Integrated Discrete Event and Motion Oriented Simulation for Flexible Manufacturing Systems

Rolf Bernhardt, Gerhard Schreck
Fraunhofer Institute for Production Systems
and Design Technology (IPK)
Pascalstraße 8-9,
D - 10587 Berlin
GERMANY

Walter Colombo, Ricardo Carelli
Instituto de Automatica
Universidad Nacional de San Juan (UNSJ)
San Martin 1109 (o)
5400 - San Juan
ARGENTINA

Abstract: In this work we present the design of a software system for integrated discrete event and motion oriented simulation of flexible manufacturing systems, through a cooperative action between the IPK-Berlin, Germany, and the Instituto de Automatica-San Juan, Argentina. Such a computer tool represents a contribution to the design and evaluation of flexible manufacturing systems dynamics, with the particular feature of considering both discrete and continuous motion dynamics. This approach leads to a more complete and realistic evaluation of the systems concerned.

Keywords: FMS modelling, Petri nets simulation, motion simulation

1. Introduction

The real-time control of Flexible Manufacturing Systems (FMSs) is a complex task including the real-time management of factory operations (CAM: Computer-Aided Manufacturing) as well as its integration with the direct control of machine tools or robots (CIM: computer integrated manufacturing). Generally, such systems are decomposed into various "abstraction levels". Although similarities exist, specific models and methodologies are used at each level for specification, validation, simulation and implementation [1].

Simulation is an important step in the design and evaluation of FMSs. It is desirable that simulation includes discrete event as well as motion and process components simulation to fully evaluate the system's performance. In this work we propose the development of an integrated discrete event and motion oriented dynamics simulation system.

One aspect is the development of the model of the FMS discrete co-ordination system. We propose a methodology for modelling and validation based on Petri Nets (PNs), of which theory of analysis is well-founded and allows the properties and performance indices of the models to be obtained [2, 3, 4, 5]. Functional analysis using computer simulation is useful to validate FMSs modeled by means of PNs.

Time parameter presence in the models allows to consider the dynamic evolution of the resources which compose the FMS under study and to consider temporal relationship among resources for completing the proposed tasks [6]. The simulation phase makes it possible a qualitative and quantitative validation of the PNs models and allows to represent the dynamics of the basic coordination control system [7]. The computational model of the co-ordination control system including time parameter is a type of discrete event system controller [3].

Beside the above -mentioned discrete event control system, continuous motion control is a further important aspect for the design and verification of FMSs. This control type is related to the components of a work-cell. An example will be the control system of an industrial robot. Based on a task description of an FMS the required motion can be planned and verified by using simulation techniques. Such aspects as kinematic constraints, systems dynamics or specific control procedures are to be considered. As a simulation result, performance parameters like the cycle time can be obtained with high quality.

For planning and programming the component's control systems, the co-ordination with the higher level control has to be considered, motion and process aspects included. This is reached by the definition of input and output signals which correspond to the activation / execution of motion tasks. Depending on the structure of the FMS, the integration of these communication aspects at the component level asks for a more complex task program and for additional efforts towards evaluating the whole system.

A simulation environment which could provide the signal states for communication as in the real world cell would be an useful tool for planning and verifying the motion oriented FMS components.

2. Discrete Event Modelling and Simulation of Flexible Manufacturing Systems

Petri Nets approach to modelling FMS

The modelling and control problem of a Flexible Manufacturing System (FMS) is in its nature a hierarchical problem [8]. Several modelling approaches have been made [9]. Good models are needed to capture the characteristics of such systems [1], namely: concurrency or parallelism, asynchronous operations, deadlock, conflicts and event driven.

