HYBRID SIMULATION IN VIRTUAL PROTOTYPING OF CYCLOTRON*

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Abstract

Virtual Prototyping of Cyclotrons is a novel engineering method based on CAD/CAE/CAM, system simulation and virtual reality technology. Virtual control is one crucial component in VP, which takes roles of modeling, simulation and validation of the control system of cyclotrons. This paper introduces the theory and method of hybrid system to simulate the cyclotron control system, using a hybrid approach to combine discrete and continuous system of cyclotrons into an integrated model. The integrated simulation environment is also discussed. An example will be presented to show the efficacy of this application. This method aims at shortening the design process and providing more support to the optimization of the prototype of cyclotrons.

INTRODUCTION

Virtual Prototyping (VP) is a new design paradigm being developed these years with the increasing demand for R&D of products in a short period and in a cost effective manner. VP is based on virtual reality (VR) and CAD/CAE/CAM techniques. Furthermore, VP provides an integrated environment in which the processes of design, development, manufacture and operation can be studied and controlled interactively. Virtual prototypes can reduce or replace the use of physical prototypes, further decreasing the expenses of products' R&D.

The compact cyclotron is an economical and versatile tool for fundamental physics research and civil medical applications. We are applying VP technique to design and develop compact cyclotrons, which conduces to generating innovational schemes and reducing risks. Figure 1 shows the framework of the Cyclotron VP integrated platform [1, 2].

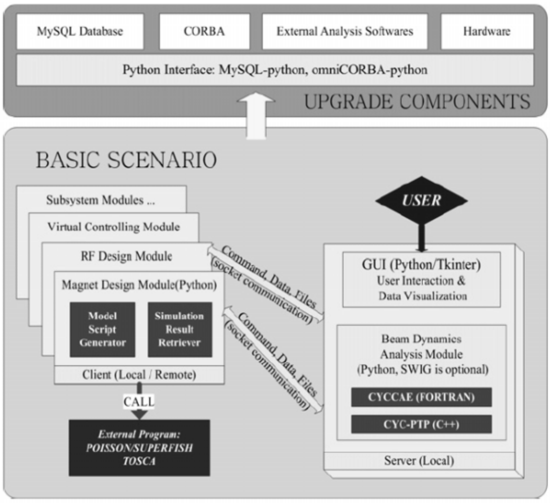

Figure 1: Cyclotron VP integrated platform

The control system, which provides a safe and effective way to manipulate the machine, is a vital section in cyclotrons. Correspondingly, Cyclotron Virtual Control Platform (CVCP) is an important module, taking roles for control system design, modeling, simulation, logical validation, intelligent diagnosis, and Human-Machine Interface design in Cyclotron Virtual Prototype System.

As known, cyclotron control system is complicated with interaction subsystems and a number of feedbacks and logical interlocks. Some components drive the continuous dynamics while others exhibit event-driven discrete dynamics. Such behaviors are characterized by interactions between continuous dynamics and discrete events. Therefore we can integrate hybrid simulation to improve the CVCP.

In this work a framework of using hybrid models to simulate the cyclotron control system as a component of CVCP is proposed. In this framework both discrete and continuous dynamics are described. The models are built and simulated with Simulink and Stateflow environments, all running in Matlab.

OVERVIEW OF HYBRID SYSTEM

Hybrid systems include both continuous and discrete system, which influence each other. The continuous dynamics of such systems may be continuous-time, discrete-time, or mixed (sampled-data), while the discrete systems are generally governed by a digital automaton, or input-output transition system with a countable number of states. The continuous and discrete parts interact at "event" or "trigger" times when the continuous state hits certain prescribed sets in the continuous state space.

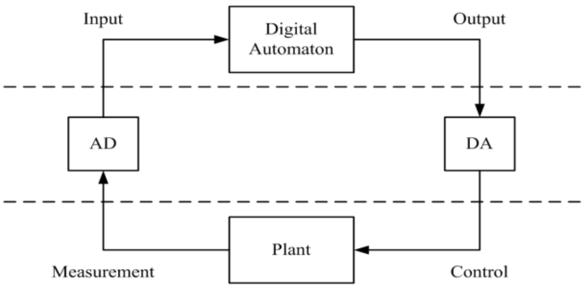

Figure 2: Hybrid System

Hybrid control systems are control systems that involve both continuous and discrete dynamics and continuous and discrete controls. The continuous dynamics of such a system is usually modeled by a controlled vector field or difference equation. Its hybrid nature is expressed by a dependence on some discrete phenomena, corresponding to discrete states, dynamics, and controls [3].

