A SLIDING MODE CONTROL APPROACH FOR PHOTON BEAM STABILITY AT THE SIAM PHOTON SOURCE

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Abstract

This paper presents the enhancement of photon beam position stability at the Siam Photon Source (SPS) through a real-time feedback control system based on a Sliding Mode Control (SMC) algorithm. The proposed system employs Photon Beam Position Monitor (pBPM) measurements within a global orbit feedback loop to minimize beam position fluctuations. The SMC-based Fault-Tolerant Control (FTC) algorithm enhances system robustness by effectively compensating for disturbances, and actuator faults, thereby maintaining stable beam conditions under various operational scenarios. Experimental results demonstrate that the integration of SMC significantly reduces photon orbit deviations and improves synchrotron radiation quality. By strengthening reliability and adaptability, the developed control system ensures precise beam positioning, making the SPS more dependable for scientific and industrial applications that demand high beam stability.

INTRODUCTION

The Siam Photon Source (SPS), a 1.2 GeV synchrotron radiation facility operated by the Synchrotron Light Research Institute (SLRI) in Nakhon Ratchasima, Thailand, has served as a national research platform for over two decades. Originally built using components from the former SORTEC synchrotron and continuously upgraded, the SPS supports a wide range of scientific applications in materials science, chemistry, biology, and applied physics. With growing user demand, achieving and maintaining excellent beam stability has become critical for experimental accuracy and reproducibility [1-3].

While electron beam orbit stability has been significantly improved through existing feedback systems, photon beam position stability remains a major challenge, especially in beamlines lacking dedicated photon Beam Position Monitors (pBPMs). Photon beam position is highly sensitive to electron orbit variations, insertion device settings, thermal drifts, mechanical vibrations, and other disturbances. Even small fluctuations can degrade beamline performance and limit experimental capabilities. Conventional hardware solutions, such as installing additional pBPMs, are often limited by space, cost, and integration constraints [4, 5].

To overcome these limitations, this work implements a real-time global orbit feedback system based on Sliding Mode Control (SMC) integrated with Fault-Tolerant Control (FTC). Leveraging the inherent robustness of SMC against uncertainties and disturbances, the proposed controller effectively minimizes photon beam position deviations and compensates for actuator faults using available pBPM measurements.

The remainder of this paper first presents the theoretical foundation of the Fault-Tolerant Sliding Mode Control strategy, followed by the experimental setup, results and discussion, and finally the conclusion.

FAULT-TOLERANT SLIDING MODE CONTROL

FTC maintains acceptable system performance despite faults and disturbances. At the SPS, actuator faults, sensor degradation, thermal variations, and modeling uncertainties can seriously degrade orbit correction. Traditional controllers often lack the necessary robustness, resulting in beam position drift and reduced reliability [6, 7].

To overcome these issues, this work implements a Sliding Mode Control (SMC)-based FTC strategy. SMC is inherently robust as it drives system states onto a sliding surface and keeps the motion there despite bounded uncertainties and disturbances. Combining SMC with FTC enables both disturbance rejection and real-time actuator fault estimation/compensation without needing an exact fault model [6, 7]. This makes it well-suited for the complex, time-varying environment of a synchrotron storage ring.

The proposed framework augments the conventional orbit feedback loop with an online fault estimation scheme. It uses pBPM measurements as feedback signals and generates corrective commands for the corrector magnets via the SMC law. When faults occur, the fault-tolerant component adjusts the control effort to maintain stability and minimize photon beam position deviations.

The next section presents the theoretical foundation of Sliding Mode Control and its extension to the fault-tolerant architecture.

SLIDING MODE CONTROL THEORY

The SMC is a robust nonlinear control technique that has gained significant attention in engineering applications due to its remarkable insensitivity to parameter variations, external disturbances, and model uncertainties. The fundamental concept of SMC is to drive the system states onto a predefined sliding surface and maintain the system motion along this surface through high-frequency switching control action. Once the sliding mode is achieved, the system dynamics become governed by the sliding surface equation, which is independent of matched uncertainties and disturbances, thereby providing strong robustness [8, 9].

This property makes SMC particularly suitable for complex systems such as synchrotron storage rings, where precise beam orbit control must be maintained despite actuator

* Work supported by SLRI
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imperfections, sensor noise, thermal drifts, and other unpredictable disturbances. In this study, the principles of SMC are adopted and extended within a fault-tolerant control framework to enhance photon beam position stability at the SPS [8, 9].

Consider the following linear time invariant (LTI) system:

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{1}$$

where: $x(t) \in \Re^n$ is the state vector, $y(t) \in \Re^p$ the output vector, $u(t) \in \Re^m$ the input control vector, the system matrices are $A \in \Re^{nxn}, B \in \Re^{nxm}$. The matrix B is assumed to have full rank and the pair (A, B) is controllable.