Systems with interacting concurrent components, such as automated manufacturing facilities, have been difficult to model with differential equations and queuing theory. Generally, such systems are decomposed into various "abstraction levels". Although similarities exist, specific models and methodologies are used at each level for specification, validation, simulation and implementation. Petri Nets (PNs) have been purposely designed to model these types of systems [2, 3, 4, 5]. They provide suitable models as

- PNs capture the precedence relations and structural interactions of unpredictable, concurrent, and asynchronous events. In addition, their graphical nature helps visualise such complex FMS.

- Deadlock, conflicts, and buffer sizes can be easily and efficiently modelled.

- PNs models represent a hierarchical modelling tool , mathematically and graphically well-developed. The PNs theory provides an integrated methodology to model physical systems and complex cognitive decision processes, such as rule-based expert control.

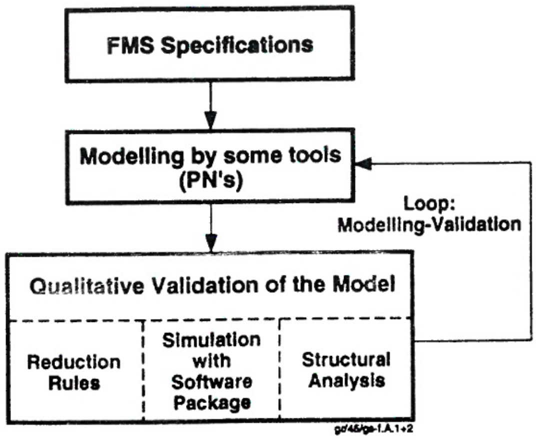

Figure 1. Qualitative Analysis of FMS

- PNs models give a structured framework for a systematical simulation of complex systems. There are various software packages for this purpose [7, 10].

To conclude, we shall say that PNs allow the use of different abstraction level models and the use of powerful modelling methodologies: refinements and modular composition. Nets can be used directly in the modeling process or can be embedded in a higher level application oriented formalism.

Simulation of Discrete Event Systems

Validation analysis is an extensive computation phase in the design of Discrete Event Systems like FMSs [3, 7]. Classically, it goes by simulation (using several formalisms) or by using simplified network models. There is an extensive bibliography for simulation concepts, techniques and languages. Simulation has to validate the various choices that have been made in the previous steps of the control system synthesis according to a set of criteria which may be numerical (machining rates, constraints deadlocks, possible change of working modes,...) or qualitative (absence of deadlocks, possible changes of working modes, ...). In order to both validate and test the dynamic behaviour of the system, there has been developed a simulation program which is able to interpret the model types used for FMSs. Simulation means first to detect errors in modelling by explaining and correcting them, and secondly, to optimize the global behaviour of the system with respect to a "modification/simulation" loop (Figure

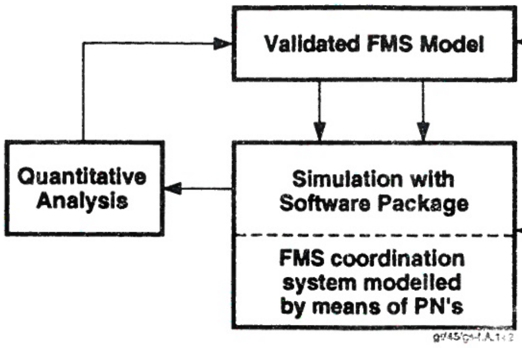

Figure 2. Quantitative Analysis of FMS

1). When the results of simulation are judged admissible, the implementation phase will then be considered.

Qualitative and Quantitative Analysis of FMS

The design process of FMSs is a relatively complex task. Thus, it is very important to validate the significant steps of model building/transformation before going on to the implementation [1, 3]. The phase of the design process is called qualitative analysis of the models. An outstanding aspect of modeling tools like PNs is their capacity for being analysed in order to check if the constructed model proves some specification properties. Among these, synchronic properties - safety properties (distance, places mutual exclusions, etc.) and activity properties - liveness properties (deadlock-freedom, liveness, home states, etc.) can be studied.

