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Model-based Tracking for Agent-based Control Systems in the Case of Sensor Failures

R. P. Yadav[1] P. V. Varde[2] P. S. V. Nataraj[3] P. Fatnani[1] C. P. Navathe[1]

[1]Accelerator Control Section, Accelerator Control and Beam Diagnostics Division, Raja Ramanna Centre for Advanced Technology, Indore 452013, India

[2]Life Cycle Reliability Engineering Lab, Safety Evaluation and Manpower Training and Development Section, Bhabha Atomic Research Centre, Mumbai 400085, India

[3]Inter Disciplinary Program in Systems and Control Engineering Group, Indian Institute of Technology Bombay, Powai, Mumbai 400076, India

Abstract: The study on artificial intelligence (AI) methods for tuning of particle accelerators has been reported in many literatures. This paper presents tuning method for agent-based control systems of transport lines in the case of sensor/actuator failures. The method uses model-based tracking concept to relax the demand on sensor data. The condition for successful operation of the stated scheme is derived, and the concept is demonstrated through simulation by applying it to the model of microtron, transport line-1 and booster of indus accelerator. The results show that this approach is very effective in transport line control during sensor/actuator failures.

Keywords: Agent, agent-based control, model-based tracking, transport line control, artificial intelligence (AI).

1 Introduction

There are over 50 synchrotron radiation source machines operating throughout the world to fulfil the requirements of scientific community ranging from chemistry, biology, physics, material science, medicine to industrial applications. Driven by the need to increase the beam brilliance and decrease beam emittance, these sources have experienced a continuous increase in their size and complexities. This has encouraged control system engineers to develop improved methods of monitoring and control. To enhance the plant operational reliability, availability and safety, the use of artificial intelligence (AI) methods in operator support/advisory systems of accelerator controls have been proposed[1−7]. The intelligent agent system was first introduced by Jennings et al.[8] for diagnosing faults in proton synchrotron facility at European organization for nuclear research (CERN) which was based on architecture for cooperative heterogeneous on-line systems (ARCHON). Since then, different architectures have been proposed for agents in accelerator environment[9−15]. All of them use the distributed, hierarchical architecture for control combining heuristic, knowledge-based and conventional control methods. These agents use hybrid architecture by integrating a variety of reasoning, search, and pattern recognition methodologies from artificial intelligence research. Both neural network and genetic algorithm (GA) based computational intelligence methods were analyzed alternatively by Schirmer et al.[16] for optimising transfer efficiency of electrons from booster synchrotron to electron storage ring. Besides, the GA based approach reported the successful original beam position recovery and reproduced the real injection efficiency to some extent successfully. It uses the transport line model along with the feedback from various beam position monitors (BPM) installed in the transport line to solve the tuning problem. However, it does not consider the case of BPM failures that may occur during the system operation thereby disrupting the optimization process.

Scheme in [17] shows the advantage of agent′s decision making based on the tracking of moving target while avoiding collision with moving obstacles and other agents. Yan et al.[18] extended this work by applying constraints on input and formulated a local and dynamic optimal algorithm. Here, each agent exchanges information only with its neighbours with optimization implemented at each update cycle. Model based tracking (MBT) is a well known principle, primarily used in the field of image processing[19−21] for reconstruction of three dimensional object information (position and orientation) from two dimensional image of the scene. In this technique, the model consists of precise three dimensional geometrical representations of known object (mainly vehicle), which can be placed in arbitrary positions and orientations, together with a carefully constructed camera model and scene model. Using this model, and given provisional position and orientation, the three dimensional object is then projected onto the two dimensional image plane and a goodness-of-fit score is obtained by comparing the modelled features with the acquired image. A search in position-space and orientation-space is then used to maximize this evaluation score. At each position and orientation in this search, the model is re-instantiated onto the scene and a new goodness-of-fit score is evaluated. Once a maximum score is found, the three dimensional position and orientation of the object is known and is used to predict a provisional position and orientation for the same object in the next frame of the scene. Thus, by having position of an object in the initial frame, it is possible to track that object in subsequent frames along with its location and direction of travel in three dimensions.

Inspired by the success of the agent-based accelerator tuning method and the fact that the sensors and actuators sometimes fail during operation, this paper presents

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methods for tuning of accelerator transport lines under limited sensor/actuator failure cases for agent based accelerator control systems. Plans for transport line tuning under various BPM failure conditions for goal-based intelligent agent with modular architecture have been formulated using the concept of model based tracking. Model-based tracking concept is used to track the beam parameter vector at the start of transport line using the injection current as feedback instead of data from beam position monitors. This allows the agent to correct injection, even in the absence of all BPM data. The effectiveness of the proposed scheme is demonstrated through simulation. Particularly, the problem of beam position variation at source is simulated for agent architecture with proposed plans applied to the indus accelerator model comprising of microtron output, transport line-1 (TL-1) and booster.

Section 2 presents a brief overview of the indus-1 accelerator facility located at Raja Ramanna Centre for Advanced Technology (RRCAT), Indore, India. In Section 3, the layout of TL-1 is given. Section 4 discusses the overall system simulation. In Section 5, the proposed transport line (TL) tuning methods are given. In Section 6, the simulation results are presented. Finally, the conclusions are given in Section 7.

Notations.

x: Horizontal direction.

y: Vertical direction.

x': Angle with horizontal.

y': Angle with vertical.

e_x: Emittance in horizontal plane.

e_y: Emittance in vertical plane.

δ_x: Dispersion in horizontal plane.

δ_y: Dispersion in vertical plane.

$\alpha_x, \alpha_y, \beta_x, \beta_y$: Twiss parameters.

a_i, b_i, m_i, k_i: Used as variables.

$I_{\rm inj,mes}$: Measured value of injection.

$I_{\rm inj,sim}$: Simulated value of injection.

$I_{\rm lim}$: Injection current limit.

$e_{\rm noise}$: Noise in system.

f: Used for function.

$\text{BPM}_{i,\rm stor}$: Stored value of i-th BPM.

$\text{BPM}_{i,\rm mes}$: Measured value of i-th BPM.

$\text{BPM}_{i,\rm MSO}$: Value at i-th BPM in most probable offspring.

$\widetilde{X} = (x, y, x', y')$: Beam parameter vector.

$\widetilde{X}_{\rm start}$: Beam parameter vector at TL-1 start.

$\widetilde{X}_{\rm end}$: Beam parameter vector at TL-1 end.

$\widetilde{X}_{a,b}$: Beam parameter vector at location a obtained by method b.

