TUNING AND OPTIMIZATION AT BROOKHAVEN AND ARGONNE: RESULTS OF RECENT EXPERIMENTS

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Abstract

Vista Control Systems Inc. is developing a portable system for intelligent accelerator control. Our system is general purpose and has been designed to be reused at multiple accelerator facilities. This portability arises from the hierarchical object-oriented nature of the architecture. The control system employs a multi-level organization in which knowledge based inferencing is used to dynamically configure a variety of optimization and control algorithms. We discuss results from recent beamline tuning tests at the Brookhaven National Laboratory ATF and the ATLAS facility at Argonne. Results are analyzed along a number of dimensions, including portability, performance as benchmarked against human tuning, adaptive behavior, noise handling, integration of control subsystems, and support for rapid knowledge capture and utilization.

1 THE ARCHITECTURE

This system is based on a hierarchical distributed architecture. At the lowest level, a physical access layer (PAL) provides an object-oriented abstraction of the target system. A series of intermediate layers implement general algorithms for control, optimization, data interpretation, and diagnosis. Decision making and planning are organized by knowledge-based components that utilize knowledge acquired from human experts to appropriately direct and configure lower level services. The general nature of the representations and algorithms at lower levels gives this architecture a high degree of portability. The knowledge-based decision-making and planning at higher levels also supports a real-time capability for adaptation to unexpected events and changing environments [1, 2, 3].

2 DESCRIPTION OF EXPERIMENTS

We carried out experiments at two accelerator facilities: Brookhaven National Laboratory's Accelerator Test Facility (ATF), and Argonne National Laboratory's Advanced Tandem Linear Accelerator Site (ATLAS). The experiments were designed to address common beam line tuning tasks which are currently performed strictly through human interaction. These experiments vary in their difficulty, but each tests some features of the control architecture These experiments vary in their difficulty but each tests some set of features of the control architecture such as knowledge based control, use of solvers (optimizers) for low level control, integration of knowledge based and analytic methods, component based programming, and task decomposition and delegation.

The Brookhaven ATF consists of a beam source, a linear accelerator, a transport line, and three experimental beam lines. Electrons are generated from a pulsed laser striking a cathode and are initially accelerated by an RF device known as a klystron. This beam source generates short bunches of electrons at a rate of 1.5, 3, or 6 Hz. Electrons travel from the source through a solenoid magnet and then a short distance into the accelerator tube. After exiting the accelerator, the beam travels through a beam line section to an achromat, then through another short beam line, and finally into one of the beam lines in the experimental hall.

Our tuning experiments were directed to experimental beam line 3, whose purpose is to support research with a free electron laser (FEL). The FEL is a device which produces a laser beam from a interaction caused by accelerated electrons passing an undulator or wiggler. In order to cause the FEL to laze efficiently, the beam must be carefully transported from the beam source, through the accelerator, and into the entrance of the FEL. At the entrance, the beam must have a specific size and shape. Tuning must also produce a waist condition inside the undulator. A waist is related to a beam's sigma matrix [1]. To date, no human operator has successfully achieved vigorous lasing in the FEL.

Our first experiments tuned and conditioned the beam to the end of the H beamline. This involved transporting the beam to a set of beam position monitors (BPMs) at the end of the H line, and then producing a minimum spot in the X and Y axis at the first BPM. For a variety of reasons, we have not yet attempted to use the control system to tune the source or the klystron themselves.

Argonne's ATLAS is a heavy-ion facility whose main purpose is to conduct experiments using isotopes of a wide variety of single elements. Ions can be generated from a high voltage platform and accelerated by the PII accelerator, or from a second platform and accelerated by a large tandem VandeGraf accelerator. A single beam line transports ions from either source down to a target area in one of many experimental lines.

At ATLAS, our tuning experiments were directed to the PII line between the high voltage platform and the PII accelerator. Ions leave the platform in a stream, are

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transported through a short section of beam line, through an achromatic bend which turns the beam 180°, and then through a section designed to chop and bunch the beam into packets and prepare it for the PII accelerator.

A standard tuning procedure for the PII linac breaks control into four sequential parts: tuning the PII0 line, tuning the PII1 achromat, tuning the PII2 beam line, and then refining the entire tune to produce proper beam conditions at the exit to the PII linac. Tuning procedures for ATLAS are similar to those at ATF. The existence of faraday cups and wire-scanning profile monitors, as well as a shortage of tuning elements, caused the full beam tuning to differ significantly. Our task was to port the control system from the ATF to ATLAS and tune the entire PII beam line.

3 FIRST STEPS AT BROOKHAVEN

To steer through the accelerator, it is required to put the beam on center in order to maximize beam intensity and minimize distortions of beam structure. This task is particularly challenging because of the lack of diagnostics inside the accelerator, making the task of correct steering wholly dependent on metrics of the beam's quality as it exited the accelerator.

We used a variety of algorithms during steering optimization. These employed an evaluation function combining metrics of beam intensity, spot size, and beam structure based on data from a profile monitor after the accelerator. Algorithms included two knob hill climbing, gradient descent, and a genetic algorithm.

The two knob hill climbing algorithm achieved tuning results that were comparable to, and in some cases exceeded, the best human tuning efforts. A key to the successful application of these algorithms was the proper sequencing of tuning actions. Heuristics derived from human experts proved effective in selecting the next tuning element and action for the tuning sequence.

The second task at Brookhaven was to steer as well as possible through a set of quadrupole magnets. A beam that passes through a quadrupole magnet off center is steered to a degree proportional to the magnetic field strength and magnitude of the offset. This is undesirable since quadrupoles are used primarily for focusing. The control system was generally more successful at this task than human operators. Minimization of quadrupole steering requires a tedious repetition of steps, including manipulation of quadrupole field strengths after each adjustment of steering magnets to measure the strength of quadrupole steering. Humans exhibit little patience for the number of steps required to effectively perform this task, and as a result, often do an inadequate job.

