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GOLD: INTEGRATION OF MODEL–BASED CONTROL SYSTEMS WITH ARTIFICIAL INTELLIGENCE AND WORKSTATIONS*

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Our experience with model-based accelerator control started at SPEAR. Since that time nearly all accelerator beamlines have been controlled using model-based application programs, for example, PEP and SLC at SLAC. In order to take advantage of state-of-the-art hardware and software technology, the design and implementation of the accelerator control programs have undergone radical changes with time. Consequently, SPEAR, PEP and SLC all use different control programs. Since many of these application programs are embedded deep into the control system, they had to be rewritten each time. Each time this rewriting has occurred a great deal of time and effort has been spent on training physicists and programmers to do the job. Now, we have developed an integrated system called GOLD (Genetic Orbit & Lattice Debugger) for debugging and correcting trajectory errors in accelerator lattices. The system consists of a lattice modeling program (COMFORT), a beam simulator (PLUS), a graphical workstation environment (micro-VAX) and an expert system (ABLE). This paper will describe some of the features and applications of our integrated system with emphasis on the automation offered by expert systems.

Up to now, our program has been developed to solve one type of problem that is often encountered during accelerator startup and commissioning. We have made a program that is generic because it can be used for the control of either storage rings or beamlines, large or small machines and also for the analysis of measured or simulated data. Also the integrated system can be run to automatically find errors in an accelerator lattice without human intervention. Finally, GOLD is transportable and can also be easily incorporated into any existing control system.

COMFORT [1] is a lattice modeling program that performs first-order optics calculations from bends, quadrupoles, drifts and accelerator sections. COMFORT uses as input the order, length and strength of the elements in the beamline. The user can also specify lattice function values or transfer matrix values at various fit points. The output are the transfer matrices across each element. The fits are done using a sophisticated nonlinear optimization program, NPSLAC [2]. A special version of COMFORT generates output that is used as input to the beam simulator, PLUS. PLUS [3] calculates beam trajectories at each Beam Position Monitor (BPM) including effects due to errors. These errors include beam kick errors such as: dipole field errors (due to misaligned quadropoles, miscalibrated bending magnet strengths); quadrupole field errors (due to quadrupole miscalibration); beam energy errors (dE/E); beam entrance errors (x,x'); and BPM errors (due to offset, miscalibration). The input to PLUS are the transfer matrices generated by COMFORT and BPM data.

To find errors with GOLD manually using interactive graphics, the user guesses which elements are causing the errors and allows the beam kick at those elements to vary during optimization. The optimization minimizes the differences between the input reference BPM data and the corresponding values computed using the model. The outputs of GOLD are the strengths of the various beam kicks and the model-predicted BPM values. By analyzing many different possible sources of the error(s) the user can often find very good candidate solutions which we refer to as "gold" candidates. The problem with this manual mode is that it is laborious, time-consuming (typically several hours to several days) and involves extensive bookkeeping by the physicist. We will now discuss how a graphical environment can be used to improve the error-finding efficiency.

The graphical display of GOLD shows the relative position of the elements and monitors along a beamline. It also plots the reference BPM data along with the model-predicted BPM values. The BPM values are connected by a straight line to give an "orbit." The user can then determine by visually pattern-matching the two orbits whether the fit is reasonable or not. The graphical environment allows the user to "play games" and develop rules for debugging lattices. Thus GOLD can be used not only by experts developing new problem-solving strategies but also as a training tool. New strategies can be learned using either simulated or real beam data. The system is generic because it can and has been used on transport lines, circular machines, large and small machines, and on real or simulated data. Examples of some applications of GOLD are described below.