$\widetilde{P} = \left[\widetilde{X}_{\rm start}(1), \widetilde{X}_{\rm start}(2), \cdots, \widetilde{X}_{\rm start}(n)\right]$.

$\widetilde{P}$: Predicted start position vector.

$\widetilde{Q} = \left[\widetilde{X}_{\text{BPM}(i)}(1), \widetilde{X}_{\text{BPM}(i)}(2), \cdots, \widetilde{X}_{\text{BPM}(i)}(n)\right]$.

$\widetilde{Q}$: Predicted position at BPM vector.

$\widetilde{I} = [I_{\rm inj}(1), I_{\rm inj}(2), \cdots, I_{\rm inj}(n)]$: Predicted injection current vector.

$\widetilde{M} = [I_1, I_2, \cdots, I_n]$: Magnet settings vector.

2 A brief overview of Indus-1 facility

Indus-1 is a 450 MeV, 100 mA, electron storage ring, operating at critical wavelength of 61 Å (angstrom), built by Department of Atomic Energy for promoting research in basic physics and material science at RRCAT, Indore. As shown in Fig. 1, the facility comprises of pre-injector microtron: a small accelerator which accelerates the electrons up to 20 MeV; TL-1: a transport line which transports the electrons from microtron to booster injection septum by matching the beam parameter of microtron output to that of booster input; booster: a synchrotron accelerator which increases the electron energy from 20 MeV to 450 MeV; TL-2: a transport line which transports the electrons from booster synchrotron to storage ring; Indus-1: the storage ring whose purpose is to store the electrons, compensate the energy lost in the form of synchrotron radiation and to provide the synchrotron light to the beam lines for performing the experiments.

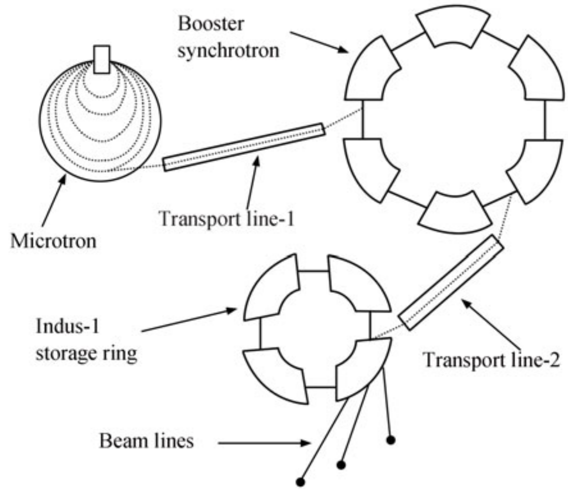

Fig. 1 Block diagram of Indus-1 facility

3 TL-1 layout

Fig. 2 shows the layout of the TL-1. TL-1 comprises of microtron extraction tube, three pairs of DC-quadrupoles (QF1-QF3 and QD1-QD3), four horizontal steerers (HSC1-HSC4), five vertical steerers (VSC1-VSC5), one 15° DC-dipole (DP1) and one 15° injection septum (pulse width 200 μs). For measurement of beam position, there are three fluorescent screen type beam position monitors (BPM1-BPM3).

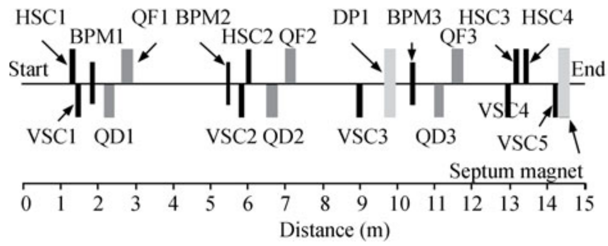

Fig. 2 Layout of TL-1

4 System simulation

The simulation program is mainly comprised of three parts. They are the agent system, the model of the accelerator environment with which the agents interact, and the graphical user interface (GUI). The principal data flow involved between different parts is shown in Fig. 3. The accelerator model is made in the form of a software entity comprising of three sub-modules. The agent system comprises of a set of agents and inter-agent communication facility. For synchronizing between the accelerator model and the agent system, messages are used. The data exchange between programs is done through messages and global variables.

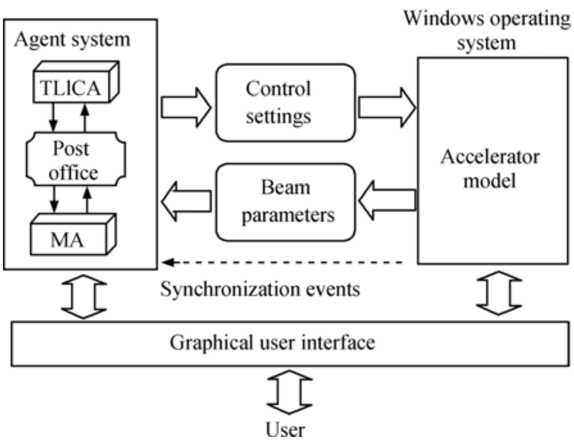

Fig. 3 Simulation program organisation

4.1 Agent system

The agent system is mainly composed of two agents: TL-1 control agent (TL1CA) and model agent (MA). TL1CA interprets the system state from percepts. Depending upon the current events and the agent beliefs, the agent decides the plans to be executed to achieve all the active goals. The agent evaluates the plan applicability function and selects the highest priority applicable plan from the list for each active goal. The architecture of TL1CA is discussed in [22]. The plans stated in Sections 5.1– 5.4 are added to the TL tuning goal of this agent. MA contains the model of TL-1, booster, and storage ring in its body and assists TL1CA in its plans by providing the information about the probable outcome of the actions on the machine. To exercise the plans stated in Sections 5.1– 5.4, three more capabilities (predict position with BPM, predict position using MBT with BPM, predict position using MBT without BPM) are added to the function list of this agent.

4.2 Accelerator model

The accelerator model comprises of three sub-models: microtron model, TL-1 model and booster model. The microtron model generates a beam consisting of 2000 macro particles. The various parameters of the beam are $e_x, e_y, \alpha_x, \alpha_y, \beta_x, \beta_y, \delta_x, \delta_y, x', y', x$ and y. Table 1 gives the value of different beam parameters used in this simulation, where RMS denotes root mean square value.