High cost of FMSs makes the quantitative analysis of these systems (Figure 2) crucial. In the design of new FMSs, the machines, the layout and the transport system are selected and dimensioned. Performance estimates at this stage need not be very accurate, and relatively simplified models can be used. Adopting a design or a shopfloor requires a detailed optimization model. In conducting studies, huge simulation models and sensitivity analysis are fundamental. Performance evaluation of FMSs [1, 6] deals with issues like: how many machines, and/or automatic guide vehicles (AGVs), which transport topology and routing strategy are best to obtain:

- higher throughput, and/or
- small make span and/or
- more balanced flows.

3. Motion Oriented Simulation of FMS

Approach to Modelling

For simulation, computer internal representations which reproduce the components of a FMS, will be needed. These representations are called simulation models. They should be structured in an unique way, and be applicable to all system components. In [11] the following structure is proposed for the motion simulation (Figure 3):

- shape models which describe the 3-D representation of components,
- kinematic models which contain the frame relations of components, and
- motion models which describe the motion behavior of components.

A 3-D modelling of all relevant components of an FMS system will be necessary in order to analyse planned motions with respect to collision. Shape models can be derived from 3-D representations of CAD systems. For an efficient visualisation of motion simulation the conversion to suitable graphical models (e.g. polygon model) is required.

An important aspect concerning the requirements for cell modelling and motion simulation consists in the determination of frames and frame relations (frame concept). Thereby each component or sub-component is associated with a frame to describe the position and orientation in space. Using homogeneous coordinates all frame relations can be calculated by uniform matrix operations.

Every kinematic structure can be described in terms of joints and links. Joints are kinematic pairs restricting the motion between two rigid objects called links. This means the kinematic joint defines where connections between two parts (links) exist which allow relative motion. The kinematic link represents the topological information associated with a rigid part of a mechanism.

While it is possible to use an arbitrary frame attached to each link, it is helpful to be systematic in the choice of these frames. A commonly used convention for selection frames of reference in robotics is the Denavit-Hartenberg, or D-H convention [12]. This notation requires a coordinate system whose orientation is based on each pair axis and the common perpendicular

Deriving the dynamic equations from motion different methods can be used, e.g. Lagrange's equation, Newton-Eulers's equations or Appel's equations [16]. For modeling and simulation of dynamcis of multibody systems many software packages are available. An overview and

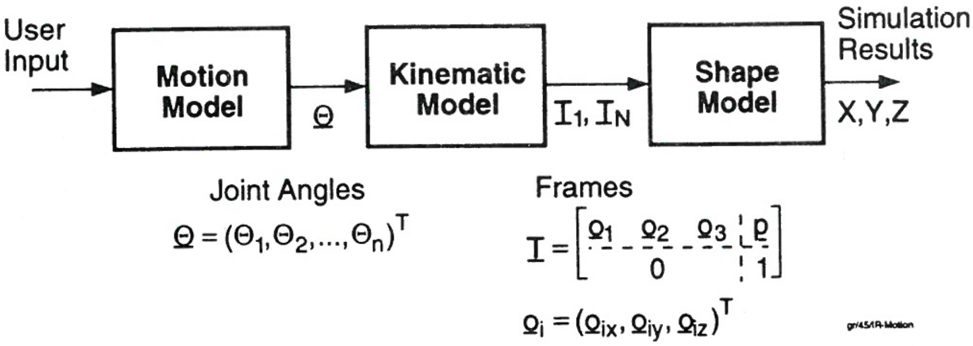

Figure 3. Reference Model for Motion Simulation

between successive pair axes, and that each co-ordinate system thereby remains rigidly attached to the link containing both pair elements [13]. The four parameters used in the D-H notation, are the essential parameters which decribe the 'shape' of each link and its motion with respect to the previous link in the kinematic loop being considered. Based on D-H a generalized notation for general kinematic structures has been introduced by Sheth-Uicker [14]. This notation is used for the definitions of a standardized kinematic description in the frame of ISO (ISO 10303, part 105).

