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MODELING AT THE MACHINE-CONTROL LEVEL USING DISCRETE EVENT SIMULATION (DES)

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ABSTRACT

Simulation at the machine-control level plays an important role in designing machine controls and operational specifications. Recently, there has been a considerable amount of work done in the area of manufacturing systems control. This micro-level type of modeling is as important as modeling at the plant level. This paper is an application case study of modeling at the machine-control level. The objective of this paper is to address the issues of augmenting control design for automated production systems through the use of DES. The case study is an automated process of a frame turnover. In this process, an inbound conveyor transfers large frames into a turnover unit. Frames are accelerated toward the lift and rotate unit using a hydraulic slide. Frames are lifted and rolled over side to side then lowered onto an outbound pedestal conveyor. The pedestal conveyor shifts frames to the unloading station. The objectives of the case study were to visualize the turnover process and to design the sequences and timing of its operations. Based on that, it is required to verify that there is enough time for the turnover process to take place in synch with the movement of the inbound and pedestal conveyors. Finally, the machine controls are designed so that the system throughput and operational specifications are achieved.

1 INTRODUCTION

Discrete Event Simulation (DES) has undergone a tremendous development in the last decade. The drastic evolution of computer technology along with the steady progress in simulation software established a solid infrastructure for this development.

The utilization of DES in designing engineering systems is commonplace among most prominent manufacturers. A wide range of DES applications have emerged in both service and production sectors. Computer tools for simulating production systems represent the largest portion of these applications. DES manufacturing applications range from designing the operation of a single tool to designing the operations of a plant or an assembly line.

A requirement in most DES studies is to ensure that the system meets the expectations and design requirements. This can be applied to both macro-level and micro-level manufacturing systems. Macro-level modeling considers plants, assembly lines, and all types of integrated systems. On the other hand, micro-level modeling considers the deep details of systems such as machine-controls and tool design.

For both macromodel and micromodel applications, it is usually essential to determine the optimum configuration of system elements so that the best performance is achieved. Accurate simulation models for each level of the system can provide the designers with the insight and knowledge necessary for designing and implementing the system correctly.

Many DES studies that are conducted on a plant or an assembly line recommend the elimination of a bottleneck at a certain production unit in order to meet system targets. Often times, designing the machine controls properly results in increasing the efficiency of the unit, which may result in eliminating the bottleneck of the production system.

DES studies at the machine-control level can be conducted in an approach similar to macro-level DES studies. The discrete digital control of the machine can be designed and validated using DES models.

2 COMPUTER SIMULATION

Computer simulation methods have been in use since the 1950s. Progress in modeling and simulation occurred rapidly. Computer simulation, as a science and art, is used to mimic the behavior of real-world systems. Attempts to use analytical models to approach real systems usually require many approximations and simplifying assumptions. This is likely to yield to inadequate solutions for implementation. If relationships that compose the model are simple enough, it may be possible to use mathematical methods to obtain exact information on questions of interest. Since most real-world systems are too complex to allow for analytical or mathematical evaluation, computer simulation is used to model these systems numerically.

Winston (1994) defined simulation as a technique that imitates the operation of a real-world system as it evolves over time. Most of other definitions to simulation were in the same track while stressing the uniqueness and the diversity of simulation concepts.

Pegden (1990) considered simulation modeling as an experimental and applied methodology that seeks to accomplish the following; describe the behavior of systems, construct theories and hypotheses that account for the observed behavior, and use the model to predict future behavior.

As shown in Figure 1, simulation models are classified based on the model type as *iconic* or *symbolic*. Iconic models are physical types of modeling that can be pilots or prototypes. On the other hand, symbolic models are deterministic or stochastic mathematical/logical representations of systems. Based on internal representation scheme, simulation models can be *discrete*, *continuous*, or *combined*. Furthermore, models are either *deterministic* or *stochastic* depending whether they model randomness and uncertainty in a process or not.

Law (1991) defines Discrete Event Simulation (DES) as “ the simulation that concerns the modeling of a system as it evolves over time by a representation in which the state variables change instantaneously at separate points in time.”