The TL-1 model is developed in MAD[23]. It accepts beam comprising of macro particles with different beam parameters. Depending upon the set values of all the power supplies, it tracks all the macro particles in the beam along the TL-1. It provides beam image at all beam position indicators and the beam parameters at TL-1 end. The booster model is also developed in MAD. It accepts the macro particle beam with beam parameters at TL-1 end. Depending upon the magnet settings, it constructs the machine lattice. Using this lattice, it then tracks the particle for the defined number of turns (1000 turns) and produces the survived/lost attribute for each macro particle. Depending upon the survived/lost condition of macro particles, it provides the normalised beam current injected into the booster. To keep the simulation simple, the injection process is not calculated and is assumed that there is no loss at the injector portion and the entire beam transfers from TL-1 output to booster centre orbit successfully.

Table 1 Value of beam parameters used in simulation

Parameter	x	y
Emittance(e)	8.0 E–7	3.0 E–6
α	−0.6708	−0.5046
β	0.9645	0.9945
δ	0.00	0.00
Angle(x'/y')	0.00	0.00
Position	0.00	Varied between ±10 mm
e_{noise}	200 μm (RMS)	200 μm (RMS)

4.3 Graphical user interface

The simulation program is developed with GUI shown in Fig. 4. to allow the user to conveniently monitor and control the simulation. Separate windows are developed for defining beam, defining beam movement, configuring accelerator simulation parameters, configuring agent parameters, and configuring agent based simulation parameters. Results of simulation can be viewed in graphic control panel and can be also stored in text file. For debugging, agent communication analyser is given in tab control. Using GUI, different fault conditions of devices can be introduced manually, and can be defined through configuration file.

5 TL tuning using model based tracking

GA based TL tuning method using the beam position feedback from BPMs is discussed by Schirmer et al.[16] Considering the cases of BPM/actuator failure scenarios, this method is modified using the model based tracking concept.

From methodology point of view, the BPM/actuator failure scenarios are divided into four cases. Case 1: when some of the BPMs fail, case 2: when only one BPM is available, case 3: when all BPMs fail, and case 4: when actuators fail. Further, case 4 may simultaneously occur along with case 1, case 2 or case 3.

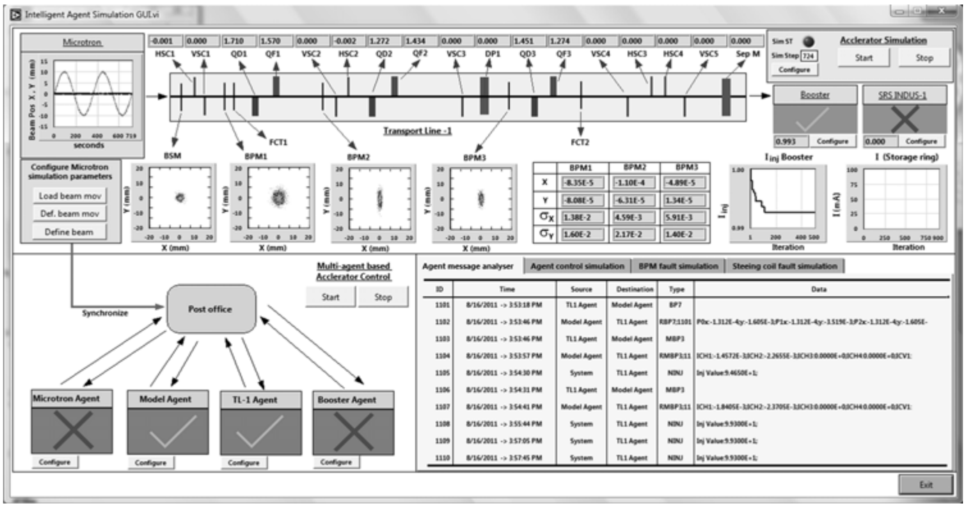

Fig. 4 GUI for the agent based accelerator control simulation

5.1 TL-1 tuning using BPM

For tuning of TL-1 using feedback data from BPM, the agent based control (ABC) utilizes the three step differential evolution (DE)[24] based scheme with fitness functions given by (1) for DE-I and (2) for DE-II. For handling the case of sensor failure, TL1CA dynamically selects the BPM data source by suitably selecting the value of a_i and b_i depending upon the sensor′s health/failure condition. For the faulty BPM, the agent selects the data from the data store whereas for the correct BPM agent selects the recent measurement data. Similarly, for handling the actuator failure cases, the agent dynamically selects the value of m_i depending upon the actuator ok/failure condition.

In the first step when operator defines the good injection event, the BPM data and set values of magnet power supplies are read. Then using TL-1 model, the beam position vector at start TL-1, and end TL-1 are calculated using the DE-I by mutating the start orbit vector $\widetilde{X}_{\rm start}$ and are stored as $\widetilde{X}_{\rm start,opt}$ and $\widetilde{X}_{\rm end,opt}$. These represent optimized beam parameters in good injection condition. In the second step whenever the injection degrades, the agent calculates the new beam position vectors at start TL-1 and end TL-1 as $\widetilde{X}_{\rm start,mes}$ and $\widetilde{X}_{\rm end,mes}$. In the third step using $\widetilde{X}_{\rm start,mes}$ and $\widetilde{X}_{\rm end,opt}$, it then calculates the suitable magnet settings $\widetilde{M}$ for matching the real beam parameters at the input with the optimized beam parameters at the output using DE-II.

$$\text{fitness}_{\rm DE-I} = \sum_{i=1}^{n}(a_i \text{BPM}_{i,\rm mes} + b_i \text{BPM}_{i,\rm stor} - \text{BPM}_{i,\rm sim})^2 \quad (1)$$

$a_i = 1, b_i = 0, [\text{BPM}_{i,\rm stor}]_{n+1} = [\text{BPM}_{i,\rm mes}]_n$, if BPM_i=OK

$a_i = 0, b_i = 1, [\text{BPM}_{i,\rm stor}]_{n+1} = [\text{BPM}_{i,\rm MSO}]_n$, if BPM_i=Faulty

$$\text{fitness}_{\rm DE-II} = \text{fitness}_{\rm DE-II}(x) + \text{fitness}_{\rm DE-II}(y) \quad (2)$$

$$\text{fitness}_{\rm DE-II}(x) = M_0 + m_1M_1 + m_2M_2 + m_3M_3 + m_4M_4 + m_5M_5 + m_6M_6$$

$$M_0 = \sum_{i=1}^{4}(\widetilde{X}_{\rm end,opt}(i) - \widetilde{X}_{\rm end,sim}(i))^2$$

$$M_1 = (x_{\rm HSC2(start),opt} - (x_{\rm HSC2(start),sim}))^2$$

$$M_2 = (x'_{\rm HSC2(end),opt} - (x'_{\rm HSC2(end),sim}))^2$$

$$M_3 = (x_{\rm HSC3(start),opt} - (x_{\rm HSC3(start),sim}))^2$$

$$M_4 = (x'_{\rm HSC3(end),opt} - (x'_{\rm HSC3(end),sim}))^2$$

$$M_5 = (x_{\rm HSC4(start),opt} - (x_{\rm HSC4(start),sim}))^2$$

$$M_6 = (x'_{\rm HSC4(end),opt} - (x'_{\rm HSC4(end),sim}))^2.$$

Similarly, the $\text{fitness}_{\rm DE-II}(y)$ is defined for vertical plane.

