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BAYESIAN OPTIMIZATION FOR BEAM CENTROID CORRECTION AT ISAC*

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Abstract

Beam tuning in a post-accelerator facility such as TRIUMF's Isotope Separator and ACcelerator (ISAC) involves a considerable amount of overhead and often leads to tunes which diverge from the theoretical optimum for the system, introducing undesirable effects such as aberrations or chromatic couplings. Bayesian Optimization for Ion Steering (BOIS) has been developed and tested to perform centroid corrective steering, after the transverse optics have been set to theory, in a method which is fully online and easy to deploy. Naïve multi-objective adaptations, scaleBOIS and boundBOIS have been introduced to perform corrective transverse steering with minimal transverse fields . Tests in the low-energy electrostatic transport beamlines at ISAC I performed comparably to human operators. This work holds promise for enhancing the efficiency and reliability of beam delivery via autonomous tuning methods, supporting TRIUMF's scientific mission.

INTRODUCTION

The BOIS algorithm can perform online centroid correction of non-space-charge dominated Rare Isotope Beams (RIBs). It has been developed and used at TRIUMF's ISAC facility [1, 2] which produces RIB by proton bombardment of targets [3], to generate a variety of radionuclides through processes including spallation [4], fragmentation [5], and to a limited extent, fission [6]. At ISAC, tuning procedures have been performed manually by trained operators who tune the many elements in a beamline while monitoring transmission on a downstream Faraday cup (FC). Recent work has developed a high-level application: Model Coupled Accelerator Tuning (MCAT) [7] which involves controlling the beam envelope by parallel modeling of the optical system using the TRANSOPTR linear envelope code [8].

The presented algorithm then consequently tunes the steerers for beam centroid correction. The BOIS approach exclusively requires online data and matches the ability of expert operators by achieving comparable transmission levels within similar time frames. Alternative versions of this framework are presented, to favor solutions that minimize steering and avoid large transverse fields and excursions.

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BAYESIAN OPTIMIZATION

Bayesian Optimization (BO) is a black-box optimization algorithm, suitable for noisy systems with expensive function evaluations [9]. In the simplest case, our objective function takes in the different steerer values and returns the current at a downstream FC. BO models the objective function using a faster to model mathematical surrogate (prior) - usually a Gaussian Process (GP) model. It then uses an acquisition function on this prior to select the next sampling point, aiming to balance *exploitation* of the expected maxima, and *exploration* in areas of higher uncertainty. Figure 1 illustrates this in a simple 1D case. Within the BO framework, our method uses a Upper Confidence Bound (UCB) acquisition function [10] , defined as:

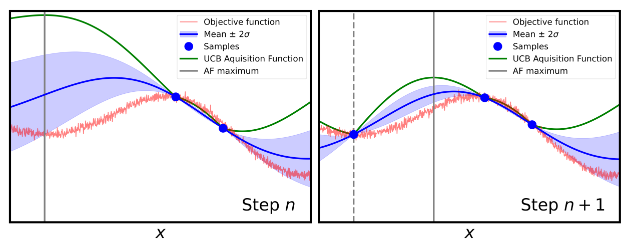

Figure 1: Considering an unknown objective function (noisy red) and some known data samples (blue dots) BO builds an acquisition function α (green) to sample it further and creates a probabilistic model (blue line and shaded area for 2σ confidence bounds). The cartoon shows two consecutive steps: the maximum of the acquisition function at step n, which guides the next sampling point at step $n+1$.

$$UCB(\mathbf{x}) = \mu(\mathbf{x}) + \sqrt{\beta}\sigma(\mathbf{x}) \quad (1)$$

where a parameter β can explicitly balance exploration or exploitation with respectively values of $\beta \ll 1$ or $\beta \gg 1$. We found that a slight focus on exploration is suitable for our problem, with $\beta \in [2, 5]$.

A GP is a collection of random variables, every finite set of which adheres to a joint Gaussian distribution, this offers a flexible approach to model an unknown objective function. The kernel encodes assumptions about the smoothness and variability of the GP; here we choose a Matèrn Kernel [11] with smoothness 5/2, corresponding to a function which is twice differentiable. The equation is:

$$k(x, x') = \sigma^2 \left(1 + \frac{\sqrt{5}r}{l} + \frac{5r^2}{3l^2}\right) \exp\left(-\frac{\sqrt{5}r}{l}\right). \quad (2)$$