In the last decade, simulation software achieved considerable progress in both development and applications. A variety of simulation software with different features and capabilities entered the business simulation through a wide range of applications. Simulation software has evolved from the use of procedural languages such as BASIC, FORTRAN, and C to special purpose languages that deal with specific simulation and industrial terminology. These languages made the simulation process much easier and more applicable to different areas.

Writing the computer code for a complex simulation model has traditionally been a difficult and a challenging task. Because of this fact, computer simulation languages have been developed to simplify or even eliminate the programming part of simulation.

Examples of simulation software are GPSS, GASP, SLAM, SIMAN/ARENA, WITNESS, PROMODEL, AUTOMOD, TAYLOR II, QUEST, XCELL+, SIMPLE++, SIMUL8, and MICROSAINT.

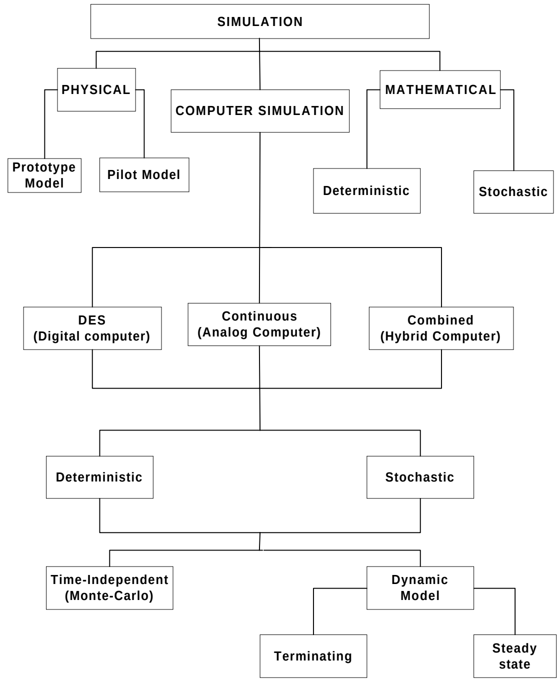

Figure 1: Simulation Taxonomy

In parallel to other computer software, simulation software is increasingly able to share information with other applications. This is done by accepting information from spreadsheet or databases and outputting data to them as well. Most products also provide access to procedural languages (such as C code or Visual Basic) which can be linked to the simulation code to perform specialized computations such as scheduling and decision-making.

The interaction between the World Wide Web (WWW) and simulation is the most interesting recent development in the field of simulation. Using the Web as a source of simulation information, the development of JAVA-based simulation, and geographically distributed simulation, are forms of this web-based interaction.

3 MODELING AT THE MACHINE-CONTROL LEVEL

Modeling at the machine-control level is an important application of DES for different manufacturing arenas. Modeling the deep details of a single machine or a workstation is similar to modeling integrated systems such as plants, logistics, and assembly lines.

This micro-level type of modeling has received less attention than the macro-level modeling approach. This is based on the belief that DES considers designing and controlling processes that result from the interaction of different system elements. These elements such as machines, operators, and robots are not usually considered in separate models.

Each machine in the system is modeled as a black box that uses a resource for a deterministic or a stochastic cycle time. To account for the machine downtime, some failure distribution is applied to the station resource. The design of sequences, timing, and control logic at the machine-level is barely considered in simulation studies.

Deficiencies in designing the production process result in lowering the performance and the quality of the production system. The integration of low-level manufacturing process into a high-level production system is shown in Figure 2.

