Study on Efficient Development of 1D CAE Models of Mechano-Electrical Products

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Abstract

To promote the use of 1D CAE model in the mechano-electrical industry, it is necessary to resolve the issues associated with the model and reduce the cost of creating it. We are in the process of developing the guidelines for creating proper 1D CAE models that will help reduce the modeling cost. A mechano-electrical product is generally a complex system of mechanical, electrical/controlling, and software components. In the industry, Modelica and MATLAB/Simulink are emerging as popular tools for modeling the mechanical and electrical/controlling components, respectively. Programming languages derived from C are usually used for describing the software necessary in the mechano-electrical product. For example, SystemC is recognized as a standard tool for describing a hardware behavior in the design of electronic circuits to be incorporated in the product. In this study, we investigated a method for the combined use of these tools. We explain our findings in our experimental construction of 1D CAE models of a mechano-electrical product using Modelica, MATLAB/Simulink, and SystemC simultaneously.

Keywords: 1D CAE model, modeling guideline, Modelica, MATLAB/Simulink, SystemC, FMI

1 Introduction

Compact, high-precision, and high-performance mechano-electrical products such as multifunctional copiers, printers, and digital cameras are products of manufacturing industry in which Japan has demonstrated its excellence traditionally. While developing these products, high functionality and low price are to be ensured. Accordingly, technologies for supporting the design are considered to be the critical success factors in realizing an efficient and reliable product.

Figure 1 illustrates a typical design process for a high-tech mechano-electrical product. We divided the process into four stages: function and performance consideration, packaging and control design, system evaluation, and producibility evaluation. In this study, we focused on the first stage that determines most of the fundamental structure and parameters of the product. To realize a high functionality and a low price, it is important to utilize the computer simulations effectively in the design processes so that the feasibility of the functions is evaluated and the appropriate design options are narrowed down at an early stage.

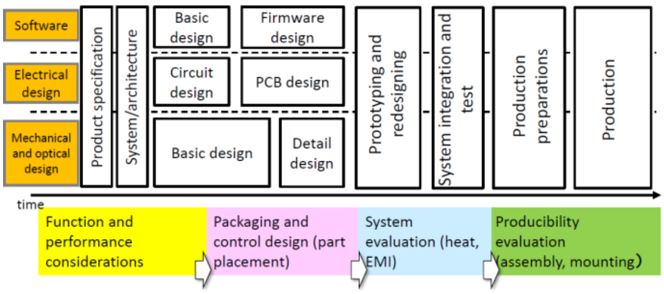

Figure 1. Typical design process of mechano-electrical products.

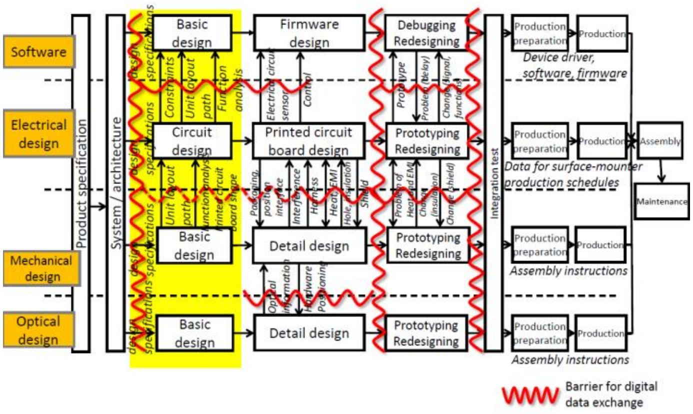

Figure 2. Barriers between design processes.

Considering that only a limited geometric information of the product is determined at an early stage of design, the existing CAE technologies are not suitable for simulations straightaway. Therefore, the Japanese manufactures prefer to develop their own original solutions such as an analysis software or a simulation model, and to use their proprietary knowledge base such as the original formulations, empirical formulae, and technology know-hows built over time. However, there are several practical issues in using these original systems especially in respect of their maintenance, integration with other CAD/CAE systems, and validation of their solutions.

