Chapter 6

Summary and future direction

The study was set out to explore the concept of distributed intelligent agent based control system for real time control of accelerator and has identified the accelerator control system architectures, specific subsystem control requirements, agent architectures, agent based cooperative control scenarios, agent representations and multi-agent distribution over different accelerator control system layers for effective resource utilisations. The study has also sought for modelling of different accelerator subsystem components from controls perspective and overall accelerator control system simulation to know whether the agent based control can result in effective accelerator tuning particularly for the case of disturbances observed at the beam source, sensor failures and orbit correction strategies in synchrotron radiation sources. The general theoretical literature on this subject and specifically in the context of synchrotron radiation sources control systems is not sufficient to answer some of the vital questions within this scope. The study sought to answer three of these questions:

- Which agent architectures are more suited for transforming the existing accelerator subsystems into intelligent agents using the existing control system infrastructure?
- How can we represent such intelligent agents suitable for integration with the accel-
erator control system?

- How to distribute different agents over the multi-layer accelerator control system framework for exercising the multi-agent control approach?

The answer to these questions are important for exercising the AI based operator support and machine control system that are required for the reliable, maintainable and easy operability of future accelerator projects in the present trend of increasing operation parameters and growing size of facilities.

6.1 Summary

To withstand the current demand for increase in the energy of charged particles the future accelerator machines needs artificial intelligence based advanced control method deployment at different system/subsystem levels. Moreover with the current technological developments in the control system support hardware the existing accelerator facilities will also explore the advantage of using agent based control for improving the system operability and reliability. From implementation point of view the first research question address the issues related with the optimised dispersion of abstract agent representation at subsystem levels based on the existing control system infrastructure.

1. Which agent architectures are more suited for transforming the existing accelerator subsystems into intelligent agents using the existing control system infrastructure?

   a. Modular architectures: The present accelerator control and operation methods group the system parameters as per the accelerator subsystems moreover many times these share different development platforms thus the modular architectures are the best suited at the subsystem level agent development. For the existing accelerator facilities this will further minimise the switch-over time during intermittent deployment and testing of such
schemes through interfacing modules that will selectively isolate the existing man machine interface commands from that of agents. Also from software programmers point of view the subsystem level agent goals with rational action sequence can be easily collected from the machine operators and system experts with clear and concise information thus supporting the speedy development. Although in software theoretically all the agent architectures discussed in chapter 2 can in one or the other form can decompose the tasks in modules with sufficient granularity but from the perspective of this study the agent architectures such as subsumption architecture and modular architecture are the one that directly comes in this category.

b. Model based decision making: The accelerator environment being complex natured (derived-parameter handling and multiple modes of operation) imposes the restriction on the decision making process of agents to encompass the physics model of subsystems for generating the intermediate derived parameters thus the agent architectures supporting the direct inclusion of system model such as the modular architecture is the suggested one for the subsystem level of agents. Moreover from controls point of view (Repeatability and operability) it is not always possible to derive the useful system model from the available physics model of the subsystem to an extent that the correct decision can be taken towards machine tuning. For such cases the on-line identification of the subsystem over the control parameters in networked control system configuration can be a solution.

c. Inter-agent coupling and integration with accelerator physics tools: The cooperative optimisation tasks in multi-agent organisations for accelerator control needs the information exchange at subsystem levels. Further the information needed by the coaliating agents may not be directly available through sensors and many times is needed to be derived through subsystem model thus the agent development framework
must integrate to some of the available accelerator modelling tools like MAD and AT.

d. Multi level goal and information distribution: The multi-agent based cooperative optimisation and control needs the information and goal distribution between different agents and on a broader perspective these agents of varying complexity may be found distributed on different accelerator control system layers thus the agent goals and meta data is needed to be travelled through different control system layers. Thus the agent framework supporting the direct coupling between inter and intra agent modules is desirable.

After formulation of the abstract requirements for such agents the next question is.

2. How can we represent such intelligent agents suitable for integration with the accelerator control system?

a. Use independent modules as building block: The simplest building block used for building agents in this study are formulated by combining the message based communication interface called as blocks postman with the blocks body that comprises of a continuous loop performing the event serving one at a time taken from message queue. This design is selected because of ease of implementation in multi platform system. As the message parser and socket based postman can be implemented in any language supporting the case construct and socket programming API. The event serving loop provides the behaviour invoking mechanism whereas the behaviour can be implemented using any platform.

b. Postman post-office based centralised inter and intra agent communication: In the distributed accelerator control environment the post-office based communication infrastructure is proposed with the custom agent communication language framework for event and data transmission across different agent. Being open to expansion it relieve the agents from the burden of managing the message routing as in this case
each agent is required to only know the address of post-office. further more this scheme also automatically handles the agent movement across different control system organisational layers and at the same time serves as the valuable tool for debugging and rational action sequence linking & verification.

c. Separate concurrent and sequential execution loops for module execution Although each agent will have some specific implementation details according to the domain and agent type in accelerator environment but broadly the agent structure is comprised of three parts a) the agents postman: the one who handles the agents communication in accelerator environment, b) concurrent module execution loop: the execution loop which handles the independent behaviours and c) The sequential module execution loop: the execution loop that handles the dependent behaviours.

with the development of agent framework the next question is about their distribute and goal assignment for the multi-agent based control scenario.i.e.