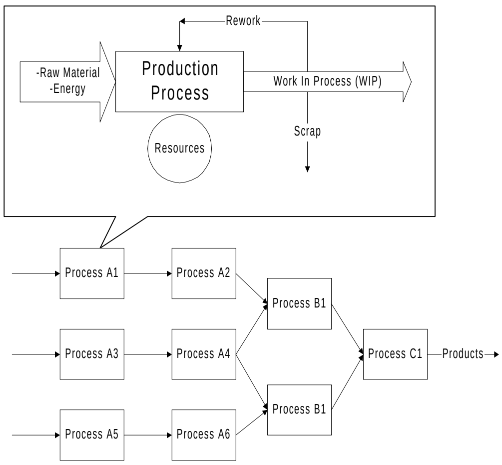

Figure 2: Micro-level Processes integrate into a High-level Production System

In the simulation process, the real system could be a single production process that receives raw materials and uses resources to develop work in process (WIP) to other processes in the system. It could also be a production system or a plant that integrates production processes in developing useful products to customers.

Since most real-world processes are complex, stochastic, and highly dynamic, the design phase becomes a particularly challenging task. DES models are capable of capturing this complex behavior. These characteristics exist in different levels of the process. These levels range from a single machine or a production process within the production system, up to a high-level production system.

There are several reasons behind the motivation toward modeling at the machine-control level:

1. Eliminating system bottlenecks. Some machines have complexity in their operation so that processing is performed through complicated logic and events sequencing. In those machines, changing the control design may result in reducing the cycle time, improving efficiency, or decreasing the number of failures in the machine. If the machine represents a bottleneck that limits the capability of the whole system, modeling at the machine-control level becomes a necessity to explore the possibility of eliminating bottleneck and boosting system capability.
2. Designing the operation of a single machine. In some cases, the interest of the designer is to develop an efficient sequence and a robust control design to optimize a single-machine operation. Building a separate DES model in such cases facilitates the machine design process by allowing the designers to try out different work elements, different timing and sequencing scenarios, and different control logic without the need to change the machine hardware. Visualizing the machine operation can also help in debugging the design and brain storming of different design issues.
3. Approaching more realistic models. Modeling expensive and sensitive systems requires combining macro and micro level design into one model. This is the closest type of modeling to reality. In such cases the *ripple effect* of the machine design (elements and logic) can propagate through out the integrated system and affect its efficiency, throughput, and reliability.

4 THE SIMULATION PROCESS

It is quite beneficial to describe a generic simulation process that considers modeling real-world processes at both macro and micro levels. This process has developed over time and in different ways. The advanced modeling methods and the breakthroughs in computer technology are the major elements in the simulation process development.

Advanced computer simulation tools are now capable of targeting both Manufacturing Process Simulation (MPS) and Business Process Simulation (BPS).

Since most manufacturing and business processes deal with discrete entities such as products or dollars, DES is usually considered in developing the process model.

The simulation process, as shown in Figure 3, has four major elements. These elements are; the real system, the human intelligence, the conceptual model, and the simulation model (Al-Aomar, 1997). These elements interact with each other in each DES study.

The real system is the focus of the DES study for design and improvement. Human intelligence, which plays the central role in the simulation process, decides on the modeling procedure for the real system. A conceptual model is created as an abstraction to the real system. Conceptual models are the blue prints for building computer simulation models.

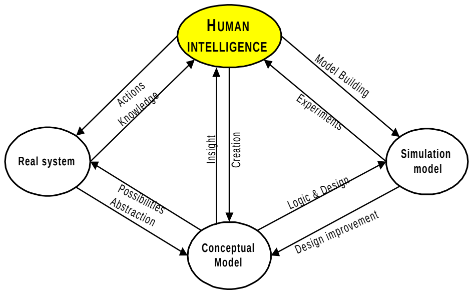

Figure 3: The Simulation Process

After validating the conceptual model, the logic is translated into a computer simulation model that mimics real system operation and estimates its performance measures. In order to prescribe solutions to the problems of the real system, human expertise and intelligence should master simulation modeling and understand the real systems operation. A clear understanding of the real system in terms of elements, logic, and measures, gives insight to redesign the logic and specifications of the simulation model.

The simulation model is validated and verified in order to be a reliable tool for decision-making (Balci, 1994). Experimental design and analysis (Montgomery, 1991), that are conducted using the model, can result in a set of conclusions. These conclusions can be translated into improvement actions that are applied to the real system.