Figure 2 illustrates the typical issues encountered by the Japanese mechano-electrical industry in interfacing the design processes. As shown in the figure, there are “barriers” to smooth digital data exchange between the design processes of the CAD and CAE systems. Therefore, many manufactures in Japan develop their own original interfaces and data sharing methods. However, this approach has a few inherent limitations particularly in respect of the distribution of data. Consequently, manual data exchange is still widely adopted in Japan.

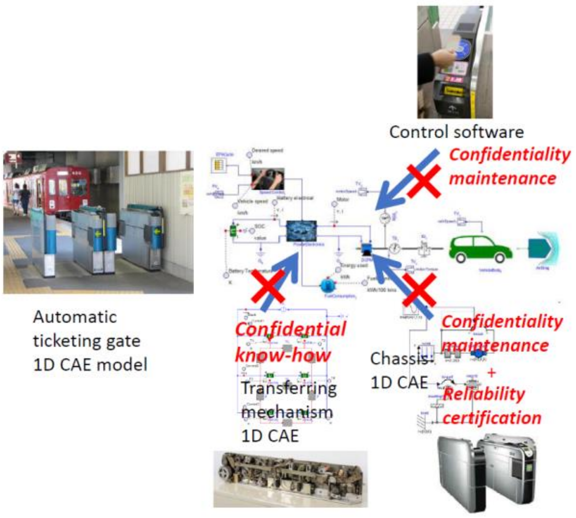

Figure 3. Problems in the joint development of a mechano-electrical product with multiple companies.

While development of a product jointly by multiple companies is becoming a common trend, there are critical issues in data exchange and co-simulations by multiple systems. Figure 3 illustrates the issues found in the joint development of an automatic ticketing gate in a railway station. In the case of a product developed by a single company, the parts are simply purchased, while their CAD models (electrical data) are required to determine the appropriate fixing and assembly methods. Nowadays, most products are developed by multiple companies jointly through collaboration. It is necessary that the engineering information (CAD and CAE data) of all the parts are available in the early stage of design to enable a comprehensive analysis of the product. In the case of the example, the major parts are the ticket transferring mechanism, chassis, and control software for automatic ticketing gate operation. Compatibility of the data and the models between the simulation systems is an essential factor to realize the collaborative product design successfully.

2 1D CAE for Mechano-Electrical Products

In Japan, we constituted a Standardization Committee of New Digital Verification Technology to establish a standard method for using the computer simulation technologies so that it can assist the design activities of a mechano-electrical product in its function and performance consideration stage.

In the design of automobiles and aircrafts, the product functions are rapidly advanced, resulting in issues similar to those related to a mechano-electrical product, and therefore a problem-solving method known as model-based development (MBD) is widely adopted. In MBD, the various conditions related to the requirements and functions of a product are defined by mathematical models. By evaluating the models, the product functions can be verified at the early design stages. Considering that simple analyses are often employed prior to determination of the 3D information, the MBD that is applied at the early functional design stage is specifically known as 1D CAE. Tools such as Modelica (Fritzson 2011) and MATLAB/Simulink (Tyagi 2012) have been used extensively in the automobile/aircraft industries. In these tools, the mathematical formulae related to the product functions are expressed as icons on the GUI of a computer, while the mathematical models for functional verification are represented by the interconnections.