Consider a system which has only matched uncertainty ([8, 9]:

$$\dot{x}(t) \; = \; Ax(t) + Bu(t) + f_m(t, x, u) \tag{2}$$

where $f_m(t, x, u)$: $\Re \, x \, \Re^n x \, \Re^m \rightarrow \Re(B)$ is unknown but bounded and satisfies:

$$\|f_m(t, x, u)\| \; \leq \; k_m\|u(t)\| + \alpha(t, x) \tag{3}$$

where k_m is a known positive constant and $\alpha(\cdot)$ is a known function. Without any loss of generality, the system in Eq. (2) can be transformed into regular form as follows:

$$\dot{x}_1(t) \; = \; A_{11}x_1(t) + A_{12}x_2(t) \tag{4}$$

$$\dot{x}_2(t) \; = \; A_{21}x_1(t) + A_{22}x_2(t) + B_2u(t) + \bar{f}_m(t, x, u) \tag{5}$$

where: $\bar{f}_m$ represent a projection of f_m into the subspace $\Re(B)$, then the following *Euclidean norm* is preserved and satisfied [8, 9]:

$$\left\|\bar{f}_m(t, x, u)\right\| \; \leq \; k_m\|u(t)\| + \alpha(t, x) \tag{6}$$

The switching function $s(t)$ can be presented as:

$$\begin{aligned} s(t) \; &= \; S_1x_1(t) + S_2x_2(t) \\ &= S_2Mx_1(t) + S_2x_2(t) \end{aligned} \tag{7}$$

where: $S_1 \in \Re^{mx(n-m)}$, and $S_2 \in \Re^{mxm}$ is designed matrix such that $det(S_2) \neq 0$, and $M = -S_2^{-1}S_1$. A common choice here, is to let $S_2 = \Lambda B_2^{-1}$ for a non-singular diagonal design matrix $\Lambda \in \Re^{mxm}$, which implies that:

$$S_2B_2 = \Lambda \tag{8}$$

Define a coordinate transformation by:

$$T_s = \begin{bmatrix} I & 0 \\ S_1 & S_2 \end{bmatrix} \tag{9}$$

Therefore, the system can be transformed into new partition as follows:

$$\begin{bmatrix} x_1(t) \\ s(t) \end{bmatrix} = T_s \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} \tag{10}$$

In the following Eq. (10), the system in Eqs. (4) and (5) can be re-arranged as:

$$\begin{bmatrix} \dot{x}_1(t) \\ \dot{s}(t) \end{bmatrix} = \begin{bmatrix} \bar{A}_{11} & A_{12} \\ \bar{A}_{21} & \bar{A}_{22} \end{bmatrix} \begin{bmatrix} x_1(t) \\ s(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \Lambda \end{bmatrix} u(t) + \begin{bmatrix} 0 \\ S_2(t) \end{bmatrix} \bar{f}_m(t, x, u) \tag{11}$$

where: $\bar{A}_{11} = A_{11} - A_{12}M$, $\bar{A}_{21} = M\bar{A}_{11} + A_{21} - A_{22}M$ and $\bar{A}_{22} = MA_{12} + A_{22}$. The proposed control law consists of two components [8, 9]; a linear component and nonlinear or discontinuous component as follows:

$$u(t) = u_l(t) + u_n(t) \tag{12}$$

The linear control component is given by:

$$u_l(t) = -\Lambda^{-1}[S_2\bar{A}_{21}x(t) - (S_2\bar{A}_{22}S_2^{-1} - \Phi)s(t)] \tag{12}$$

where: $\Phi \in \Re^{mxm}$ is any stable design matrix.

The nonlinear component is given by:

$$u_n(t) = -\rho_c(t, x)\Lambda^{-1}\frac{P_2s(t)}{\|P_2s(t)\|} \qquad \text{for} \quad s(t) \neq 0 \tag{14}$$

where: $P_2 \in \Re^{mxm}$ is a S.P.D matrix satisfying the Lyapunov equation:

$$P_2\Phi + \Phi^TP_2 = -I_m \tag{15}$$

and $\rho_c(t, x)$ is any scalar function, which depends *only* on the magnitude of uncertainty, and satisfies:

$$\rho_c(t, x) \; \geq \; \frac{\|S_2\|(k_m\|u_l(t)\| + \alpha(t, x)) + \gamma_c}{(1 - k_m\|B_2^{-1}\|)} \tag{16}$$

In other words, $\rho_c(t, x)$ must be greater than the magnitude of the uncertainty, and γ_c is a positive scalar design parameter. It should be noted here that following the above analysis, the uncertainty is assumed to be matched. For the case when unmatched uncertainty terms can be included in the above analysis [8, 9].