The kinematic model is related to the 'geometry of motion', which means the possible motions to be performed by a mechanism. In some cases also the analysis of the dynamic properties are of interest. Considerations of kinematics play a central role in dynamics. But furthermore masses, mass distribution and forces are to be considered. In addition to the rigid links, the complete description of mechanism dynamics includes the dynamics of the actuators that produces the forces and torques to drive the mechanism, and the dynamics of the drive trains that transmit the power from the actuators to the links [15,12].

comparison ist given in [17].

Motion models are required for all components which can generate a motion (e.g. industrial robot, gripper, conveyor, revolving table). These components can be characterized as active components. Their drives can be controlled by numerical controllers including feedback loops or by simple on / off switches using a PLC. In the case of an industrial robot the motion model is represented by a model of the behaviour of the robot controller (controller model).

Modelling of the motion behaviour can be realized on different levels of abstraction. For modelling and simulation of control structures, general - purpose software packages are available. Simulation as a test method for task programs needs a more accurate modeling. Since different controller types possess different task languages, motion generators and methods for inverse kinematics, special controller models are required for an accurate motion simulation of each type.

Simulation of Motion Oriented Systems

Simulation of motion oriented systems requires the functional connection of the above mentioned models. In the case of an industrial robot (IR) this is as follows (Figure 4): The robot task program is loaded into the control model of the IR. This control model interprets the task program and supplies the kinematic model with the joint values of the links. Within the kinematic model the frames describing position and orientation of each robot part are calculated. Connection of these frames to the relevant shape models enables the visualization of the robot motion on a graphic screen [18]. The same procedure can be applied to all active components of a workcell. For those without an own motion generator (passive components, e.g. workpiece) no motion models are needed. Their motion is described via the linkage with active components.

Simulation can be done on different levels of detail, depending on the planning task to be assisted. Selection of components and layout planning for FMS can be performed by more abstract models, e.g. using the nominal kinematic values out of data sheets or using a generalized motion planning module. Simulation as a tool for task programming requires the modeling of the specific behaviour of each component.

extensive on-side adaptions can be minimized or avoided.

In summary the main results of motion oriented simulation are:

- the check of the practicability of planned layouts,
- the test of the feasibility of task programs,
- the determination of cycle times, and
- the collision check

The above mentioned feasibility test contains testing of the defined trajectories related to positions, orientations, velocities, and accelerations [19].

4. Integration of Discrete Event and Motion Oriented Simulation

Integration Approach

The overall integrated systems concept is shown in Figure 5. Integration of discrete event and motion

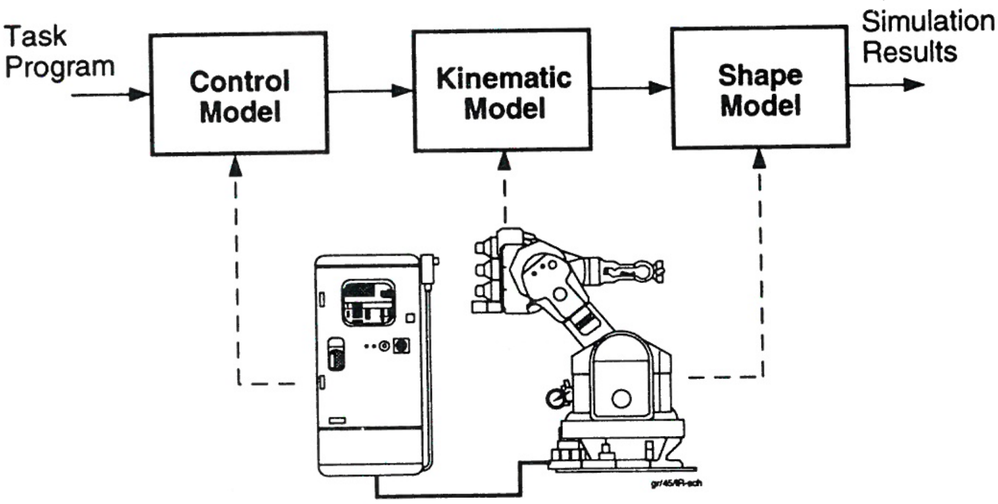

Figure 4.Example of Robot Motion Simulation

Simulation systems available on the market consider these different requirements and provide for example generalized task description languages applicable for all cell components but also native languages for individuell motion controllers.