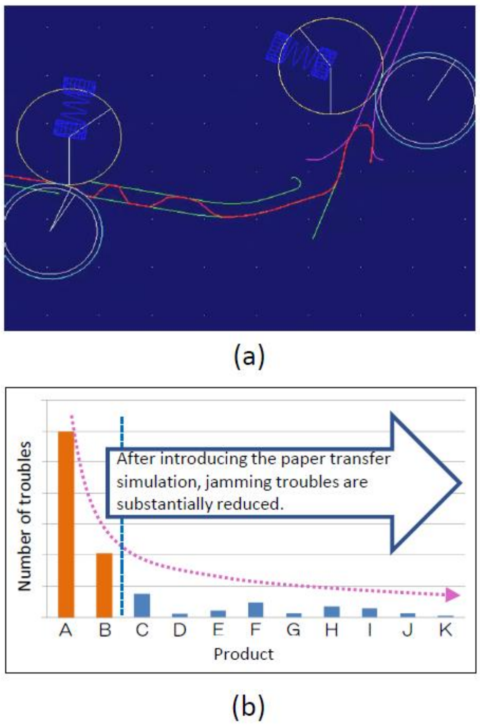

Figure 4. Paper transfer simulation of a plain paper copying machine in early design stage.

The 1D CAE model is considered to be effective for assisting the functional design of mechano-electrical products. Figure 4 illustrates an example of MBD for the design process of a plain paper copying machine, which is a typical mechano-electrical product whereby it is critical to analyze the behavior of the paper while it is moving.

In earlier days, the paper behavior was checked by using a trial product. When a paper was jammed during the real-time use of a machine, the position and posture of the parts were slightly adjusted by guessing the paper behavior. Nowadays, the designers themselves analyze the paper behavior right at the initial stage of design by suitable paper transfer simulations (see Figure 4(a))(Hayakawa 2008). After introducing the paper transfer simulation, the jamming troubles are substantially reduced (see a graph in Figure 4 (b)).

As shown in this example, the 1D CAE model is effective in assisting the functional and performance design of the mechano-electrical products. Unlike the automobile and aircraft industries, the 1D CAE model is not a popular design method for mechano-electrical products. Some reasons for its limited use include the facts that:

- The development cycle of a mechano-electrical product is relatively brief, and therefore, the cost of preparing the mathematical model for 1D CAE represents a relatively large proportion of the total cost of the product.
- The basic structure of a mechano-electrical product changes rapidly, and therefore, the prior models cannot be used in new designs for obvious reasons. In other words, a new model needs to be created for every new product.
- The scale of business of a mechano-electrical product is relatively small, and therefore, it is not economical to train the engineers in 1D CAE that is a specialized subject.

To promote the use of 1D CAE in the mechano-electrical industry, it is necessary to resolve the issues associated with the use of 1D CAE as much as possible, and to reduce the cost of creating the model. We consider that the following two methods are effective in increasing the efficiency of creating a 1D CAE model.

1. **Development of modeling guidelines:** Creation of a 1D CAE simulation model is a complex task, and therefore, a trial and error process is indispensable. Accordingly, the cost of creating the model increases. To reduce the cost arising out of the trial and error process, we are developing guidelines for creating the 1D CAE models especially for mechano-electrical products. In the guidelines, the desirable steps in the modeling process as well as the important points to be noted in each step are mentioned. Accordingly, the guidelines help reduce the trials and thereby minimize the modeling cost.
2. **Clarification of important points in the combined use of Modelica, MATLAB/Simulink and SystemC:** A mechano-electrical product is generally a complex system comprising mechanical, electrical/controlling, and software components. In the industry, Modelica and MATLAB/Simulink are emerging as popular tools for modeling the mechanical and electrical/controlling components, respectively. Programming languages derived from C are usually used for describing the software necessary in the mechano-electrical product. For example, SystemC (Müller 2003) is recognized as a standard tool for describing a hardware behavior in the design of electronic circuits to be incorporated in the product. We are investigating to consolidate the important points to consider in the combined use of Modelica, MATLAB/Simulink, and SystemC.

In this paper, we explain our guidelines that facilitate efficient development of the mechano-electrical products. We also explain our findings in our experimental construction of the 1D CAE model of a mechano-electrical product using Modelica, MATLAB/Simulink, and SystemC simultaneously. In the next section, the guidelines developed by us are explained in detail. In Section 4, our findings on the combined use of Modelica, MATLAB/Simulink, and SystemC software are explained with an example. We expected that FMI/FMU (functional mock-up interface / unit) (Modelica Association 2014)(Hirano 2018) is a promising standard to connect the 1D CAE models and software components, however, the expected effect could not be realized in some cases due to some restrictions and issues. We summarize our conclusions in Section 5.