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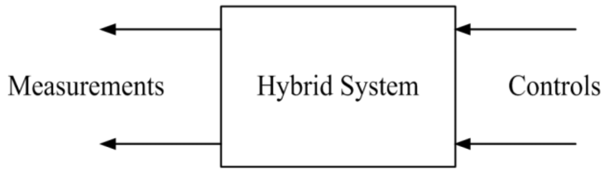

Figure 3: Hybrid Control System

The cyclotron control systems, which cover the control of magnet system, RF system, cooling system, vacuum system, ion source, diagnostics system, extraction system, and safety interlock, usually manifest complex behaviour characterized by interactions between continuous dynamics and discrete events. Therefore the cyclotron control system can be viewed as a hybrid system.

FRAMEWORK OF SIMULATION

In hybrid system continuous components can be easily described by ordinary differential equations, while we use finite state machine to handle discrete components, and then combine the model into an integrated environment.

Finite State Machine Concepts

A Finite State Machine is a representation of an event-driven (reactive) system. In an event-driven system, the system transitions from one state (mode) to another prescribed state, provided that the condition defining the change is true.

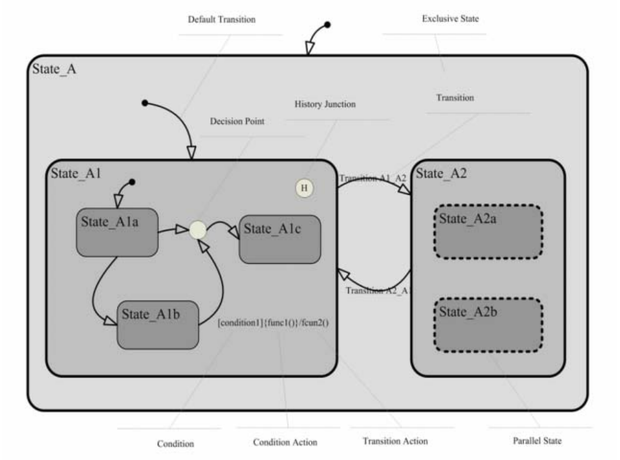

Figure 4: A sample of Finite State Machine

The base components of an FSM are states. There are different sorts of States called States, Super-States and Root-States. States are used to describe the different modes of operation which a system can be in. States can be connected by Transition, which describes when to change to other states (the given condition has to be satisfied) and what states it can change to. [4]

Simulation Environment

We hope the environment for the hybrid simulation provides a coherent framework that can ensure interoperability. We also hope the tools share the model and data of the whole system. Such need comes up in the embedded systems community where Matlab Simulink/Stateflow is used for the simulation.

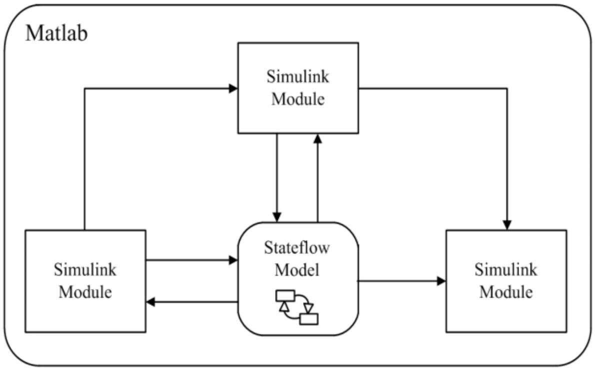

Figure 5: Matlab Simulink/Stateflow

Simulink provides an interactive graphical environment and a customizable set of block libraries that can design, simulate, implement, and test a variety of time-varying systems, including communications, controls, signal processing, video processing, and image processing.

Stateflow extends Simulink with a design environment for developing state machines and flow charts. Stateflow provides the language elements required to describe complex logic in a natural, readable, and understandable form to support the designing of the embedded systems that contain control, supervisory, and mode logic. For the Stateflow is tightly integrated with MATLAB and Simulink, it's an ideal way to simulate the hybrid simulation with Stateflow and Simulink. [5]

CASE

In order to illustrate the usage of hybrid simulation in virtual prototyping of cyclotrons, a simple example is given. The example model represents the process of beam tuning for an 11 MeV cyclotron. The beam tuning follows:

- The Cooling Water, Vacuum, Magnet and RF systems are OK;
- Events "is_on" / "is_off" determine the status of IS;
- Flip-in Probe is used to measure the extraction beam current;
- Regulate the coil current of magnet to improve the foil current;
- Regulate the position of the foil to promise the currents of collimators are equal and the total current of collimators is lower than 10% of the foil current.

Beam tuning involves several different plants of ion source, flip-in probe, magnet, foil, and collimators, and exhibit complex behaviors in response to each parameter. Such behaviors are characterized by interactions between continuous dynamics and discrete events.