Evaluation Results

Motion oriented simulation is a helpful tool for system and task planning in the field of flexible manufacturing systems. Alternative system layouts can be modelled and simulated before a specific one be implemented. This leads to more accurate planning data and in general to optimized solutions. In the frame of off-line programming, task programs can be generated and tested before transfer and execution at the real system. Cost

oriented simulation can be analysed from different viewpoints. Discrete event simulation including time parameter requires estimated or calculated time values for processes and operations to be executed in the modelled system. Accurate cycle times could be provided by motion oriented simulation. Motion oriented simulation has to consider process related commands, interactions with peripherals, and communication with higher control levels. These signals / information could be provided by discrete event simulation. From the global view of FMS planning the tasks to be performed are to be subdivided into sub-tasks on different levels, to reduce the planning complexity. This sub-tasks can contain event control or motion control aspects. The allocation of task execution to devices (e.g. cell controller, robot controller) can be

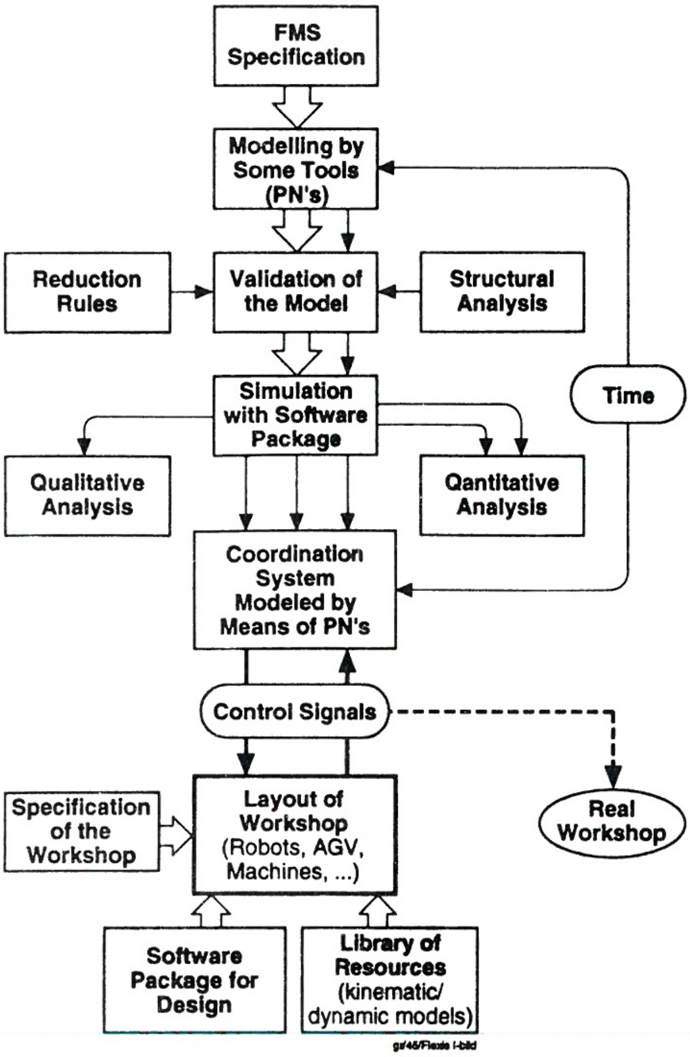

Figure 5. Overall System Concept

done after modeling and simulation of the overall system.