3 Guidelines for Creating 1D CAE Models of Mechano-Electrical Products

There are some researches are known on the guidelines of modeling. For example (Yazdani 2011) gives a guideline of modeling power system model. (Mathworks 2018) provides several guidelines for model construction using MATLAB/Simulink. In this paper, we explain our guideline for modeling behaviors of mechano-electrical products. Figure 5 presents an overview of our 1D CAE modeling guidelines. It depicts a flowchart of a typical model development process comprising 7 steps. In this chapter, we explain these steps briefly.

Step 1 Target selection: In this step, the design target is defined, and the function of the target product is clarified. It is desirable to perform functional development and reduce the function to physical models with proper input and output parameters. It is also desirable to establish communications with the designer in charge of the target product in advance so as to understand the solutions expected from the 1D CAE model.

Step 2 Modeling policy determination: In this step, the modeling level of the components is defined based on the results of the functional development. The functional specifications, scope of modeling, design parameters and their ranges, potential disturbance, and modeling accuracy are also formulated. The modeling method depends on the functional specifications of the model. For example, in the case of a gear train, it is adequate to model a simple gear ratio if the conveying rotation needs to be analyzed. However, if the purpose is the analysis of the vibration of the gear train, it is necessary to model the rigidity of the teeth of the gear.

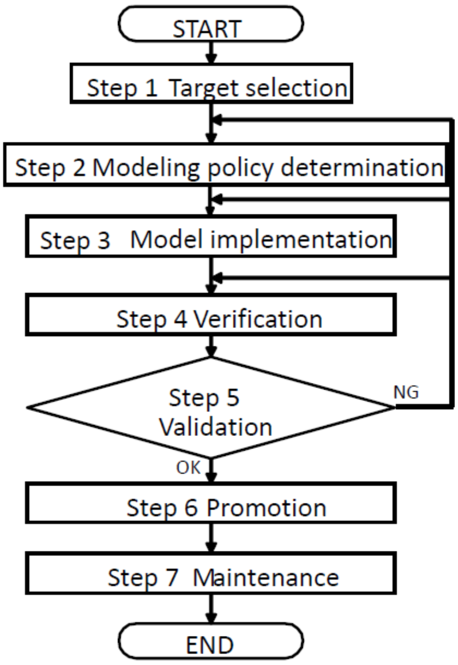

Figure 5. Flowchart for creating proper 1D CAE model.

Step 3 Model implementation: In this step, a model is implemented according to the modeling policy formulated. Modelica-based tools (OpenModelica or other commercial tools) or MATLAB/Simulink are the usually employed tools. Selection of the proper tool is critical in this step. Many Modelica-based 1D CAE systems such as Dymola and SimulationX are commercially available in the market. Each of these systems has its own unique characteristics. It is important that the most appropriate tool is selected according to the design target.

Step 4 Verification: The models constructed are verified in this step. There are two types of verification: operation and accuracy. The operation is verified by evaluating the following questions:

- Does the model involve physical movements of any of the parts during the operation?
- Does the model work properly with multiple design variables within their specified upper and lower limits?

Additionally, we strive to confirm that the implemented model exhibits a stable motion with errors within the specified limits with reference to the accuracy verification.

Step 5 Validation: In this step, the model of the complete subsystem is constructed by connecting the component models. The model is subsequently verified at the subsystem level by comparison with actual measurement values. The results are checked for the accuracy requirements formulated in Step 2. If they do not meet the requirements, then the Steps 2–4 are repeated to refine the model. The outcome is then compared with the actual machines, including the past models or experimental benches, to confirm the accuracy of the model. Finally, the PDCA (plan-do-check-act) cycles are executed to improve the accuracy of the model.

Step 6 Promotion: The models constructed are forwarded to the design department. To encourage the designers to use them, various promotional measures are necessary. These may typically include distribution of a usage manual, formulation of a report explaining the theoretical background of the model, accuracy reports, and other relevant documents. It is important that the designers use the model with confidence.