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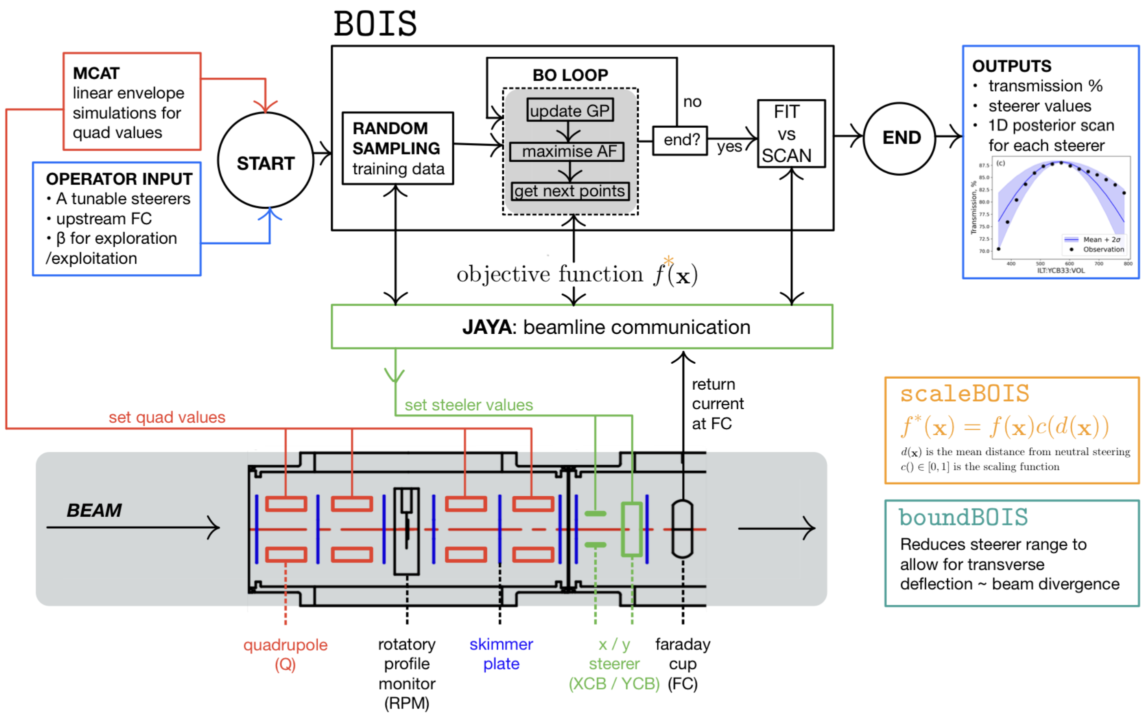

Figure 2: Framework showcasing the intended use of BOIS.

Here the length-scale parameter l is determined using an inverse gamma distribution GP prior of the form:

$$p(x|\alpha, \beta) = \frac{\beta^{\alpha}}{\Gamma(\alpha)} x^{-\alpha-1} e^{\frac{-\beta}{x}}, \tag{3}$$

which gets updated at every BO step, and where we worked with concentration parameter $\alpha = 3$ and rate parameter $\beta = 6$.

METHODS: BOIS

Given the description of BO and the model choices above, the BOIS framework is outlined in Fig. 2. The optimizer in general uses $2d + 1$ random sampling points, where d is the number of variables, or steerers, to then build the GP model and proceed with the optimization step, which continues until the current increase is not significant. In the end, the performance of the optimizer is assessed via 1D posterior scans: each of the steerers (dimensions) is scanned around a neighborhood of the optimized value while keeping the rest constant at their optimum values, and this is compared to the GP posterior.

ISAC beamlines are designed [12, 13] with transverse acceptances of 600 μm, while beam emittances are typically around 30 μm. Various solutions with different beam misalignements can therefore achieve comparable transmission levels, and BOIS could find a solution that produces beam which isn't well centered at the FC. While human operators would not be able to manually aim for less steered solutions, a model can account for this. For this work, we tested two naïve solutions, which are simpler to implement and less computationally intensive than a formal multi-objective treatment to find the Pareto front [14].

scaleBOIS employs a non-linear scalarization approach by utilizing a super-objective function that modifies the traditional objective (i.e. optimizing the current at an FC). The original objective function is scaled by a factor $c \in (0, 1)$, with $c = 1$ indicating a beamline section with neutral steering. The scaling function uses the normalized mean steering deviations from neutral for each steerer $s(x)$ as its input. We have achieved optimal results with a quadratic scaling function:

$$c(\mathbf{x}) = -ps(\mathbf{x})^2 + 1 \tag{4}$$

and choosing a penalization parameter of $p = 1/4$.

boundBOIS limits the input space and for each steerer allows a maximum deflection of ± 2 mrad, which is in the order of the beam divergence. To impose a bound on the deflection angle, the limit on steering voltage scales with beam energy.

RESULTS AND DISCUSSION

Beam was transported through 30 meters of beamline, including from the mass separator through the low-energy transport section and polarizer [15] at ISAC-I, as well as Offline Ion Source (OLIS) beam through the RFQ [16] and accelerated into the MEBT section. Beam compositions and energies varied depending on availability at time of testing, specifically were $^{7}Li^{+}$, $^{12}C^{+}$, and $^{22}Ne^{4+}$. Standard BOIS, as

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well as scaleBOIS and boundBOIS, were all shown to be effective as operators, in terms of transmission and time.