The impact of these actions can be tried out using the simulation model before being recommended to the real system. Each stage in the simulation process incorporates time and cost, which limits the amount of experimentation and analysis.

5 CASE STUDY

The case study is an automated process for a frame turnover. The unit receives large frames from an inbound conveyor, rolls them over side by side, and places them back on an outbound pedestal conveyor. The movement system that brings frames into the turnover unit is in synch with the movement system that transfers frames outside the unit. In order to facilitate the turnover, some acceleration to the frame is required. After the turnover takes place, frames are lowered and placed on pedestal legs moving on the pedestal conveyor. The pedestal conveyor transfers the frame outside the unit to the unloading station.

The process begins by the frames entering the unit on the inbound conveyor and ends with frames leaving the unit on the pedestal conveyor. As shown in figure (4) the system consists of four main elements each with a certain role in the process:

- Inbound conveyor: The movement system that transfers frames into the turnover units. The rate at which the transfer takes place is 75 UPH (Units Per Hour) and the transfer distance is 72 inches.
- Hydraulic slide: The hydraulic cylinder that accelerates and forwards the frame to the hydraulic lift and rotate unit. In order to match the frame movement with the lift and rotate speed, the hydraulic slide is used to mediate the transfer to the unit and facilitate the turnover. The slide transfers the frame 36 inches at a speed of 12 inch/sec.
- Turnover unit (Hydraulic lift and rotate): This is the core operation in the turnover process. The hydraulic cylinder lifts the frame by 40 inches. The Frame is rolled over by 180° using a rotating disk. After the turnover is performed, the frame is lowered and placed on the pedestal legs of the conveyor.
- Pedestal conveyor: The movement system that transfers the rotated frames 72 inches out of the turnover unit. It moves at the same rate as the inbound conveyor, which is 75 UPH. Before transferring the frame outside the unit, it has to be placed on the legs of the pedestal conveyor. To do so the hydraulic lift has to lower the frame in synch with the movement of the pedestal legs so that they meet at the pick up point.

The objectives of the study can be summarized as follows:

- Simulate the turnover process and visualize the concept of operation.
- Verify that enough time is available for the process to take place without affecting the motion of the inbound and the outbound pedestal conveyors.
- Develop the design for the sequence of events that take place at the turnover unit.
- Develop the timing design for the work elements so that the unit targets are met.
- Develop control logic that is able to operate the unit efficiently.

6 MODEL DESCRIPTION

The DES model is developed using the 8.5 version of AutoMod™ simulation package. Two important features of AutoMod™ are essential for modeling at the machine-control level; modeling the deep details of the system elements and the flexibility to develop complex logic and make decisions with the code.

