Adaptive Cascaded Beam-Based Feedback at the SLC*

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Abstract
The SLAC Linear Collider now has a total of twenty-four beam-steering feedback loops used to keep the electron and positron beams on their desired trajectories. Seven of these loops measure and control the same beam as it proceeds down the linac through the arcs to the final focus. Ideally each loop should correct only for disturbances that occur between it and the immediate upstream loop. In fact, in the original system each loop corrected for all upstream disturbances. This resulted in undesirable overcorrection and ringing. We added MIMO (Multiple Input Multiple Output) adaptive noise cancellers to separate the signal we wish to correct from disturbances further upstream. This adaptive control improved performance in the 1992 run.

I. INTRODUCTION
The SLC presently has twenty-four steering feedback loops running [1]. Seven of these loops are placed one after the other along the linac.

A typical loop measures and controls eight states: the position and angle of the electron beam in both the horizontal and vertical directions and the same for positrons. The loop measures these states using ten beam position monitors (BPMs). Each monitor gives the horizontal and vertical position for electrons and positrons. Hence, there are a total of forty measurements.

Each feedback loop is designed using our knowledge of accelerator optics and the state-space formalism of control theory. The linear quadratic Gaussian (LQG) method is used to design optimum filters to minimize the rms disturbance seen in the beam. Since there is a fair amount of white noise in the incoming beam disturbance, this filter averages measurements of about six beam pulses. Hence the typical loop corrects most of a step change in six pulses.

A problem exists with the system as described so far. Seven loops in a row examine the same beam. Figure 1 depicts the beam trajectory in the region of two of these loops. Figure 1a shows the trajectory on the first pulse after a sudden disturbance (such as an operator adjusting a dipole magnet strength) upstream of the two loops. The plot of transverse beam position as a function of distance along the linac shows the sine-like trajectory caused by the focusing quadrupole lenses. At this time, the loops have not made a correction. Figure 1b shows the trajectory on the next pulse. To keep this example simple, the loops were set to completely fix an error detected in one pulse instead of in six. The first loop completely corrected the original disturbance. The second loop also made a correction, which was unnecessary because the first loop corrected for the disturbance. Of course, on the next pulse the second loop would correct its error but the damage has been done, the loops have overshot the mark for a pulse. The problem gets much worse with seven loops in a row. The overshoot can be reduced by having each loop respond more slowly but the system still overshoots and then rings for many pulses. The system is stable and the ringing gradually dies out, but the overall response of the loops is not optimal, hence the beam positions and angles have a larger rms than need be.

The proper solution is to have each loop correct only for disturbances which happen between it and the next upstream loop. This would completely eliminate the overshooting caused by multiple loops correcting for the same disturbance.

ADDITIONAL MIMO ADAPTIVE NOISE CANCELLER
An individual loop (say loop \( n + 1 \)) has only a few local BPMs to detect disturbances in the beam. It has no way to tell how far upstream the disturbance occurred. Since we want loop \( n + 1 \) to correct for disturbances downstream of

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Before diving into the details of the adaptive calculation, it is worthwhile to ask why adaptation is necessary at all. What is wrong with the simple transport of the beam, an adaptation downstream of the previous loop? This action corrects the problem.

ADAPTIVE CALCULATION

In addition to the simple transport of the beam, an additional "Disturbance between n and n+1" may be added. Consequently, the transport of the beam is not static, the transport of the beam from loop n to loop n+1 is non-linear, and thus represents a disturbance that must be adapted to.
n becomes an angle at loop \( n+1 \), and an angle transforms into a position. The transformation is critically dependent on the number of betatron oscillations between the loops. This is parameterized as the phase advance where 360° of phase advance corresponds to one full oscillation. Figure 1 shows two loops separated by 5 \( \times \) 360° of phase advance, the average for the loops in the SLC. The dotted line in Figure 1a shows a betatron oscillation where the focusing strength is incorrect by 1 percent, an error typical of the real linac. Note that the position and angle at the second loop are quite different due to the 1 percent error. This significant variation of the “Transport from \( n \) to \( n+1 \)” forces the use of an adaptive method for the noise canceller.

The updates of the weights in the adaptive filter are made using the Sequential Regression (SER) algorithm [2]. The equations used in the SER algorithm are explained in Reference [2].

Basically the inverse of the input correlation matrix is estimated. This estimate is used to scale the inputs so that all the eigenvalues of the correlation matrix of the scaled inputs are equal to one.

Using the SER method, the calculation of the weights becomes unstable for a short time if the beam jitter suddenly increases. During the time it takes for the estimate of the inverse of the input correlation matrix to converge to the new value, the weights diverge rapidly. This problem and the solution were found in simulation: not to update the weights if the inverse correlation matrix is receiving large updates.

After testing the algorithms with the computer simulation we implemented them in the SLC control system.

**EXPERIENCE ON THE REAL ACCELERATOR**

First we turned on just the adaptive algorithm. The results were not used to control the beam. After confirming that the matrices had converged to reasonable values, we turned on the noise cancelling system. As shown in Figure 3 the response to a step disturbance in the beam trajectory was greatly improved with the startup of the adaptive noise-cancelling system.

Over the next few weeks we varied the learning rate to find the optimum value that would allow the adaptation to converge rapidly without having too much noise introduced by the adaptive process. We settled on a learning rate of 0.001 and an adaptive update rate of 10 Hz. A convergence time of about 100 seconds resulted. The system ran for several days with learning rates of 0.1 and 0.01 and was completely stable, but with these higher learning rates more random noise showed in the adaptive matrix elements.

The adaptive noise-cancelling addition to the fast feedback system has been running stably in seven locations on the SLAC linear collider for over six months. Probably the best measure of its robustness and stability is that operators have made no middle of the night phone calls asking for help to recover from a problem. In fact there have been no significant problems with the system. Adaptive noise cancelling has significantly improved the performance of our feedback systems and helped us achieve our goals of accelerating two beams over a distance of three kilometers, pointing the beams at each other, and then colliding them head on so they pass through each other even though they have a radius of only 2 \( \mu \)m at the collision point.

In fact we have received an unexpected bonus from the adaptive calculation. The adaptive weights can be interpreted as measurements of the beam transport matrix from one loop to the next. These measurements are recorded on disk and can be displayed. Such data shows a typical variation of over 30 degrees which is about 1 percent of the total phase advance between the two loops. We have made many checks and convinced ourselves that this variation is caused by a real variation in the focusing strengths in the linac (typically due to rf phase and energy changes). Accelerator physicists are using this data to identify and try to fix the cause of the changes in focusing strength. This would make a still more stable accelerator.

**REFERENCES**


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