Figure 1 shows data from the CERN SPS. The SPS consists of six sextants each with two full superperiods. The data analyzed extended over two sextants. As can be seen from the figure, the reference and model prediction do not agree after the seventh monitor. Figure 2 shows that by putting an error in at element 16 the good match between data and prediction extends to monitor 13. Two other errors are needed to fit all 36 monitors as is shown in Figure 3. The results of Figure 3 allow several important statements to be made regarding the machine, namely, the model is good, the BPM's are good and the calibrations are good because the answer obtained is correct to within 5 % of the actual measured changes made to the machine. This example shows the importance of solving this class of problems (first order) because it tells so much about the hardware and software of the machine. It is also crucial to understand the first-order properties of the machine before worrying about higher-order problems. Figure 4 shows a similar application for the small CERN EPA (Electron–Positron Accumulator) ring. GOLD has been used to find errors in other storage rings and transport lines at CERN and SLAC including: bending errors in LEAR (Low-Energy Anti-proton Ring), quadrupole focus errors in the SLC (SLAC Linear Collider) damping rings, BPM errors in the ring-to-linac system of the SLC, energy errors in the beam switchyard at SLAC and coupling errors within the arc achromats of the SLC. We wish to acknowledge S. Kleban from SLAC for his invaluable assistance in analyzing data and for his help with the graphics.

Starting up and commissioning an accelerator facility is similar to a doctor diagnosing a patient for some illness. In our case the patients are accelerators with first-order optical problems. The symptoms are large closed orbit or trajectory errors, improper launch feedback control, lattice change errors, automatic steering not working, or difficulty in storing or restoring the beam. When these symptoms are present, the causes cannot be found, or the symptoms cannot be corrected, it is time to call the "accelerator doctors." Just as with people doctors there are many kinds of accelerator doctors. In the paragraphs above the doctors are the ones who use the state-of-the-art diagnostic tools (model simulation with graphical interface). Unfortunately, most doctors are more traditional and do not use the most up-to-date tools and simply "knob" the accelerator. Even worse, in some cases the physicists are not even the ones developing the diagnostic tools or the tools themselves may have bugs. For these reasons there needs to be close collaboration between the tool users and the tool makers when building and using the tools. In the 1970's researchers in Artificial Intelligence attempted to capture the diagnostic capabilities of experts in infectious diseases [3]. We have chosen to apply these methods of "expert systems" to the diagnosis of accelerator lattice errors.

Expert systems provide a means for automating the expert problem-solving methods used by accelerator physicists. Highly specialized hardware and software environments have been devised to aid in the construction of expert systems. We used these tools to develop the ABLE [5] system which finds dipole field errors in beamlines. ABLE incorporates a rule-based strategy for finding these errors along with the information provided by the PLUS beam simulator. We used GOLD as a training tool for inventing new error-finding methods and for testing the codified rules. We were able to achieve good performance on simulated data with ABLE offline at the Stanford Knowledge Systems Laboratory.

Unfortunately, these specialized environments used by Artificial Intelligence practitioners have not made their way into the accelerator control room. Also, the maturity of this hardware and software is not yet at the high level of reliability that has come to be expected by accelerator physicists. Finally, many expert systems have never made it out the computer science laboratory. To avoid all these shortcomings we thought it wise to get an accelerator debugger into an accelerator control room as soon as possible. To this end we developed GOLD to run on an "ordinary" computer. For example, the graphics used by GOLD allows it to run on a micro-VAX workstation, which is found in many accelerator control rooms. Like ABLE, GOLD contains a rule-based system but with higher performance. GOLD has also been tested on many more sets of actual beam data. Since GOLD can be run in a fully automated fashion there is no need for a sophisticated interactive graphical environment. GOLD obtains its data from simple database "puts" and "gets" the details of which may vary between control systems. This standalone feature enabled us to develop our system completely independent of any control system, but at the same time it has "hooks" so that it can run on any control system.

Since GOLD contains all the tools of the trade, an accelerator "knobber" can knob GOLD manually with interactive graphics instead of knobbing the machine. This allows him to see the effects of his change without wasting beam time or causing damage to the machine. An accelerator doctor who likes to knob several elements at once can use GOLD automatically and see how good his guesses are (knobbing more than two elements simultaneously becomes too complicated). We have found that using the automated expert system first is the most efficient because it either solves the problem outright or helps to reduce the number of cases to be examined. Our experience has shown that for cases we can solve using GOLD manually, such as those described here (see Figure 3), the expert system can always find the same answer. If the expert system cannot find a sensible solution it means that the experts cannot find one either without a lot of guessing and trial and error effort. As we learn more by solving the problems the expert system cannot handle we can add that new knowledge into GOLD so that the expert system can automatically do the job next time. Since the integrated GOLD system contains every tool anyone ever needs, we believe the use of GOLD to be the only sane way to debug accelerator lattices.