By the time of our last visit to Brookhaven in March 1997 we were able to build individual subsystems to perform each of the required control tasks at a level of performance comparable to that of the human operator. At the time what we lacked was a methodology for coordinating the sequencing of control operations, i.e., for executing a control *plan*, that would take the beam from the source to the FEL.

4 PORTING TO ARGONNE

The primary effort in porting the PAL from the ATF to ATLAS was in modifying Vsystem channels [3] encoded in various objects to point to appropriate values in the ATLAS control database. Similarities between magnet types were reflected by similar channel structures between the facilities. We added new classes to the PAL [2] for Faraday cups and slits, and modified existing classes for profile monitors and steering, quadrupole, and dipole magnets. We estimate that porting the control system was accomplished in approximately one person week of programming time.

5 NOISE HANDLING

Noise is significant in inhibiting effective beam tuning at ATLAS, where the difference between peak intensities of two beam profiles taken in series can exceed 50%. Background noise in a single profile or pulse is high, causing simple feature detection algorithms to fail. Human operators ignore noise without use of conscious thought. Experienced tuners understand the difference between incidental beam loss due to aberration and recurring loss from source instabilities. Experts are good at identifying relevant features from noisy distributions.

The control architecture does not deal with noise in a single standard way, but divides the problem into various levels based on correspondence between noise frequency and knowledge necessary for its interpretation and filtering. The initial processing of information in the control architecture occurs in the PAL, where data filtration is necessary to respond to higher level beam feature measurement requests. The PAL allows the control system to select from a variety of tools to deal with observed noise. The PAL performs initial averaging of the beam data retrieved from both Faraday cups and profile monitors. Averaging is through software internal to the PAL and PAL manipulation of various device drivers and hardware features. The controller selects an averaging level based on signal to noise ratio versus the time delay necessary for taking extra samples.

To compensate for pulse-to-pulse noise, we implemented a solver-level algorithm for taking measurements based on prediction. The solver worked by tracking control actions performed in succession, and comparing new values to the projected trajectory. The trajectory was defined by a vector of first and second derivatives calculated from changes in control values from changes in beam measurements. This predictive algorithm is simple and works well for well-behaved functions whose measured derivatives offer good local approximations.

6 GOAL REDUCTION AND REACTIVITY

The beam tuning experiments at ATLAS illustrate a control architecture designed to respond to and implement user goals. Goals are given to a high-level controller which decomposes them and delegates action to other controllers. As these units meet conditions outside their locus of responsibility, they request assistance from their parent. Parents coordinate the activity of child controllers based on an understanding of the tasks each can accomplish [1]. The controllers coordinating beam sections implement plans adopted from human experts. Plans are carried out in a reactive manner using the teleo-reactive (TR) paradigm [3].

Two events in our experiments at Argonne were particularly noteworthy. We interviewed the resident tuning [1] expert to learn the proper sequence of actions necessary to tune the PII beamline. This physicist found the TR condition-action rule representation particularly intuitive and was able to directly encode appropriate tuning algorithms. The second was the observation of the control system exhibiting spontaneous adaptive behavior that had not been intentionally preprogrammed. In performing a sequence of focusing actions the control system would regularly backtrack to steering whenever quadrupole steering would cause excessive movement of the beam centroid and a consequent loss of beam transmission.

7 COMPARISONS OF PERFORMANCE

The two knob hill climbing algorithm achieved results that were comparable to, and in some cases exceeded, the best human tuning efforts. A key to the successful application of these algorithms was the proper sequencing of tuning actions. Heuristics derived from human experts proved effective in controlling the selection of the next tuning element and tuning action in the sequence.

During our visit to Argonne in late March we demonstrated the feasibility of a larger scale integration of control components to perform an extended tuning task. The control system used a total of 18 controllers and solvers to tune a sequence of three transport sections. It used four teleo-reactive controllers [3], corresponding to the three sections of the beamline and a supervisory controller, to orchestrate the sequence of control actions and to alternate back and forth between control and diagnostic elements in different sections. On two separate days of testing, and under somewhat different beam conditions, this system achieved beam transmission levels equaling or exceeding the best tunes of human operators in roughly comparable amounts of time (Table 1). In every case, human operators could not improve the tune achieved by the control system, indicating that the control system had found each time at least a local optimum.

Control Element	Our Tune	Operator Tune
STP001_X	-0.65	-0.69
STP001_Y	-0.20	-0.14
QDP001_X	4.09	3.91
QDP001_Y	4.29	4.02
STP002_X	0.05	0.07
STP002_Y	-0.10	-0.12
Transmission	3.55 mA	3.65 mA
PMP001 Sigma_X	3.0513	
PMP001 Sigma_Y	5.3918	

Table 1. Comparing Control System and Operator Tunes at Argonne's ATLAS Facility[1].

8 SUMMARY

Over the past two years we have used more than four weeks of beam time running experiments at Brookhaven and Argonne. The result of this effort was construction of individual control components capable of a single tuning task such as producing a waist in the beam or minimizing steering through a sequence of quad magnets. In almost every case, performance achieved in these individual tuning tasks was comparable to the best tunes achieved by human operators. A good portion of our more recent effort has been spent coordinating the activity of these control subsystems to adaptively execute sustained sequences of control actions of the type required to tune the entire accelerator from source to target. At present, experiments using a teleo-reactive mode of execution have been very successful and suggest that this architecture may be well suited to the kind of control coordination demanded by the dynamic nature of the accelerator tuning task.

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