3. How to distribute different agents over the multi-layer accelerator control system framework for exercising the multi-agent control approach?

a. Place small response time demanding agents at lower layers and large response time demanding agents at higher layers: With every increase of layer in the control system of accelerators the distance of actors(system controlling agents) from machine increases. thus increasing the overall system response time. Therefore the policy is to place the small response time demanding agents towards lower layers.

b. Place simple agents at lower layers and complex agents at higher layers: For agents both speed and intelligence can not be increased simultaneously, the limitations arise due to the limitation on available resources. In the multi-layer architectures of accelerator control systems the computational resources increases with every increase of system layers, This advocates the policy of placing large computation demanding agents
towards higher layers.

With the developed agent framework the thesis further investigate the possibility of performance enhancement in the accelerator control through agent based control simulation. As a case study the basic model of the typical synchrotron radiation source facility is developed with the interface similar to the actual machine interface. Particularly for the synchrotron radiation sources application wise the agent based realtime control is studied towards automated tuning of transport line to maintain the injection current above a certain threshold for the case of beam movement at the source. The results show that with the inclusion of model assessed genetic algorithm based plans (MAGAP) agent can successfully derive the beam parameters at source in real time using measurement data. In a feedback manner from these derived beam parameters the agent was successful in calculating the control settings again using different MAGAP. The results supports the Schirner et al.[103] findings for GA based methods suitability in restoring the beam position at BPI’s. further to this the study shows with this method injection current can be maintained above 90% value for the practical case of beam movement bounds observed during cathode life cycle, moreover this is found true for the different booster settings thus the proposed method when implemented will assist operators in fast machine tuning on day to day basis. The study shows this improvement in injection current can not be exploited fully by the machines that uses interceptive type of BPI’s in transport lines. This occurs because of non availability of beam during the measurements using such BPI’s. For such cases the multi-agent based approach with model based tracking plans are investigated. Study shows this approach can also handle the cases of limited sensor (BPI) and Actuator (Correctors) failures thus improving the overall system reliability and robustness along with supporting operators during machine tuning.
Four input five output nonlinear model is formulated for Microtron accelerator through system identification method. Using this model Microtron agent is developed with system dynamics learning plans. The study carried out for the multi-agent based cooperative control for the problem of beam disturbance at source (at Microtron output) shows that provided there exists a method for online model identification and an adaptive controller for Microtron, the agents can successfully maintain the injection current at booster above threshold value while reducing the number of changes required in transport line settings. This scenario further improves with the cooperative optimisation by both agents using the system dynamics learning and future moves prediction plans. Where both the agents Microtron and TL-1 cooperatively work towards common goal of maintained the injection current at booster while fulfilling their individual goals without operator interventions.

For controlling the electron beam orbit in synchrotron radiation sources the conceptual multi-agent based operator support and beam orbit control scheme is formulated. The orbit control job is distributed among multiple low complexity reactive agents at lower layer to control the local orbit for individual beam lines and insertion devices in an optimized manner. The high complexity monitoring agents at higher layer evaluates the performance of the beam line control agents and insertion device control agents and facilitates the generation of medium complexity trainer and fault assistance agents at the middle layer. In this multi-agent based environment study shows that with gradient based constrained trainer agents the lower layer agents can be trained online in the dynamic accelerator environment. Further with this constrained training the beam availability to beamlines can be improved as during the agent training, the local orbit bump leakage is constrained to within beam usable limits thus rest of the beam lines (beam lines other than the one whose control agent is being trained) can be used for routine experi-
ments. Moreover with this scheme the available beam quality to users can be improved through prioritized optimization for the cases when multiple beam lines demand the beam correction simultaneously. Assuming that under dynamic environment the agents can successfully maintain their up to date skill levels with the presented skill learning method, the further study can be done on using this distributed skill information for extracting the systems model which can be used to improve the system performance.


For ensuring the safe operation of the machine in multi-agent based control of the potentially hazardous and safety critical systems like accelerators, the safety measures are needed to be taken at each level of system design. On the positive side the agent based control provides opportunity for maintaining system in stable states through automatic alarm handling. The agents with goals to handle undesirable system events (events that indicates the likelihood of system approaching towards potentially unstable system states) can be made so that the correction can be done much before the system actually lands to some unstable state. Realisation of these goals requires that the agents must posses all the safety related parameter values and action list, at all instants of time. One of the possible method for this is the pre-built action recipe and the limit bounds set as the default by the designer at the time of system design. For avoiding the potentially hazardous system states resulting as the outcome of the agent’s action in response to some changing environment condition, the online formal method of logic verification through model-checking algorithms can be adopted. This approach mainly requires a clear formulation of structural (static) and behavioural (dynamic) system specifications. The loss of communication and loss of functionality (resulting out of failure of some of the coaliating agents in the multi-agent environment) is another important parameter that needs attention. This can be avoided to some extent using the method of online system integrity
checking through token passing within the coaliating agents. Using the state qualification methods and maintaining action and state history, the agents can easily recover the system from unstable state through action reversal for recoverable systems. Although the cases discussed in this thesis are all of recoverable type, for non-recoverable systems the agent plans can be built that allows the agent to control the system for limited states. Also for easy testing and validation of the inter agent actions and their sequence the inter agent interactions are advised to be through centralised data concentrating agents. Also it is advised to distribute the agents in the multi-agent environment at different layers considering their data grouping requirement as per the critical safety capability served by the individual agents (in other words the agents are to be built in such a way that the safety related capability served by the individual agent is dependent only on the system parameters that are in direct perception of that agent). This can avoid the loss of safety related services of the agent, in the event of malfunction/failure of the neighbouring agents. Also the thorough testing of the complete system in simulation mode along with the formal method of verification is a must to be done before allowing such systems to actually control the safety critical parts of the machine such as the automatic operations of safety shutters and vacuum gate valves in case of accelerators.