Table 1: Transmission (tx) along Sections of the IMS to Polariser Beamline, Comparing BOIS and Operator Performance

Section (FC-FC)	Section Length (m)	Used / tot Steerers	Operator tx (%)	BOIS tx (%)
IMS:14 - IMS:34	9	13/13	80	73
IMS:14 - IMS:34	9	4/13	80	89
IMS:34 - ILE2:1	15	17/21	95	95
ILE2:1 - ILE2:11	3	4/4	94	91
ILE2:11 - ILE2:19	4	7/7	73	75

The beamline from the ISAC mass separator (IMS) to the polarizer was split into 4 sections, and $^{7}Li^{+}$ beam at 25 keV was optimized using BOIS. Table 1 displays the transmission achieved from the algorithm, with reference to operator transmission. The section from IMS:FC14 to IMS:FC34 includes a set of slits after the first steerers; with this knowledge an operator would use the upstream steerers. We artifically implant this information into the algorithm which achieves better transmission in less time (due to lower number of variables/inputs).

The two different steering-minimizing methods, and a combination of them, were tested using a $^{22}Ne^{4+}$ beam from the Multicharge Ion Source (MCIS), as shown in Fig. 3. Table 2 summarizes the steering. The classic BOIS runs explore the whole parameter space, and find solutions where steering angles are larger (at all steerers but ILT:XCB49). The alternative options find solutions with less steering, and from Table 2 using boundBOIS or a combination of scale+boundBOIS show the least final steering. In the presented run scaleBOIS reduced steering negligibly but it did lower the steering when used in combination with boundBOIS.

Table 2: Summarized results from the run displayed in Fig. 3. Values calculated as the absolute value mean of all steering applied. Results are only for one run of data.

BOIS type	mean abs final steering angle (mrad)
BOIS	1.05
scaleBOIS	1.003
scale+boundBOIS	0.61
boundBOIS	0.78

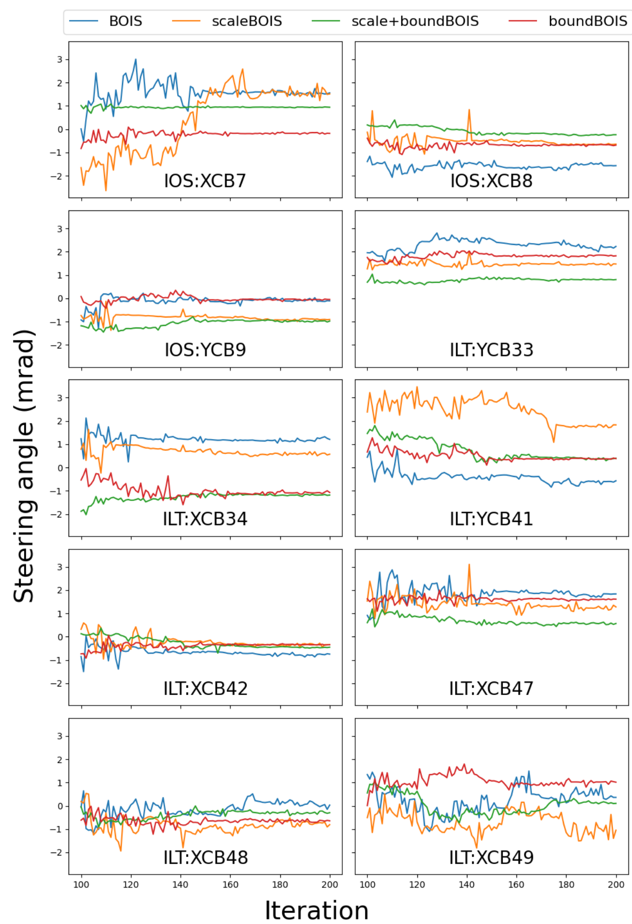

Figure 3: Angles explored by BOIS for 10 consecutive steerers from OLIS to the RFQ injection. We compare classic BOIS and different steering reducing methods: scaleBOIS, boundBOIS and a combination of both. The beam used is $^{22}Ne^{4+}$, with a source bias of 22.48 kV. All tests used $\beta = 4$.

CONCLUSION

Bayesian optimization has been applied to beam centroid steering in a method which can find an optimal solution in relatively few function evaluations, while accounting for noisy data. The scaleBOIS and boundBOIS adaptations have been able to optimize steering for a reduced field solution by reducing the multi-objective problem to a single-objective, and using both methods shows to be most effective. BOIS performs comparably to human operators. Current and future developments intend to expand the usage of the method in the ISAC facilities and include high-energy (magnetic) steering, and eventually become operational standard.

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