Theorem 1. To analyze the scheme of ABC system for this case the block diagram for overall control system is shown in Fig. 5. To find the condition for successful tracking of beam and tuning of TL-1, let the rate of change of beam parameter at start TL-1 due to un-modelled dynamics/disturbance be $\frac{{\rm d}\widetilde{X}_{\rm start,s}}{{\rm d}t}$. Let A given by (3) be the area at end TL-1 in vector space that will tune the TL-1 as per (4) by applying magnet settings $\widetilde{M}_{\rm TL}$. Let $A_{\rm start}$ be the corresponding tuning area transformed to start TL-1 using TL-1 inverse model given by (5). Let $X_{\rm BPM1}$, $X_{\rm BPM2}$, $X_{\rm BPM3}$ be the beam position vector at corresponding BPM locations (obtained by direct measurement or from model-based tracked data) with errors $e_{\rm BPM1}$, $e_{\rm BPM2}$, $e_{\rm BPM3}$, respectively, then the error ($e_{\rm DE-1}$) in estimation of $\widetilde{X}_{\rm start,c}$ by DE-I is given by (6) when $\triangle t_1$ is given by (7) and $\triangle t_{\rm cal}$ be the calculation time taken by DE-I and DE-II. Then the error ($E_{\rm start}$) in the estimation of beam parameter at start TL-1 at the time of applying the correction will be given by (8). The condition for successful tuning will be given by (9).

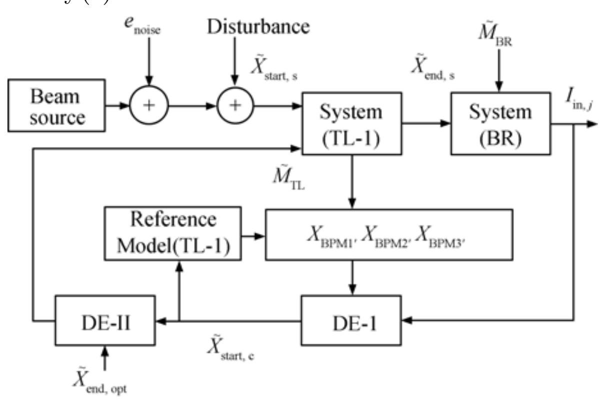

Fig. 5 Control system block diagram for case 1

$$A = f(I_{\rm inj,lim}, \widetilde{X}_{\rm end,opt}, \widetilde{M}_{\rm BR}) \quad (3)$$
$$I_{\rm inj} > I_{\rm inj,lim} \quad (4)$$
$$A_{\rm start} = {\rm Model}^{-1}_{\rm TL}(A) \quad (5)$$
$$e_{\rm DE-I} = f(e_{\rm BPM1}, e_{\rm BPM2}, e_{\rm BPM3}, \triangle t_1) \quad (6)$$
$$\triangle t_1 = t_{\rm last\ correction} - t_{\rm inj\ degraded\ below\ limit} \quad (7)$$
$$E_{\rm start} = e_{{\rm DE}-I} + e_{\rm noise} + \frac{{\rm d}\widetilde{X}_{\rm start,s}}{{\rm d}t}\triangle t_{\rm cal} \quad (8)$$
$$E_{\rm start} < A_{\rm start}. \quad (9)$$

5.2 TL-1 tuning with only one BPM data

For tuning of TL-1 in the case when only one BPM is available, the TL1CA uses the extended system model, which incorporates the booster model along with the TL-1 model. This extended model provides the calculated injection current value. In this case, the agent calculates beam position vectors at start TL-1 ($\widetilde{P}$) and all the available BPMs ($\widetilde{Q}$) for injection current $I_{\rm inj,mes}$. From $\widetilde{P}$, it then selects one position vector say $\widetilde{X}_{\rm start}$ which gives the calculated values at the available BPM, nearest to the measured value. It then uses $\widetilde{X}_{\rm start}$ for calculating the magnet settings ($\widetilde{M}$) for optimising the injection current in the same way as in case 1. The flow chart for the overall process is shown in Fig. 6.

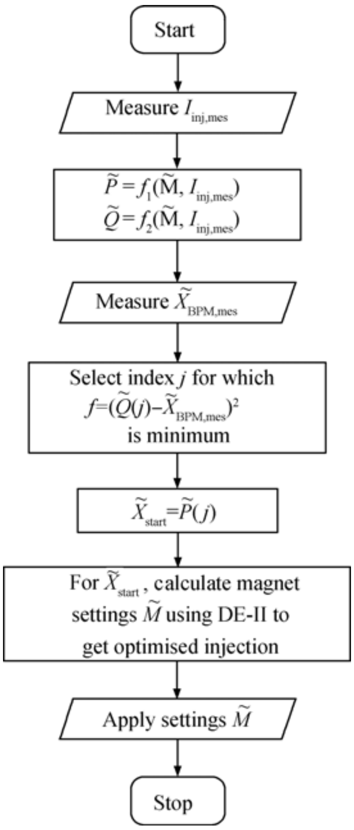

Fig. 6 Flow chart for TL-1 tuning with only one BPM data

Theorem 2. To analyse the scheme of ABC system for case 2 the block diagram for overall control system is shown in Fig. 7. Let $e_{\rm BPM}$ be the error in measured beam position vector $X_{\rm BPM}$, and $e_{\rm model}$ be the error in estimation of $\widetilde{X}_{\rm start,c}$ using reference models of TL-1 and booster. Let $\triangle t_{\rm cal}$ be the calculation time taken by ABC. The error in the estimated beam parameter at start TL-1 at the time of applying the corrections will be given by (10). The condition for successful tuning is given by (9). Here it is to be noted that theoretically it is possible to generate $\widetilde{Q}$ and $\widetilde{P}$ using $\widetilde{M}_{\rm TL}$, $\widetilde{M}_{\rm BR}$, and $I_{\rm inj}$ but the use of tracked $\widetilde{X}_{\rm start}$ decreases $t_{\rm cal}$ and therefore it decreases $E_{\rm start}$.

