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# A MULTI-VARIABLE APPROACH TO MID-RANGING CONTROL FOR UNIFIED OPERATION OF FAST AND SLOW CORRECTORS IN FAST ORBIT FEEDBACK SYSTEM *

P. Kallakuri† and N. Sereno
Advanced Photon Source, Argonne National Lab, Lemont USA

*Abstract*

Advanced Photon Source Upgrade (APS-U) Fast Orbit Feedback (FOFB) system uses 160 fast and 160 slow corrector magnets to stabilize orbit measured at 560 Beam Position Monitors (BPM). We plan to operate both fast and slow correctors in a unified feedback algorithm at 22 kHz correction rate. Mid-ranging control is a proven approach for feedback systems with two manipulated inputs each exerting distinct dynamic effects to regulate a single output. This method resets the fast input to its chosen DC setpoint and proves beneficial when cost of fast input is more than the slower one. Unified operation of fast and slow correctors is a fitting application to mid-ranging concept which is well founded for two input one output systems. In this work, based on the cross-directional nature of the FOFB system we developed a multi-variable approach to mid-ranging control. It can be applied to FOFB with multiple fast and slow correctors, and multiple BPMs. Performance of proposed scheme is tested in simulations with APS-U FOFB prototype model in MATLAB. The feedback loop with fast and slow correctors is stable with mid-ranging algorithm, and the fast corrector drives effectively tracked set-points.

## INTRODUCTION

A new fast orbit feedback system is under development for the APS Upgrade, where the expected beam sizes are 13 µm and 2.8 µm for horizontal and vertical planes respectively with 1 kHz target unity-gain bandwidth. A distributed network of 20 feedback controllers is used to compute orbit corrections at 22 kHz, and the system will use 560 BPMs, 160 fast and 160 slow correctors. Previously at APS, orbit feedback was developed as separate fast and slow systems with different sampling rates, and a feed-forward mechanism is implemented to deal with the dead-band problem. The slow system predicts orbit at its next iteration and transfers it as a new reference to the fast system [1]. At NSLS2, SOLEIL the fast and slow orbit feedback algorithms are operated together by combining the orbit prediction algorithm with the DC download algorithm [2, 3]. For APS-U we are investigating different methodologies to operate both fast and slow correctors in a single feedback algorithm at 22 kHz correction rate. Unified operation of fast and slow correctors is a fitting application to mid-ranging concept. The term mid-ranging control typically refers to the class of control problems where two or more control inputs i.e., actuators are manipulated to control one output [4, 5]. The inputs differ in their dynamic effect on the output and relative cost of manipulating the fast input is normally more than the slow input. The control scheme seeks to manipulate all inputs upon an upset but then gradually resets or mid-ranges the fast input to its DC set-point. This concept is extensively established for Two Input Single Output (TISO) configuration, where one fast actuator and one slow actuator are manipulated to control one process output. In FOFB R&D for DIAMOND-II [6] generalized singular value decomposition is used to simultaneously diagonalize the systems formed by slow and fast actuators, and mid-ranging concept is used in the control resulting TISO systems. In this work, based on the cross-directional nature of the FOFB system we developed a multi-variable approach to mid-ranging control. It can be applied to FOFB with multiple fast and slow correctors, and multiple BPMs. Effectiveness of the proposed approach is tested in simulations using APS-U FOFB prototype model in MATLAB/Simulink.

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† pkallakuri@anl.gov

## PROPOSED MULTIVARIABLE APPROACH TO MID-RANGING CONTROL

Schematic of closed loop orbit feedback system with fast and slow correctors used for beam stabilization is shown in Figure 1. We consider the case where the BPMs are common to both fast and slow correctors. Assume feedback configuration has $m$ BPMs, $n_f$ fast correctors and $n_s$ slow correctors. The fast and slow corrector drive vectors are denoted by $\Delta c_f$ and $\Delta c_s$ respectively. $\Delta p$ is the measured BPM position vector. Open loop model of the orbit feedback

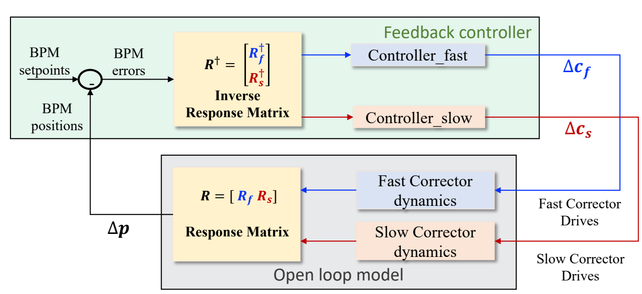


Figure 1: Closed loop orbit feedback configuration with fast and slow correctors.

system is a two-dimensional process, since the variations are continuous in both time and space. There are power supply transients, DC ohmic losses in the magnet coils, and eddy current loses in the walls of the vacuum chamber accounting to open loop dynamics. The corrector magnets are spatially