6.2 Future work

The thesis clearly brings out the benefit of intelligent agent based control implementations for the accelerator control system scenarios particularly for the synchrotron radiation source facilities like Indus-1 and Indus-2 in the form of enhanced machine operation and machine availability. Since at present there is no active control working at the Indus accelerator complex based on the developed system models and the distributed intelligent object based accelerator control system framework. The developed intelligent object
can be deployed for automatic controlling of two subsystems, pre-injector Microtron and Transport line-1 of Indus-1. This requires modifications to the existing control system as well as some of the existing beam diagnostics in both of the subsystems (Like development and testing of the low level hardware interface for the new Microtron control system, installation of online beam position indicators in the TL-1 and development of their interfaces). In future we plan to put the accelerator control system up-gradation proposal based on intelligent object concept in-front of Indus accelerator committee for seeking relevant approvals and machine time allotment. Although the implementation and commissioning depends on the final availability of required hardware and software components, with the present level of developed system interfaces, agent framework and system models we expect that if this work is taken on priority basis (including the related material procurements) than this work can be completed within one and half year time.

Also there are three agent based active control implementation related works (not

![Figure 6.1: GUI of Beam line SR position control system.](image)
discussed in this thesis) taken up at Indus complex that are inspired by this thesis and use
the agent framework and system models developed as part of this thesis work. First one
is the agent based controller for fast magnet power supply of fast orbit feedback control
system of Indus-2. This system uses the developed subsumption reactive agent framework.
In its first phase the agent based maximum rate digital controller is synthesized over
National Instruments PXI platform using NI PXI-7841R, R Series Multifunction RIO with
Virtex-5 LX30 FPGA for hardware in loop simulation and tested ok with simulated power
supply transfer function over PXI-7841R card. Then in its second phase the hardware
prototype for the system is being developed with the help of power supply section. Second
is the model predictive controller for slow orbit feedback control system of Indus-2. This
system uses the developed Indus-2 model in its implementation. Third is the agent based
beam line synchrotron radiation position control system for Indus-2. This system is
basically the cut-set version of the distributed intelligent agent based beam orbit control
of synchrotron radiation sources presented in section 5.4 of this thesis. The main difference
lies in the control system layer where the different agents are distributed and also that
in this implementation only the minimal set of agents are considered for simplicity in its
first version. This uses the developed agent framework with beam line control agent and
insertion device control agents. In its first version, activation of the agent plans are being
performed only by operator and the agents autonomy is restricted to only suggesting the
applicable plan to operator. Figure 6.1 shows the GUI for this system. We expect these
to be commissioned in the coming year.

There are many promising directions for future research and applications like it was
shown that the multi-agent based beam orbit control scheme can successfully perform
the orbit control job and at the same time can impart training to individual local orbit
controlling agents to learn the skills of maintaining the closed orbit bump leakage within
bounds. Future work can be carried out on the schemes for combining this distributed skill information towards extracting the overall systems response matrix. This can greatly improve the global orbit feedback control system performance for the dynamic environment cases.

The study shown that with the agent based control using model based tracking concepts the transport line performance in accelerators can be enhanced for the case of sensor and actuator failures. Further study can be done on similar grounds towards system robustness enhancement for the global orbit feedback control systems in synchrotron radiation sources by online identify the faulty BPM’s and substituting their measurement values with the model based tracked data values for the purpose of calculating the correction settings. Moreover the continuous model based tracked data at BPI locations can be used with the statistical techniques to qualify the data from BPI showing the problem of time dependent offset error. This can improve the overall electron beam orbit stability in the synchrotron radiation sources.

Another promising area of the agent based control in synchrotron radiation sources can be the fast orbit feedback control system. In the fast orbit feedback control the orbit is sensed using BPI’s at the rate of few KHz (5 to 10KHz) and correction is applied to fast correctors. One of the important limiting factor in this type of systems in the overall system delay which restrict the overall control system bandwidth. Future study can be carried on the agent based methods using the systems dynamics and the noise learning capabilities to improve the overall systems noise suppression ability thus this can result in the over all electron beam stability at rate up to hundreds of hertz. Further with the inclusion of online system identification methods for network control systems based plans for the agents this enhancement can be carried further by adaptive controller design.