$$E_{\rm start} = e_{\rm BPM} + e_{\rm noise} + e_{\rm model} + \frac{{\rm d}\widetilde{X}_{\rm start,s}}{{\rm d}t}\triangle t_{\rm cal}. \quad (10)$$

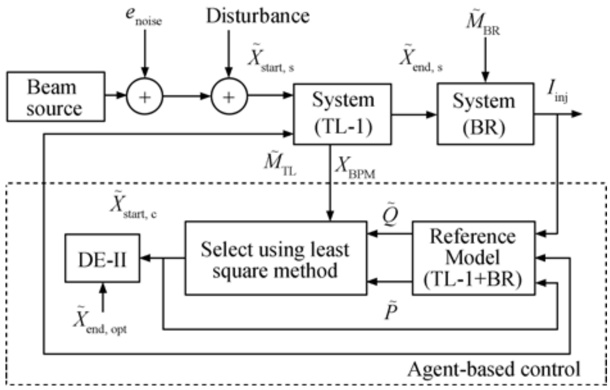

Fig. 7 Control system block diagram for case 2

5.3 TL-1 tuning in total absence of BPM data

For tuning of TL-1 in total absence of BPM data, TL1CA calculates all the possible beam position vectors at start TL-1 $\widetilde{P}$ for the currently measured injection current value. Then, based on the historical trend of beam position movement, it selects the most probable beam position vector $\widetilde{X}_{\rm start}$. Using $\widetilde{X}_{\rm start}$ it then calculates the magnet settings ($\widetilde{M}$) with DE-II and applies it to system. Using ($\widetilde{M}$), it then calculates the injection current ($\widetilde{I}$) for all elements of ($\widetilde{P}$). Using $\widetilde{I}$ and the newly measured injection current value ($I_{\rm inj,mes}$) it then refines its decision of selecting the most probable beam position $\widetilde{X}_{\rm start}$. The overall process is shown by the flow chart given in Fig. 8.

Theorem 3. To analyze the scheme of case 3, the control system block diagram is shown in Fig. 9. Let $\triangle t_{\rm cal,1}$ be the calculation time in the first step, i.e., when all the three switches (S1, S2, S3) are in position 1 and the flow of control passes through various blocks in the order-reference model (TL+BR) block, select most probable block, DE-II block and system (TL-1) block. Let $\triangle t_{\rm cal,2}$ be the calculation time in the second step, i.e., when all the three switches (S1, S2, S3) are in position 2 and the flow of control passes through various blocks in the order-select using least square method block, DE-II block and system (TL-1) block. To calculate the condition for successful tracking, assume that the TL-1 is tuned to operate at point P (see Fig. 10) by the last successfully applied correction. Then P1, P2, $P_{x1,y1}$, $P_{x2,y2}$, $\cdots$, $P_{xn,yn}$ elements of $\widetilde{P}$ can be said the points corresponding to $I_{\rm inj,lim}$. Let P1 be the point corresponding to actual beam position at the time when correction is demanded. Considering the worst case that the algorithm of selecting the most probable operating point wrongly selects the point P2 which is at the maximum distance from P1 (see Fig. 10). The $I_{\rm inj}$ can now be plotted for points P, P1 and P2 as shown in Fig. 11. The curves C, C1, C2 correspond to the $I_{\rm inj}$ when the TL-1 is tuned at point P, P1, P2, respectively. And the electron beam at TL-1 input moves in vertical plane. Let D be the maximum distance from the tuned position corresponding to the $I_{\rm inj,th}$, when $I_{\rm inj,th}$ is the threshold limit of $I_{\rm inj}$, using which the point P1 can be successfully identified by the system in presence of noise and errors. Let d_1 be the distance between P1 and P2 given by (11) and d_2 be the distance moved by the beam during the calculation time $\triangle t_{\rm cal,1}$ because of disturbance/un-modelled dynamics given by (12), then the condition for successful tracking will be given by (13). Now let P_s be the point corresponding to actual position of beam when the magnet setting $(\widetilde{M})$ are applied to the system as a result of the second step, the condition of successful tuning will be given by (15).

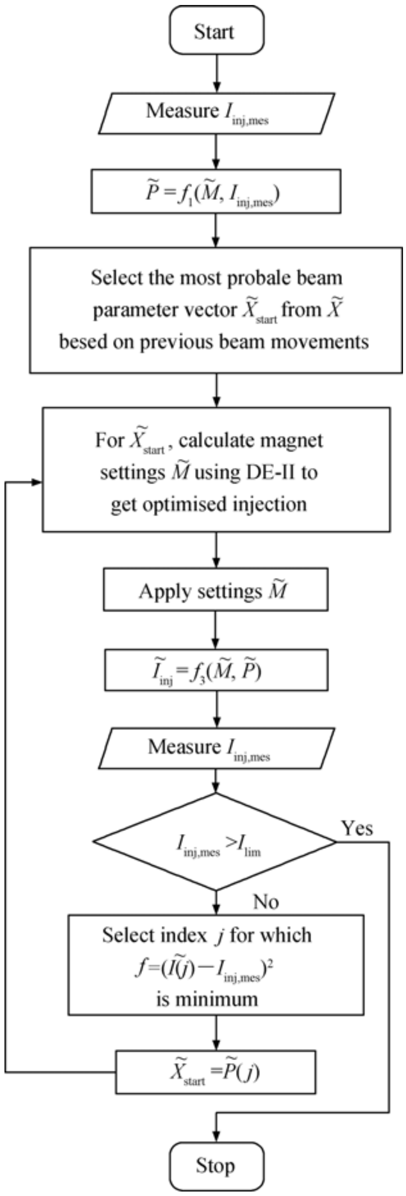

Fig. 8 Flow chart for TL-1 tuning in total absence of BPM data

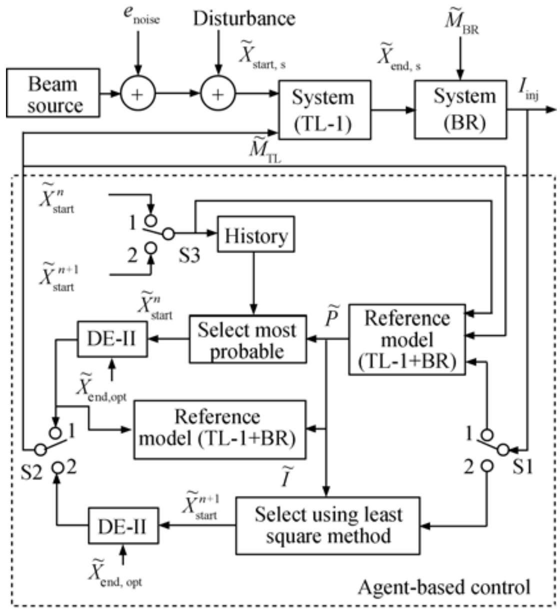

Fig. 9 Control system block diagram for case 3

$$d_1 = f(A_{\rm start}) \tag{11}$$

$$d_2 = \frac{{\rm d}\widetilde{X}_{\rm start,s}}{{\rm d}t}\triangle t_{\rm cal,1} \tag{12}$$

$$d_1 + d_2 < D \tag{13}$$

$$\triangle t = \triangle t_{\rm cal,1} + \triangle t_{\rm cal,2} \tag{14}$$

$$e_{\rm noise} + e_{\rm model} + \frac{{\rm d}\widetilde{X}_{\rm start,s}}{{\rm d}t}\triangle t < A_{\rm start} \tag{15}$$