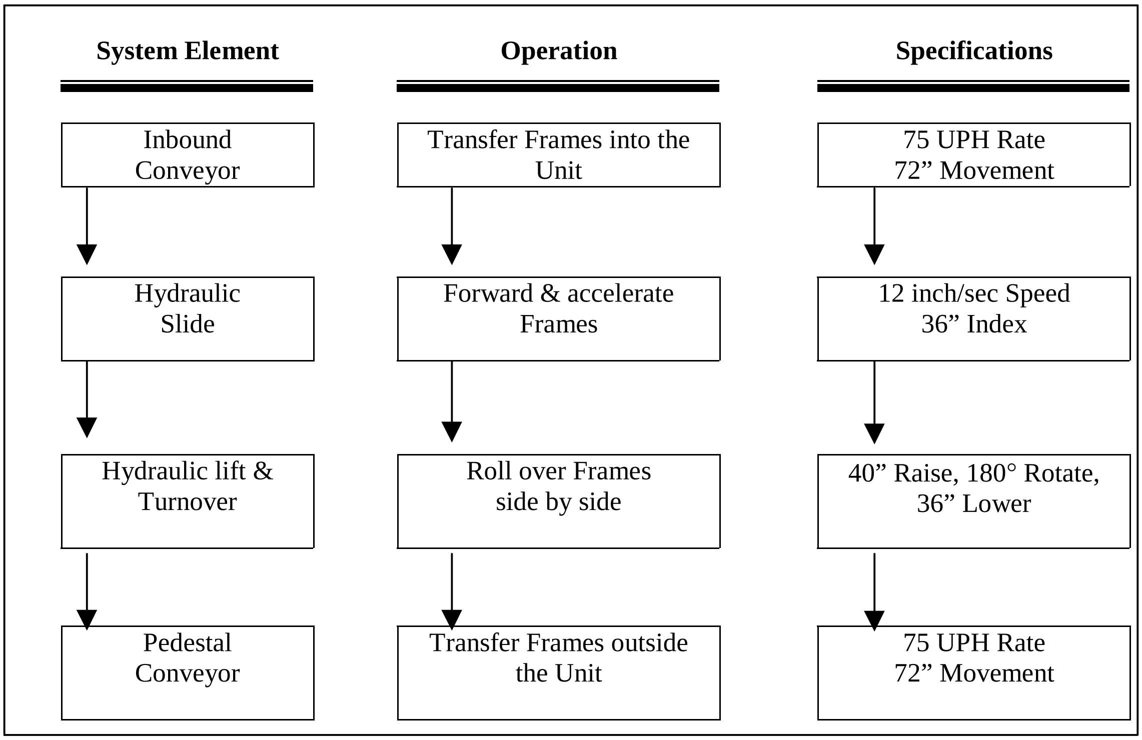

Figure 4: System Elements and Specifications

The capability of the software in developing system details facilitates visualizing and validating the process.

By providing a flexible platform to program and manipulate the code of the process, AutoMod™ facilitates developing the control logic of system elements.

Based on the conceptual model, the simulation elements such as processes, resources, and entities are defined. Kinematics systems are used to develop the motion for different elements such as transfer, lift, lower, and rotate.

Conveyor systems, which are a part of most simulation environments, are used to simulate the inbound and pedestal conveyor.

Different load types are used to represent the progress of operations while moving between system elements.

To integrate the operation of different system elements, the control logic is developed and programmed into the model.

After validating and verifying the model, experimental design and output analysis can take place.

7 RESULTS AND ANALYSIS

Analyzing the results of simulation runs is a crucial stage of every simulation study. Conducting experiments and analysis should aim at meeting the objectives of the study and producing the deliverables.

7.1 Sequence design

Designing the sequence of work elements that take place at the turnover unit is necessary to the process design.

The followings are the sequences of events that take place at the turnover unit:

- The inbound conveyor is continuously moving at 0.187 ft/sec bringing a frame every 48.0 seconds.
- Frames travel 72 inches on the inbound conveyor to the hydraulic slide.
- The hydraulic slide extends the frame 36 inches (12 inch. /sec speed).
- The turnover unit (the lift and rotate unit) raises the frame 40 inches.
- The turnover unit (lift and rotate) rotates the frame by 180° at the 40 inch level.
- The turnover unit (lift and rotate) lowers the frame by 32 inches.
- Empty pedestal legs travel on the pedestal conveyor to the frame pick up point.
- The turnover unit (lift and rotate) lowers the frame by 8 inches upon the arrival of the pedestal legs.
- The full pedestal-leg conveyor travels 72 inches out of the pick up station at 0.187 ft/sec.
- The turnover unit (the lift and rotate unit) raises empty 40 inches.

- The turnover unit (lift and rotate) rotates back by 180° at the 40 inch level.
- The turnover unit (lift and rotate) lowers 40 inches to the original point

7.2 Timing design

After designing the sequence of events or work elements, it is essential to design the times of this sequence so that the unit target (75.0 UPH) is met.

The turnover process (lift and rotate operations) has to take place while both the inbound and pedestal conveyors are moving in synch.

The total cycle of the turnover process can be broken down as shown in Table 1.

