PROGRAM FOR AUTOMATIC CONTROL OF BEAM TRANSFER LINES

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The traditional manual tuning of the beam transfer lines becomes inefficient with the increasing of both the beamlines' length and the number of the magnets. That's why computer controlled beamlines are widely used now [1-3]. The set of programs is presented, which can be used for beamline automatic control.

1. Mathematical Formulation of the Problem

Let $A_i$ be the transfer matrix between the monitors $M_i$ and $M_{i+1}$ and $B_i$ be the influence of the correctors on the beam, which are located between these monitors. If $X_i$ is the beam state vector on the $i$ monitor, which is consisted of $r$ and $z$ coordinates and of their derivatives, then one will have

$$X_{i+1} = A_i X_i + B_i U_i, \quad i=0,1,...,n,$$

where $U_i$ is the vector which includes the strength of the correctors and $n$ is the number of the monitors.

Usually we get the coordinates $r$ and $z$ with some errors from the monitors. The observation vector on the $i$ monitor will be

$$Z_{i} = H_i X_i V_i, \quad i=0,1,...,n,$$

where $H_i$ is the matrix for separation of the coordinates from the state vector, $V_i$ is the measurement errors.

Let's discuss some versions of the mathematical formulation of the beamline optimal control versus the sequence of observation and control.

1. It is assumed that after sequential measurements of beam coordinates $Z_{i}$, $i=0,1,...,n$ we need to calculate the control vector $U_k$. If to take the result of minimizing

$$\sum_{i=0}^{n-1} \frac{1}{2} ||X_{i}||_2^2 + \frac{1}{2} \sum_{k=0}^{2} \left( ||U||_2^2 + ||Q||_2^2 \right),$$

with the constraints (1), (2) as a criterion of optimal $U_k$, we shall have a well known problem of optimal regulator [4], where $S, Q$ and $R$ are weighting matrices. Here

$$||U||_2^2 = U_k R_k U_k,$$

Optimal control will be

$$U_k = -L_k \bar{X}_k,$$

where the matrix $L_k$ is a result of Riccati equation solved backward in time

$$L_k = R_k - T_k \left( P_{k+1} + B_k R_k B_k^T \right) A_k,$$

$$P_k = Q + A_k \left( P_{k+1} + B_k R_k B_k^T \right) A_k^T,$$

where $P_n = S$ and $k$ is changed from $n$ to 0. $X_k$ is the estimate of the state vector formed by the Kalman filter [4].

$$X_{k+1} = X_k + P_{j+1} A_j H_j + R (Z_{j+1} - H_j A_j X_k - R_j B_j U_j),$$

$$P_{j+1} = P_j - P_j A_j H_j + (R_j + H_j A_j P_j A_j H_j - R) H_j A_j P_j,$$

where $\bar{X}_k$ is the initial guess of $X_k$ state vector and if more information is available it can be the mean value of $X_k$. $R$ is the noise covariance matrix of $\bar{X}_k$, it shows the uncertainty of the initial guess and during the iteration procedure its diagonal components are decreasing, because the increase of available information reduces the parameter uncertainty. In this algorithm if the apriori information is not sufficient to get the Kalman estimation i.e. the matrices $P_0, R$ and the mean value of $X_0$ are not known, then one can use the sequential least square estimation or optimal estimation of maximal likelihood estimator ($\bar{X}_k=0$ and $P_0=\infty$).

It is important that the calculations structure is the same for all cases. These algorithms are attractive, because they are efficient in the case that there are unknown parameters in matrix $A_j$.

2. From the measurements of $Z_{i}$ on the all monitors one can estimate state vector $X_0$ and after that calculate the optimal control $U_1$.

The estimation of $\bar{X}_0$ one can do with the Kalman filter and the control $U_k$ can be
calculated by the (4), where the sequence of
\[ X_{i+1} = A X_i + B U_i, \quad \tilde{X}_0 - X_0 \] (7)
can be used as \( X_k \).

3. It is easy to get
\[ X = AX_0 + BU, \] (8)
\[ HX = HAX_0 + HB U \] (9)
from (1), (2), where
\[ X = [X_1, X_2, \ldots, X_n]^T, \]
\[ U = [U_1, U_2, \ldots, U_n]^T, \]
\[ Z = [Z_1, Z_2, \ldots, Z_n]^T, \]
\[ H = [H_1, H_2, \ldots, H_n]^T, \]
\[ V = [V_1, V_2, \ldots, V_n]^T. \]
The aim of optimal control is to have
\[ ||HX||^2 \leq \alpha \text{ if } ||HX|| \geq 0, \text{ then} \]
\[ HAX_0 = HB U, \quad Z = HAX_0 + V, \]
\[ Z = HB U + V. \] (10)

If we consider (10) as linear model of observation of \( Z_i \) measurements, the optimal estimation of \( U \) can be realized with the sequential Kalman estimator.

We consider, that the least approach of optimal control formation must be most efficient practically in spite of its heuristical form, because it is simple in calculation and the a priori information about \( X \) matrix can be easily improved experimentally by the simple calculation.

2. The Structure of the Program

A set of programs is written for the investigation of the estimation and control algorithms. The program consists of several modules, each of them can be operated separately in real time scale.

The "TRANSPORT" [5] formalism is used here. The structure of the beamline is the input file of the program. It can include bending magnets, quadrupoles, synchrotron magnets, correctors. The tilts of the elements are given by the rotation matrix. The corrector is assumed to be an element which gives a kick in the middle.

It is possible to simulate the disturbances of the elements by vertical and horizontal kicks in the middle of each element. The program consists of following modules:
- the module of beam trajectory simulation;
- estimation of the beam parameters \( X, X', Z, Z', \Delta P/P \);
- the control module.

This module can operate separately using the structure file of the beamline. The control module is consisted subroutines of optimization based on the least square method (ordinary and sequential) and the subroutines for making local corrections.

3. The Results of Simulations

The efficiency of the algorithms are investigated on the electron beam transfer line from PETRA to HERA. The beam line is about 219 meter and is consisted of 19 bending magnets and 19 quadrupoles. The control system includes 20 monitors and 22 correctors: 12 vertical and 10 horizontal. Almost all the monitors and the correctors are attached to the quadrupoles. The tilts of bending magnets and the quadrupoles cause the coupling of horizontal and vertical motion [6].

The process of measurement from the monitor is simulated with help of the beam trajectory simulation module and random number generation program. The normal distributed noise with 0 mean value and variance of 1 mm is used (the accuracy of the monitors is of 0.5 mm).

The beam initial parameters estimation quality and efficiency of control algorithms are investigated.

1. The beam parameters estimation.

The sequential maximal likelihood filter is used. The general results of the simulation are:
- the estimation convergence is not sensitive to the initial elements of covariance matrix \( P_0 \); if their are chosen to be \( 10^5 \), \( 10^6 \) order of magnitude of the \( \tilde{X}_0 \) and the initial values of \( X_0 \) are 0;
- after 10 iterations estimated values are in the range of tolerable accuracy.

The typical process of parameters
2. The optimal control estimation.

The distorted trajectory is the result of not 0 initial \( X_0 \) values and/or disturbances of the beamline elements. The estimation is done by the algorithm 3 without \( X_0 \) estimation using sequential least square algorithm (maximal likelihood).

The results of the simulation show that after 5 iteration the corrected trajectory is in the range of tolerable accuracy.

The typical results of the control algorithm are shown in fig.6, 7. Here the trajectories before and after correction are presented.

References


