included into the instrumentation applications for generalising the correction (conversion from magnetic values to electrical settings). This is illustrated in a simplified version of the data-flow diagram (Fig. 4).

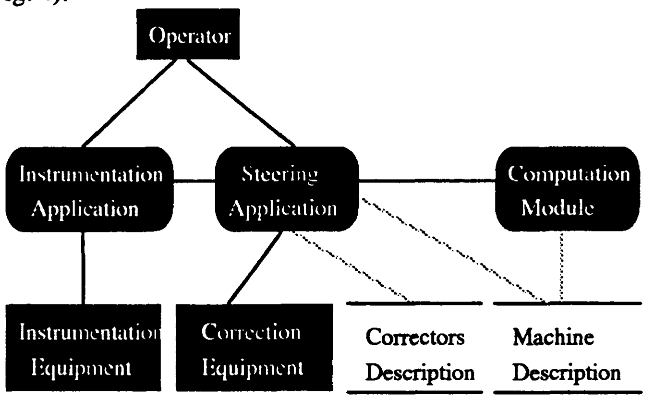

Fig. 4. Full system software architecture with its present status (black background) and planned extensions (white background).

5. CONCLUSION

An automatic beam steering procedure has been successfully implemented in a transfer line of the CERN PS complex and all the stages of development from machine experiments to integration into a control system have been described. As a net result, a manipulation which required operator's expertise and a substantial setting-up time in the past is now routinely used and performed in a few seconds, the incompressible time for data acquisition and trajectory correction. The next step is to make the present application generic so that it can be used on any machine and even for other classes of problems such as chromatic or geometric aberrations whose solution relies on the iterative solution of a linear system. In that context, a new architecture containing relational data bases is being designed.

6. REFERENCES

[1] S. Wolfram, *Mathematica*, a system for doing mathematics by computer, Addison Wesley (1992).

[2] B. Autin, Y. Marti, Closed orbit correction of A.G. machines using a small number of magnets, CERN ISR-MA/73-17 (1973).

[3] E. Courant and H.S. Snyder, Theory of the Alternating Gradient Synchrotron, Ann. Phys. 3, 1-48 (1958).

[4] M. Arruat, M. Martini, The new standard method to measure emittances in the PS transfer lines, CERN/PS 92-59 (PA).

[5] G.H. Golub, Numerical methods for solving linear least squares problems, Numer. Math. 7, 206-216 (1965).

[6] S. Maury, Private communication, 1994.

[7] R.Bailey, A.Belk, P.Collier, M.Lamont, G.de Rijk, M.Tarrant, Development of the LEP high level control software using *Oracle* as an on-line database, Proc. ICALEPCS 1993 (to be published).