In summary, we have integrated several powerful problem-solving techniques, modeling, simulation, optimization, interactive graphics and expert systems into a single generic orbit and lattice debugging and correcting program, GOLD. GOLD has been used successfully in closed-loop analysis to find errors in beamlines using real data. The importance of GOLD is that it provides the analysis of kick errors in a machine that is needed before any other errors can be found and corrected. To close the loop that includes the online control systems all that is needed is to use simple database "puts" and "gets." To use GOLD for correcting lattices, choose the actual correctors closest to the gold candidates found by GOLD and then ask GOLD to find the corrector strengths. According to the expert (M. L.) the program can find errors as well as he can and in much less time. The structure and methods of GOLD can be used for the analysis of other problems such as emittance analysis, dispersion correction and other applications.

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References

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Figure Captions

Figure 1. Analysis of SPS data with data and model prediction. Fit is good only through first seven monitors. The X's on the plots are the location of the magnet elements along the beam line. The height of an X above the x-axis is proportional to the value of the error.

Figure 2. Same SPS data as Figure 1 but now including an error at element 16. Note that the fit is now good over 13 monitors.

Figure 3. Using three errors the fit is good over all 36 monitors. The elements and strengths found agree with the actual change made to within 5%. Manual and automated use of GOLD give the same answer.

Figure 4. CERN EPA data and the fit found by analysis.