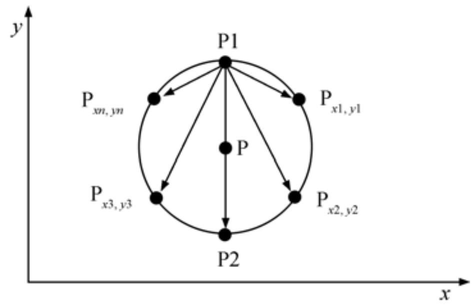

Fig. 10 TL-1 operating points corresponding to $I_{\rm inj,lim}$

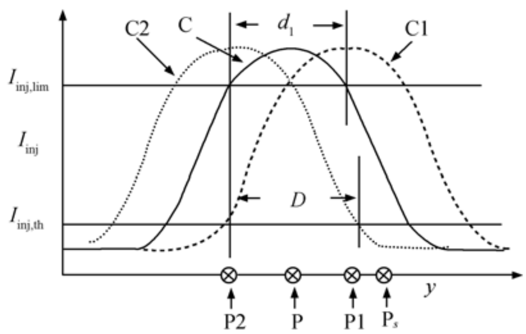

Fig. 11 $I_{\rm inj}$ for TL-1 tuning corresponding to points P, P1, P2

5.4 TL-1 tuning when actuators fail

To handle the case of actuator failure scenarios, TL1AC dynamically selects the values of m_i depending upon the actuator ok/failure condition using the simple rule set.

Rule 1. Find the two OK correctors (C1 and C2) coming first in the direction of beam traversal.

Rule 2. Use C1 to correct the beam position at C2 start location.

Rule 3. Use C2 to correct the beam angle at C2 end location.

For simplification, the following assumptions are made in implementation and simulation of the above stated plans.

Assumption 1. It is assumed that the device failures can be identified by the system.

Assumption 2. Although the BPM may fail in different ways, it is assumed that the BPM failure only causes the loss of BPM data and does not affect the operation of system in any other way.

Assumption 3. Although the correctors may fail in different ways, it is assumed that the failure of corrector is equivalent to switching off of power from the corrector power supply and does not affect the system in any other way.

Assumption 4. For case 3, it is assumed that either the system is in tuned condition or the initial beam position (only rough estimate) is known initially.

6 Results and discussion

Fig. 12 shows the beam position variation measured near TL-1 beginning (at Beam Slit Monitor) during one hour operation. Fig. 13 shows the simulated value of $I_{\rm inj}$ for beam movement along y. Table 2 lists the calculated limiting value (maximum value) of calculation time for successful tuning, and the actual calculation time values (observed on Windows Vista$^{\rm TM}$, Q9400 @ 2.66 GHz). Fig. 14 shows simulation result graphs for booster injection current ($I_{\rm inj}$), tracked beam position and tracking error plotted for different BPM failure scenarios. During this simulation, the beam at the TL-1 input is varied sinusoidally with an amplitude of 10 mm along y. Fig. 15 shows the simulation results for the injection current ($I_{\rm inj}$) for beam position variation along y from -10 mm to 10 mm under different actuator failure conditions. For all the simulations, the lower limit of injection current in booster is taken as 95 % (i.e., whenever the injection current in booster will fall below 95 %, the corrective action by the TL-1 agent will be initiated) and $I_{\rm lim} = 98\,\%$ is used by the model based tracking plan discussed in Section 5.3.

It can be seen from Fig. 12 that the beam position along x does not show larger variation from the operating point, whereas the variation along y is large and needs correction. From Fig. 12, the value for $|\frac{{\rm d}\widetilde{X}_{\rm start,s}}{{\rm d}t}|$ along y is calculated as 2.2 μm/s. From Fig. 13, the value of $A_{\rm start}$ (for $I_{\rm inj,lim} = 95\,\%$) along y, d_1, and D (for $I_{\rm inj,th} = 10\%$) is calculated as 1.5 mm, 3 mm, and 6.1 mm, respectively. Then using these for the stated conditions, the limiting value of $\triangle t_{\rm cal}$, $\triangle t_{\rm cal,1}$, and $\triangle t$ are calculated for successful tuning of TL-1 as shown in Table 2. From Table 2, it can be concluded that since the measured value of calculation time is less than the limiting value of calculation time for all the discussed cases, the proposed TL tuning method can be used successfully for tuning of TL-1 under different sensor/actuator failure scenarios. Further, it can be seen that limiting value of $\triangle t_{\rm cal,1}$ needed for successful tracking is more than the limiting value $\triangle t$ for successful tuning. Therefore, it can be said that if the condition of successful tuning is met, the condition for successful tracking will also be satisfied. It can be seen from Figs. 14 and 15 that using the proposed TL-1 tuning methods, the injection current can be successfully retained within the specified limit of 95 % criteria under different sensor/actuator failure scenarios.