EXPERIMENT AND RESULTS

Experimental Setup

The experimental setup for the SMC-based fault tolerant orbit feedback system was implemented in the SPS control room. A hybrid programming environment integrating MATLAB and LabVIEW was developed to acquire and process real-time data from 20 electron Beam Position Monitors (eBPMs) around the storage ring and 4 photon Beam Position Monitors (pBPMs) located at the front-ends of beamlines No. 2, 4, 6, and 8. Corrective actions were applied through 16 horizontal and 12 vertical corrector magnets.

In this setup, MATLAB performed the main feedback computations, including the SMC law. Meanwhile, LabVIEW was responsible for data acquisition, Ethernet communication via the DataSocket Transfer Protocol (DSTP), and real-time interfacing with the accelerator control system. This hybrid architecture provided seamless real-time data exchange, effective system monitoring, and convenient parameter tuning during system commissioning and experimental testing.

Results and Discussion

The vertical photon beam position monitors (BPMs) at beamlines BL2, BL4, BL6, and BL8 were analyzed to evaluate the effectiveness of the SMC orbit feedback system. Figures 1 and 2 present the beam position behavior without and with the feedback system, respectively.

As shown in Fig. 1, in the absence of the SMC orbit feedback system, the vertical photon beam position exhibits noticeable fluctuations and gradual drift over time across all monitored beamlines. These variations indicate the presence of orbit disturbances caused by factors such as magnet instabilities, thermal effects, and external vibrations. The lack of correction leads to reduced beam stability, which can negatively impact experimental accuracy and consistency.

In contrast, Fig. 2 demonstrates that when the SMC orbit feedback system is activated, the vertical photon beam position becomes significantly more stable. The amplitude of fluctuations is clearly reduced, and the beam position remains tightly controlled around the reference value. This improvement confirms that the feedback system effectively compensates for dynamic disturbances and suppresses orbit deviations.

Overall, the comparison highlights the critical role of the SMC orbit feedback system in maintaining beam stability at the Siam Photon Source. Enhanced stability not only improves the quality of photon delivery but also supports higher precision and reproducibility in beamline experiments. These results validate the implementation of the feedback system as a key component for reliable accelerator operation.

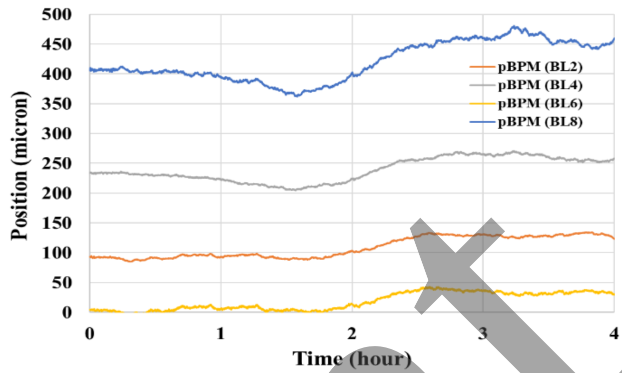

Figure 1: The vertical photon BPM data without the SMC feedback system.

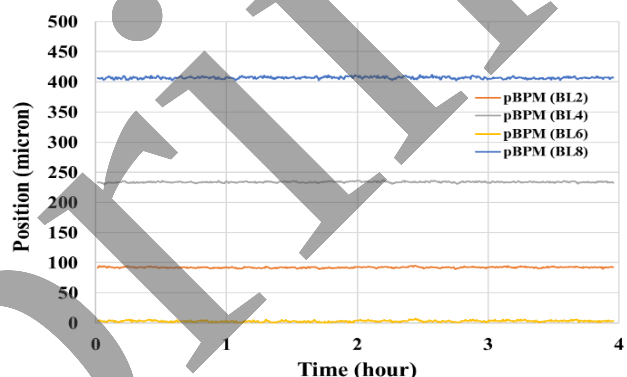

Figure 2: The vertical photon BPM data with the SMC feedback system.

CONCLUSION

This paper successfully demonstrates a Sliding Mode Control (SMC)-based Fault-Tolerant Control system for improving photon beam position stability at the Siam Photon Source. By integrating real-time pBPM measurements into the global orbit feedback loop, the proposed controller effectively suppresses beam fluctuations and compensates for disturbances and actuator faults. Experimental results show significant reduction in vertical photon beam deviations across beamlines BL2, BL4, BL6, and BL8, achieving markedly improved stability. Future work will focus on extending the SMC-FTC to simultaneous horizontal and vertical correction, implementing the controller on a dedicated real-time platform for higher bandwidth, and developing adaptive schemes to achieve even better long-term sub-micron photon beam stability.

ACKNOWLEDGEMENTS

We would like to express our deep appreciation to the Technical Support teams at SLRI for their essential technical support during this project. Special thanks to the machine operators for supporting the experimental runs and to the engineering department for their valuable input in hardware development.

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