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coupled i.e., steady state BPM response to the corrector magnet perturbations is a function of beam longitudinal position. This coupling is described by spatial Response Matrix (RM). The two dimensional nature of the open loop model allows us to apply cross directional control where the spatial and dynamic components of the actuator response can be separated. Hence the open loop system $P[z]$ can be modeled as a product of dynamic transfer function $H[z]$ and response matrix $R$.

$$P[z] = R \cdot H[z] \tag{1}$$

With fast and slow correctors operating together,

$$R = \begin{bmatrix} R_f & R_s \end{bmatrix} \tag{2}$$

$R_f$ is response matrix from fast correctors to BPMs, and $R_s$ is response matrix from slow correctors to all BPMs.

$$H[z] = \begin{bmatrix} H_f[z] & 0 \\ 0 & H_s[z] \end{bmatrix} \tag{3}$$

$H_f[z]$ represents dynamics of the open loop system from fast correctors to all BPMs, $H_s[z]$ represents dynamics of the open loop system from slow correctors to all BPMs. Relation between input corrector drives to BPM spatial responses can now be written as,

$$\begin{bmatrix} R_f & R_s \end{bmatrix} \begin{bmatrix} H_f[z] & 0 \\ 0 & H_s[z] \end{bmatrix} \begin{bmatrix} \Delta c_f \\ \Delta c_s \end{bmatrix} = \begin{bmatrix} \Delta p \end{bmatrix} \tag{4}$$

The controller for this open loop configuration will be a series combination of Inverse Response Matrix (IRM) $R^\dagger$ and dynamic controller. The inverse response matrix is concatenation of rows corresponding to fast and slow correctors as shown below.

$$R^\dagger = \begin{bmatrix} R_f^\dagger \\ R_s^\dagger \end{bmatrix} \tag{5}$$

In general case shown in Figure 1 the input to both fast and slow feedback loops is the BPM error. The fast and slow dynamic controllers generate corrector drives to correct the BPM error as shown below.

$$\Delta c_f = K_f[z] \cdot R_f^\dagger \cdot \Delta p \tag{6}$$

$$\Delta c_s = K_s[z] \cdot R_s^\dagger \cdot \Delta p \tag{7}$$

In mid-ranging case shown in Figure 2 input to fast feedback loop is the BPM error, and input to slow feedback loop is the fast corrector drive error. The fast dynamic controller generates fast corrector drives to correct the BPM error using equation (6) as in general case. We derive the equation to use in slow feedback loop computations to generate slow corrector drives to correct the fast corrector drive error.

$$\Delta c_s = K_s[z] \cdot R_s^\dagger \cdot R_f \cdot \Delta c_f \tag{8}$$

The IRM used for fast feedback loop is $R_f^\dagger$ and the IRM used for slow feedback loop is,

$$\tilde{R}_s^\dagger = R_s^\dagger \cdot R_f \tag{9}$$

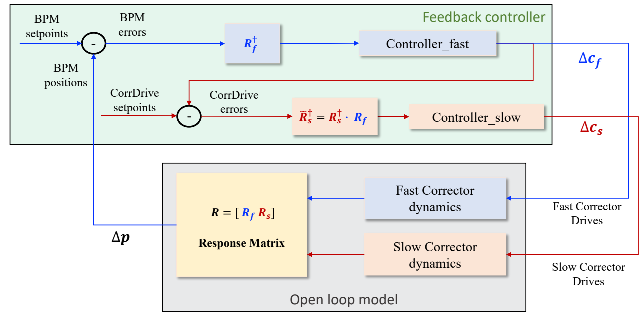

Figure 2: Closed loop unified orbit feedback configuration using proposed mid ranging concept.

## SIMULATION STUDY

Prototype of APS-U fast orbit feedback system [7] with 22.6 kHz sampling rate is implemented at APS sectors 27 and 28. This system integrated APS-U prototype feedback controllers, fast corrector power supplies, and BPM electronics with original APS storage ring correctors and vacuum chamber. The feedback configuration has 16 BPMs, 4 fast and 4 slow correctors. Discrete transfer function model of the open loop fast corrector dynamics $H_f[z]$ is estimated using beam based measurements, and closed loop simulation model is validated against measurements [8]. Discrete transfer function representing slow corrector dynamics $H_s[z]$ is also modeled based on beam based measurements.

In this work we used prototype system dynamic model for initial simulations. We plan on replacing the open loop model with APS-U dynamics when the upgraded system is ready. Multi Input Multi Output simulation model representing our orbit feedback with mid-ranging concept in Figure 2 is developed in MATLAB/Simulink. The top level window of the Simulink model with 4 BPMs, 2 fast and 2 slow correctors is shown in Figure 3. Prototype open loop discrete transfer function models $H_f[z]$ and $H_s[z]$ are used to represent fast and slow corrector dynamics respectively.