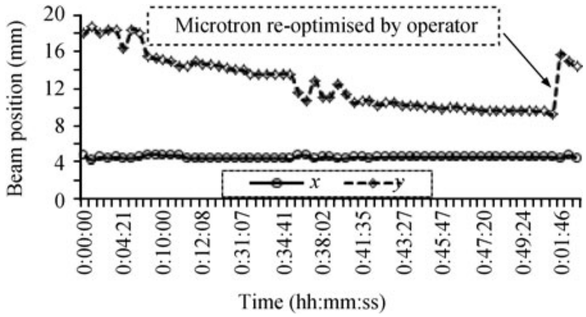

Fig. 12 Beam position variation measured near TL-1 start

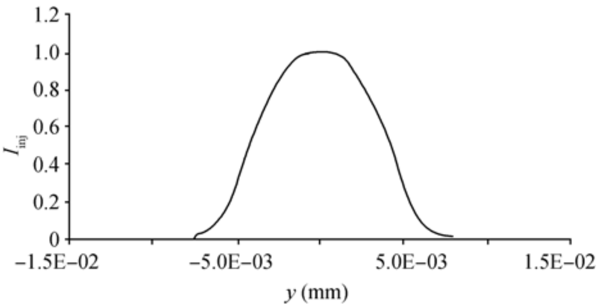

Fig. 13 Normalised $I_{\rm inj}$ for beam position variation in vertical plane y at $x = 0$

Table 2 Limiting value of calculation time

Scenario	limiting value	Actual value
Case 1	$\triangle t_{\rm cal}$=500 s	≈ 13 s
Case 2	$\triangle t_{\rm cal}$=409 s	≈ 40 s
Case 3	$\triangle t$=500 s	≈ 81 s
	$\triangle t_{\rm cal,1}$=1409 s	≈ 43 s
When	$e_{\rm DE-I}, e_{\rm noise}$,	$e_{\rm model}, e_{\rm BPM} = 200\,\mu$m

7 Conclusions

In accelerator, the transport lines are used for transporting the electron/charged particle beams from source to destination. During transportation, they modify the beam characteristics to match with the beam acceptance characteristics of destination. Various AI based methods proposed by many researchers in the past have successfully improved the system availability by reducing the tuning time. In this paper, the method for controlling transport lines, based on model-based tracking concept, for agent-based control systems is presented. And the condition for its successful operation is derived. The proposed method increases the overall system availability under different sensor/actuator failure conditions by tuning of TL if beam position at source varies. The ability to work under total loss of BPM data can be further exploited to optimize injection current for transport lines having only interceptive type of BPM (e.g., fluorescent screen type BPM). The simulation results of the proposed scheme on the Indus-1 accelerator subsystems models showed their effectiveness towards the automatic tuning of transport line under different sensor/actuator failure scenarios.

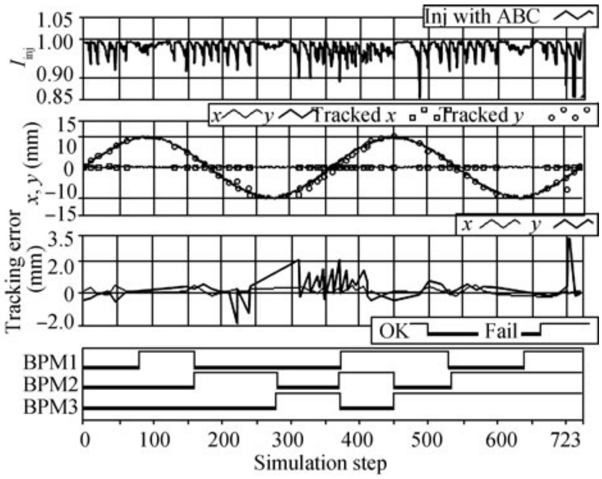

Fig. 14 Normalised injection current, tracked beam position, and tracking error for different BPM failure conditions when beam position at TL-1 input along y is varied sinusoidally with amplitude of 10 mm

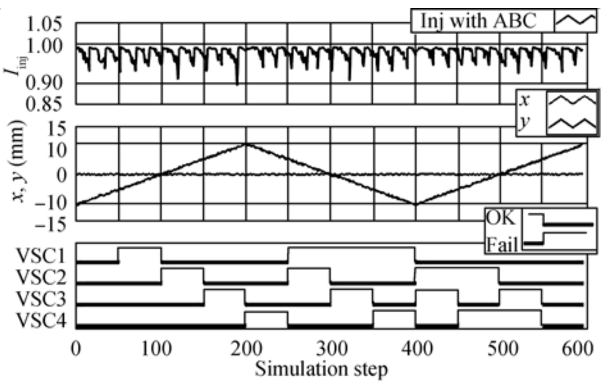

Fig. 15 Normalised injection current under different steering coil (actuator) failure conditions (the beam at TL-1 input along y is varied from −10 mm to 10 mm with 100 μm/s)

References

[1] T. Higo, H. Shaoee, J. E. Spencer. Some applications of AI to the problems of accelerator physics. In *Proceedings of the 12th IEEE Particle Accelerator Conference*, IEEE, Washington DC, USA, pp. 701−703, 1987.

[2] D. P. Weygand. Artificial intelligence and accelerator control. In *Proceedings of the 12th IEEE Particle Accelerator Conference*, IEEE, Washington DC, USA, pp. 564−566, 1987.

[3] M. Lee, S. Clearwater. GOLD: Integration of model-based control systems with artificial intelligence and workstations. In *Proceedings of Workshop on Model-based Accelerator Controls, Brookhaven National Laboratory*, Upton, New York, USA, pp. 1−8, 1987.

[4] J. E. Spencer. Accelerator diagnosis and control by neutral nets. In *Proceedings of the 1989 IEEE Particle Accelerator Conference*, IEEE, Chicago, Illinois, pp. 1642−1644, 1989.

[5] A. Corneliusen, P. Terdal, T. Knight, J. Spencer. Computation and control with neural networks. *Nuclear Instruments and Methods in Physics Research Section A*, vol. 293, pp. 507−516, 1990.

[6] J. A. Howell, C. W. Barnes, S. K. Brown, G. W. Flake, R. D. Jones, Y. C. Lee, S. Qian, R. M. Wright. Control of a negative-ion accelerator source using neural networks. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 293, no. 1−2, pp. 517−522, 1990.

[7] W. C. Mead, P. S. Bowling, S. K. Brown, R. D. Jones, C. W. Barnes, H. E. Gibson, J. R. Goulding, Y. C. Lee. Optimization and control of a small-angle negative ion source using an on-line adaptive controller based on the connectionist normalized local spline neural network. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 72, no. 2, pp. 271−289, 1992.

[8] N. R. Jennings, J. M.Corera, I. Laresgoiti, E. H. Mamdani, F. Perriollat, P. Skarek, L. Z. Varga. Using ARCHON^{TM} to develop real-world DAI applications for electricity transportation management and particle accelerator control. *IEEE Expert*, vol. 11, no. 6, pp. 60−88, 1996.

[9] W. B. Klein, C. R. Stern, G. F. Luger, E. T. Olsson. Designing a portable architecture for intelligent particle accelerator control. In *Proceedings of the 17th IEEE Particle Accelerator Conference*, IEEE, Vancouver, BC, Canada, vol. 2, pp. 2422−2424, 1997.