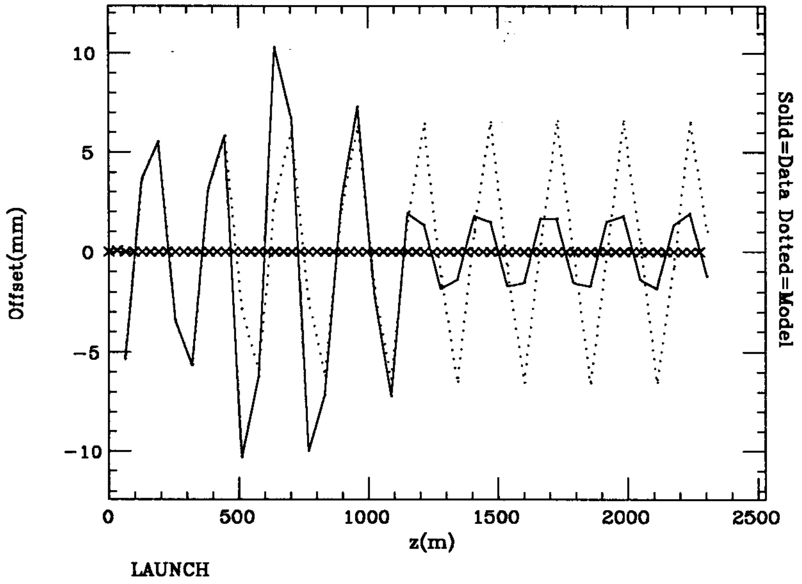


Figure 1

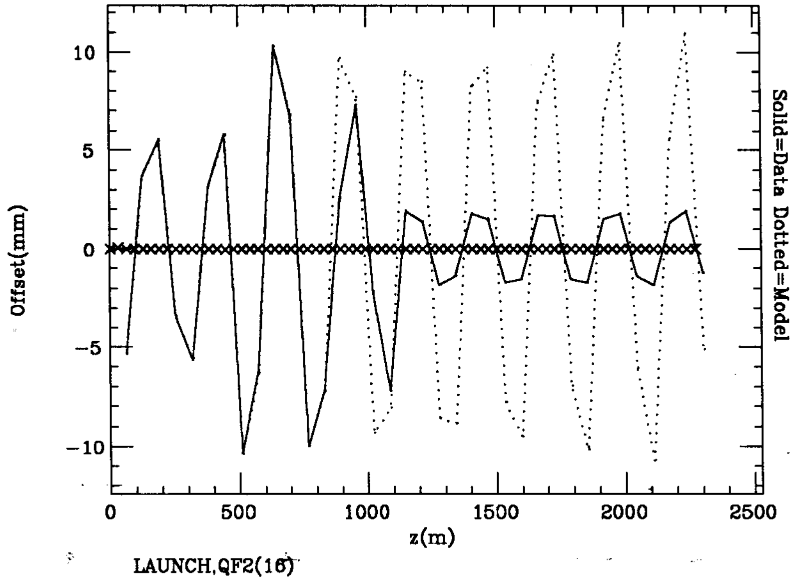
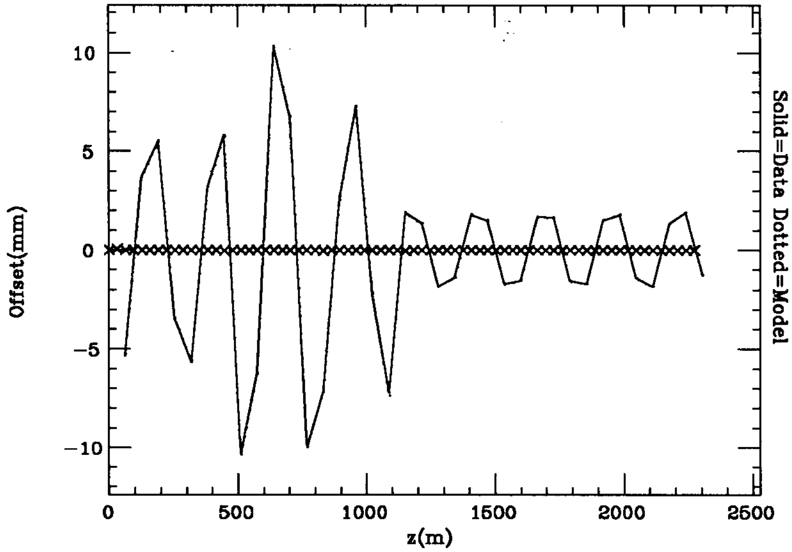
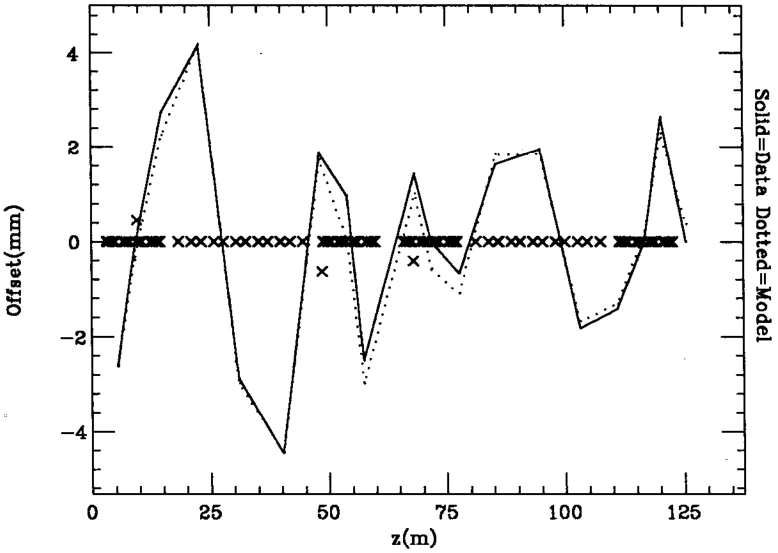


Figure 2



LAUNCH,QF2(16)=−.072,QF2(28)=−.068,QF2(38)=−.058MRAD

Figure 3



LAUNCH,QFLH(22)=.9,QFWH(63)=−1.25,QTRH(108)=−.82

Figure 4