We simulated closed loop feedback responses for offset bump applied to 4 BPM set-points and DC set-point applied to 2 fast corrector drives. BPM set-point signal with 20 µm, 30 µm step inputs, and fast corrector set-point signal with 0.1 A and 0 A DC set-points are shown in Figure 4. Closed loop with proposed mid-ranging configuration is stable when both fast and slow correctors are used in single feedback algorithm. We used PID_fast [$K_p = 0.02$, $K_i = 0.09$, $K_d = 0.002$] and PID_slow [$K_p = 0.02$, $K_i = 0.01$, $K_d = 0.01$] which are tune for closed loop stability. The steady state BPM errors are zero after the initial transients at the step changes. The fast correctors are acting in the transient state and reached their DC set-points in steady state. Slow correctors will take over the correction in the steady state and the slow corrector drives are larger when the fast corrector DC set-points are smaller. This algorithm gives us flexibility to design fast and slow corrector contribution for optimal use of drive resources.

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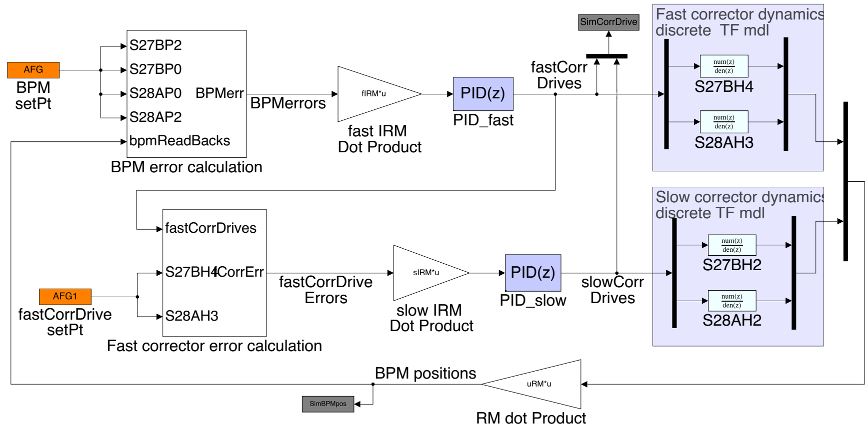


Figure 3: Mid ranging control simulation model in MATLAB/Simulink.

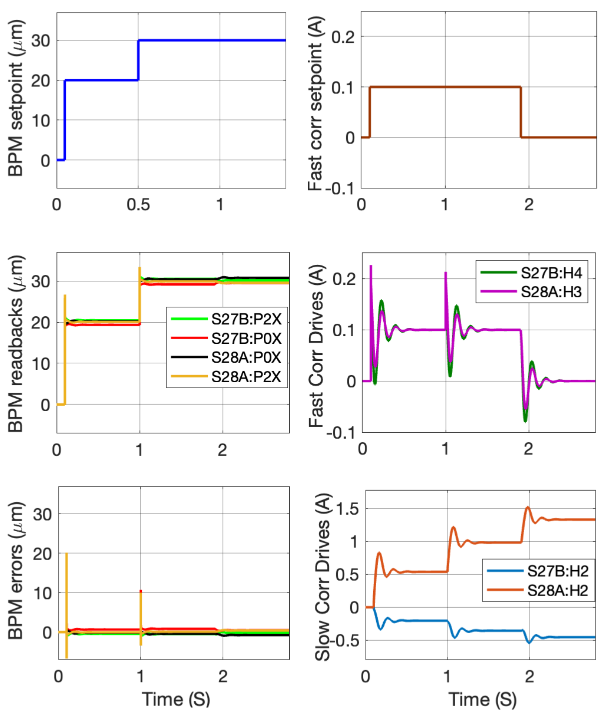


Figure 4: Simulated BPM error and corrector drive responses for BPM and fast corrector DC set-point inputs.

The controller gains used in these simulations are manually tuned for closed loop stability not for optimum performance. We observed that BPM position and corrector drive responses are under damped with large overshoots present in fast corrector drive transients. As the effectiveness of the approach is verified in these proof-of-concept simulations, our next step is to improve the closed loop performance. We are exploring model based controller design methods that are applicable to multivariable, mid-ranging feedback configurations.

## CONCLUSIONS

We developed a multi-variable approach to mid-ranging control that can be applied to FOFB system with multiple fast and slow correctors, and multiple BPMs. This algorithm also gives flexibility to design fast and slow corrector contributions for optimal use of actuator drive resources. Performance of proposed scheme is tested in simulations with APS-U FOFB prototype model in MATLAB/Simulink. The feedback loop with fast and slow correctors is stable with mid-ranging algorithm, and the fast corrector drives effectively tracked set-points. We are working on extending the simulation model to full APS-U configuration and plan to replace the prototype open loop dynamics with APS-U model. Also, the simulation model is being used to investigate advanced controller design algorithms applicable to multi variable mid-ranging feedback systems.

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