To consider this different viewpoints in a first step a common reference model for FMS planning (planning procedure) has to be elaborated. In a second step suitable interfaces for the integration of discrete event and motion oriented simulation have to be identified and specified. A first draft is shown in Figure 6.

Expected Improvement in FMS Design and Evaluation

In order to achieve these two main improvements, new software has to be implemented by using discrete event and motion oriented simulation. With this software, an off-line simulation can be performed during the production planning phase for the design and evaluation of a FMS. This software is also used to determine the process control parameters for satisfying -insofar as possible- the following main objectives; short lead times for orders, minimum workshop and

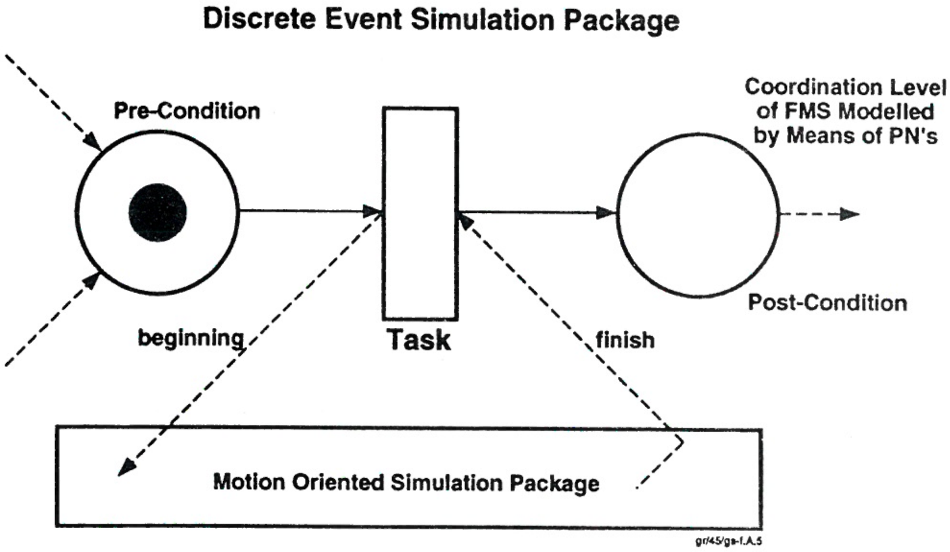

Figure 6. First Integration Approach

warehouse stockage levels, low transportation costs, and investment optimization.

Based on the above viewpoints, the present work aims to develop an integrated computer-aided system to reach the following main objectives:

1. to obtain the detailed planning of flexible production systems using a computer discrete event and motion oriented systems tool.
2. to develop an integrated computer internal model of the system under study, taking into account its discrete event characteristics.
3. to validate the FMSs modeled with tools like Petri Nets
4. to simulate and test the task execution for every equipment of the planned production system with regard to its kinematic and dynamic evolution
5. to link the computer tools for discrete event systems and motion oriented system designs, in order to obtain a complex software package for helping the FMS system designer.

5. Conclusion

Since simulation is an important step in the design and evaluation of FMSs, it is desirable that it includes discrete event as well as motion and process components simulation to fully evaluate the system's performance. In order to aid the designers of FMSs to design and examine manufacturing system dynamics quickly and effectively, we propose in this work the development of an integrated discrete event and motion oriented dynamics simulation system.

The real time control of Flexible Manufacturing Systems (FMSs) is a complex task including the real-time management of factory operations (CAM: Computer-Aided Manufacturing) as well as its integration with the direct control of machine tools or robots (CIM: Computer Integrated Manufacturing). This work intends to produce a contribution to the design in the CIM field, by integrating the two main computer-aided design tools previously cited and developed by the IPK (Berlin, Gerrmany), and the Instituto de Automática (San Juan, Argentina).

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