In our example, we assume the Cooling Water, Vacuum, Magnet, and RF systems are steady during the beam tuning. The system is built and simulated with the Beam Tuning Blockset, which operates in the Simulink

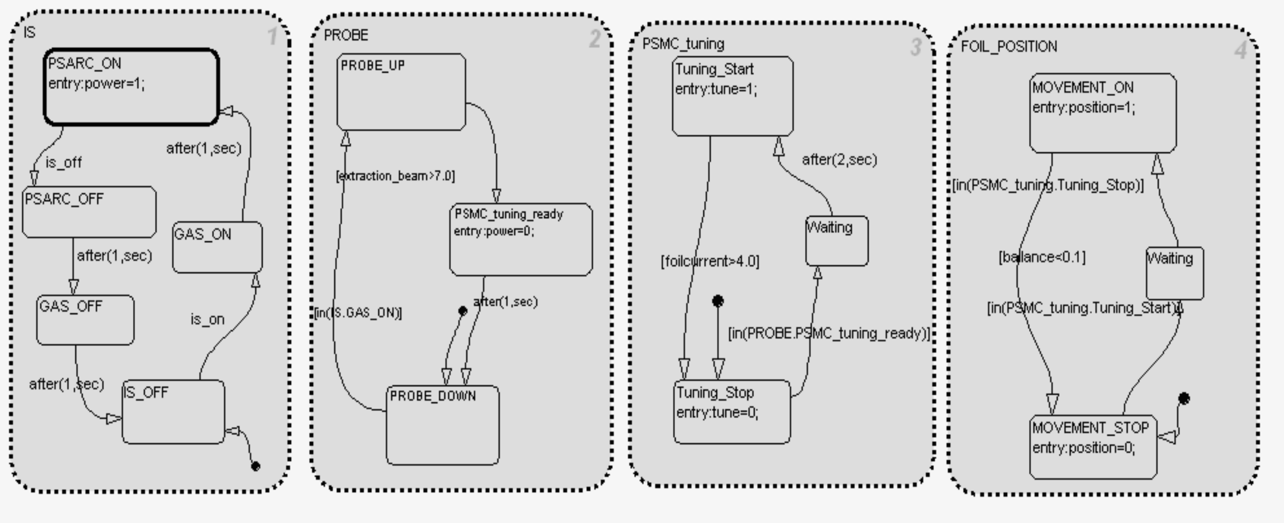

Figure 6: Stateflow: complete state chart

environment, and the Stateflow, all running in the Matlab. Figure 7 shows the entire system.

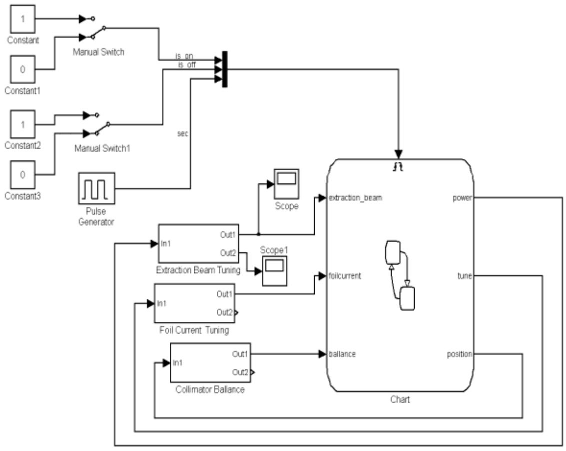

Figure 7: Beam tuning system

Figure 6 shows four parallel super states of ion source, flip-in probe, magnet current tuning and foil position. Each state has sub-states that represent the status of that particular part. These sub-states are mutually exclusive. Transitions determine how states can change and are guarded by conditions.

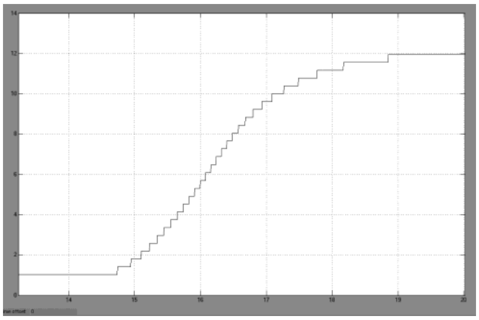

Figure 8: Extraction beam tuning

CONCLUSIONS

In this paper, hybrid simulation in virtual prototyping of cyclotron has been suggested. A framework of an integrated simulation environment of Matlab Simulink and Stateflow has been shown. Such method provides us with the ability to combine and simulate the discrete and continuous systems of cyclotron control system in an integrated model. This approach was illustrated via a simple application of simulating the beam tuning of an 11 MeV cyclotron, and proved to be efficient and flexible for the simulation of cyclotrons.

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