The following issues are considered in designing the timing scheme:

- Since the two conveyors move at the same speed, the turnover process has to take place before the full pedestal conveyor clears the slide to extend a new frame.
- The maximum time available for the process is 48.0 seconds. Clearance time for the pedestal conveyor is 32 sec (72 inches).
- The pedestal conveyor has to signal the turnover unit 1.0 second ahead of pedestal arrival so that nesting at the frame pick up point can be achieved. This leaves (48.0 – (32.0 + 1.0)) = 15.0 seconds for the turnover process to take place. Only 12.0 seconds are required for the turnover process to take place.
- The turnover unit waits for a signal from the empty pedestal conveyor before lowering the frame. The accepting-frame signal has to come 1.0 second (2.25 ft) before the arrival of the pedestal legs. Within this time, the frame is lowered by 8 inches so that it is placed on the legs of the pedestal without stopping the conveyor.
- The pedestal leg fixtures are on the same center distances as the frames.
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Work elements 6, 7, and 8 have a total of 7.0 seconds. This means that (32.0 – 7.0 = 25.0 seconds or 56.3 inches) are left to the pedestal legs to clear.

7.3 Control logic design

At the machine-control level, logic should be developed and designed to integrate the operations of different work elements. Several waiting and signaling activities take place in the logic. Designing the limit switches that

Table 1: Timing Design of the Process Work Elements

Step No.	*Work Element*	*Time (seconds)*
1	Extend the frame 36 inches (Hydraulic slide)	3.0
2	Raise the frame 40 inches (Lift and rotate unit)	3.3
3	Rotate the frame 180° (Lift and rotate unit)	3.0
4	Lower the frame 32 inches (Lift and rotate unit)	2.7
5	Lower the frame 8 inches (Lift and rotate unit)	1.0
6	Raise empty 40 inches (Lift and rotate unit)	2.0
7	Rotate back 180° (Lift and rotate unit)	3.0
8	Lower the frame 40 inches (Lift and rotate unit)	2.0
Total	*All work elements (after considering simultaneous steps)*	**12.0**

Table 2: Critical Limit Switches in the Process Control Design

Limit Switch	Description	Waiting element	Activating element
LS1	Frame present at the hydraulic slide	Hydraulic slide	Inbound conveyor
LS2	Before extending the frame	Hydraulic slide	Hydraulic lift & rotate
LS3	Before extending the frame	Hydraulic slide	Pedestal conveyor
LS4	Frame present at the lift and rotate	Lift & rotate unit	Hydraulic slide
LS5	Before lowering the frame to pedestal	Lift & rotate unit	Pedestal conveyor
LS6	Before rotating back	Lift & rotate unit	Pedestal conveyor

sequence and time the events of the process provides a solid infrastructure for the actual control architecture. Examples of signaling issues in the model include the following:

- The hydraulic slide can not extend a new frame until the pedestal clears the unit and the lift and rotate unit is rotated back to its original position.
- The lift and rotate unit has to wait for the pedestal legs before lowering the frame on the conveyor
- The empty pedestal legs have to signal the lift and rotate unit.
- The lift and rotate unit can not rotate back before the pedestal conveyor clears the unit at 56.3 inches

Limit switches can be used to perform different signaling requirements in the machine. Critical limit switches in the control design of the process are summarized in Table 2. The operation of these switches together is validated through the DES model.

8 CONCLUSION

Modeling at the machine-control level is an important application of DES modeling. This micro-level modeling type is less popular than the conventional macro-level modeling. Modeling at the machine control level is essential when it is required to eliminate a bottleneck from the system at a certain workstation or unit. It is also beneficial when designing the operations of a single machine or modeling expensive and sensitive machines. The simulation process for modeling at the machine-control level is quite similar to that of regular DES studies.

Modeling at the machine-control level with AutoMod™ simulation package allows for visualizing the deep details of the process and developing complex control logic. These capabilities assist in validating the process, developing robust machine controls, and brain- storming of different design issues.

Through the case study, it has been shown that designing the sequence of events, timing, and control logic, at the machine level is quite possible using DES. Having this information available makes it easier to develop and implement the machine control architecture, to operate the machine, and troubleshoot possible problems.

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