[10] C. Stern, E. Olsson, M. Kroupa, R. Westervelt, G. Luger, W. Klein. A control system for accelerator tuning combining adaptive plan execution with online learning. In *Proceedings of the 1997 International Conference on Accelerator and Large Experimental Physics Control Systems*, Beijing, China, 1997.

[11] W. B. Klein, R. T. Westervelt, G. F. Luger. An Architecture for intelligent control of particle accelerators, [Online], Available: http://www-bd.fnal.gov/icalepcs/abstracts/PDF/wpo63.pdf, May 20, 2012.

[12] R. Pugliese, F. Bille, A. Abrami, O. Svensson. Applying intelligent system concepts to automatic beamline alignment. In *Proceedings of the 1997 International Conference on Accelerator and Large Experimental Physics Control Systems*, Beijing, China, 1997.

[13] W. B. Klein, C. R. Stern, G. F. Luger, E. T. Olsson. An intelligent control architecture for accelerator beamline tuning. In *Proceedings of the 14th National Conference on Artificial Intelligence and 9th Conference on Innovative Applications of Artificial Intelligence*, AAAI Press, Menlo Park, CA, USA, pp. 1019−1025, 1997.

[14] W. B. Klein, R. T. Westervelt, G. F. Luger. Developing a general purpose intelligent control system for particle accelerators. *Journal of Intelligent and Fuzzy Systems*, vol. 7, no. 1, pp. 1−12, 1999.

[15] W. B. Klein, C. R. Stern, G. F. Luger, D. Pless. Teleoreactive control for accelerator beamline tuning. In *Proceedings of Artificial Intelligence and Soft Computing*, ACTA Press, Banff, Alberta, Canada, pp. 372−379, 2000.

[16] D. Schirmer, P. Hartmann, T. Büning, D. Müller. Electron transport line optimization using neuronal networks and genetic algorithms. In *Proceedings of the 10th European Particle Accelerator Conference*, Edinburgh, Scotland, pp. 1948−1950, 2006.

[17] J. Yan, X. P. Guan, F. X. Tan. Target tracking and obstacle avoidance for multi-agent systems. *International Journal of Automation and Computing*, vol. 7, no. 4, pp. 550−556, 2010.

[18] J. Yan, X. P. Guan, X. Y. Luo, F. X. Tan. Target tracking and obstacle avoidance for multi-agent networks with input constraints. *International Journal of Automation and Computing*, vol. 8, no. 1, pp. 46−53, 2011.

[19] A. D. Worrall, R. F. Marslin, G. D. Sullivan, K. D. Baker. Model-based tracking. In *Proceedings of the British Machine Vision Conference*, Glasgow, UK, pp. 310−318, 1991.

[20] D. Kragic, H. I. Christensen. Confluence of parameters in model based tracking. In *Proceedings of the 2003 IEEE International Conference on Robotics and Automation*, ICRA, Taipei, Taiwan, China, vol. 3, pp. 3485−3490, 2003.

[21] V. Kyrki, D. Kragic. Integration of model-based and model-free cues for visual object tracking in 3D. In *Proceedings of the 2005 IEEE International Conference on Robotics and Automation*, IEEE, Barcelona, Spain, pp. 1554−1560, 2005.

[22] R. P. Yadav, P. Fatnani, P. V. Varde. Intelligent agent based control of TL-1. In *Proceedings of the 5th DEA-BRNS Indian Particle Accelerator Conference*, Delhi, India, 2011.

[23] H. Grote, F. C. Iselin. The MAD Program (Methodical Accelerator Design) Version 8.16, User′s Reference Manual, CERN/SL/90−13(AP), (rev. 4), March 27, 1995.

[24] R. Storn, K. Price. Differential evolution, a simple and efficient heuristic for global optimization over continuous spaces. *Journal of Global Optimization*, vol. 11, no. 4, pp. 341−359, 1997.

R. P. Yadav graduated from Sir Chhotu Ram State College of Engineering (CRSCE), India in 2000, and completed one year orientation course for engineering graduates and science postgraduates (OECS) from Centre for Advanced Technology Training School, India in 2001. He is currently working as scientific officer in Accelerator Control Section at Raja Ramanna Centre for Advanced Technology, Indore, India. And he is also a Ph. D. candidate in Homi Bhabha National Institute, India.

His research interests include feedback control system, accelerator control, agent based feedback control systems, and intelligent control systems.

E-mail: rpyadav@rrcat.gov.in (Corresponding author)

P. V. Varde received his Ph. D. degree from Indian Institute of Technology, India in 1996. He is currently working as scientific officer at Bhabha Atomic Research Centre (BARC), India. And he heads Safety Evaluation and Mampower Training and Development Section (SE and MTD Section). He is also a professor at Homi Bhabha National Institute (HBNI), India.

His research interests include probabilistic safety assessment (PSA) of research reactors, application of artificial intelligence (AI) tools like artificial neural network and knowledge based systems for developing probabilistic safety assessment (PSA) based systems for operations, and fault diagnosis of nuclear plant.

E-mail: varde@barc.gov.in

P. S. V. Nataraj received his Ph. D. degree in process dynamics and control from IIT Madras, India in 1987. He has been a professor in the Systems and Control Engineering Group at IIT Bombay since 1988. He is the chief coordinator of the control, automation, reliability, instrumentation, measurement and optimazation cell setup at IIT Bombay to foster interaction with the industry in the areas of control, automation, reliability, instrumentation, measurement, and optimization. He received a NASA/US Navy commendation and memento for the Best Applied Research Paper awarded at the International Symposium on Air Breathing Engines (ISOABE), Cleveland, Ohio, September 2003.

His research interests include robust and fractional order control, global optimization, reliable computing, parallel computing (GPU), and robust statistics.

E-mail: nataraj@sc.iitb.ac.in

P. Fatnani graduated from Pandit Ravishankar Shukla University, India in 1985 and completed one year orientation course for engineering graduates and science postgraduates (OECS) from Bhabha Atomic Research Centre Training School in 1986. He is currently working as scientific officer at Raja Ramanna Centre For Advanced Technology(RRCAT), India, and heads accelerator control section.

His research interests include accelerator control systems, agent technology, supervisory control, and data acquisition.

E-mail: fatnani@rrcat.gov.in

C. P. Navathe graduated from University of Pune in 1978, and he received M. Eng. degree from Devi Ahilya Vishwa Vidyalaya, Indore in 1997. He is currently working as scientific officer at Raja Ramanna Centre For Advanced Technology, India. And he heads Accelerator Controls and Beam Dynamics Division.

His research interests include microprocessor based systems, data acquisition, and high speed electronics.

E-mail: cpn@rrcat.gov.in