Step 7 Maintenance: When the model is deployed in the design, new demands emerge, such as expansion of functions, addition of new design parameters, and so on. To respond to the demands, it is essential that a model maintenance system with proper human resources is realized. It is also necessary to establish the rules for the control and reuse of the models.

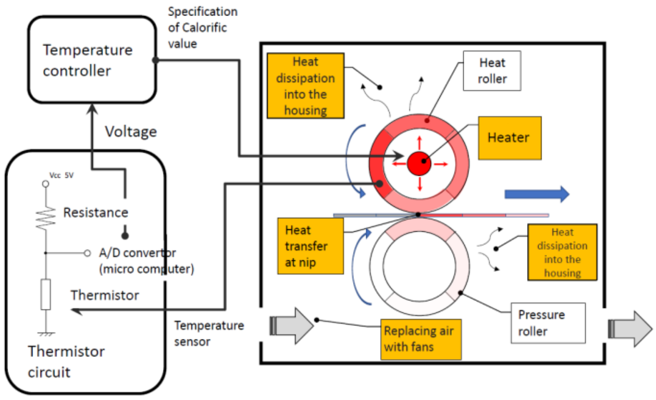

Figure 6. Simplified model of the image fixing unit of a plain paper copying machine.

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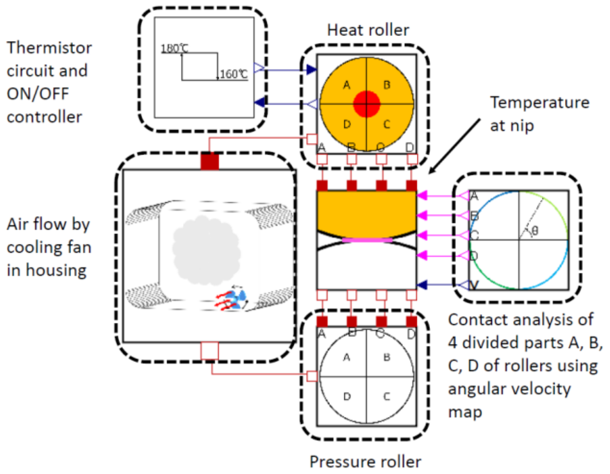

Figure 7. Temperature control model of the heat roller and the pressure roller.

To evaluate the applicability of the guidelines to the construction of a 1D CAE model, we conducted empirical studies on the modeling of typical components of a mechano-electrical product. In our test case, several components that simplified the functions of the plain paper copying machine were studied by employing OpenModelica (Open Source Modelica Consortium) as the modeling tool. We constructed the model by adhering to the method described in our guidelines as much as possible.

Figure 6 illustrates a block diagram of the implemented 1D CAE model. It shows a simplified mechanism of the image fixing unit of a copying machine (Ricoh 2018). To generate a stable image on a paper, the image fixing unit melts the toner by heating and pressurizing and fixes it on the paper surface. As shown in the figure, the heating and pressurizing are performed when the paper and toner pass between a heat roller and a pressure roller. The portion of the paper in contact with the heat roller and the pressure roller is called as nip. An electric heater is contained inside the heat roller. The temperature is controlled by a thermistor and an electric circuit so that the surface of the heat roller is maintained at a temperature within a limited range.

An analysis model of the temperature control is illustrated in Figure 7. This model consists of five components: a heat roller, a pressure roller, a paper, a thermistor circuit with a temperature controller, and a heat exhausting fan of the housing. The components are modeled by considering the design of the heating and pressurizing mechanism of actual copying machine. The heat generated by the heat roller is transmitted to the surface of the heat roller, the nip, and the pressure roller, in this order. In our model, the heat roller and the pressure roller were divided into four parts, respectively. In the rotation process of the rollers, the combination of the heat roller part and the pressure roller part in contact was calculated to realize the switching of the heat transfer model. In this model, heat transfer between the adjacent part of the heat roller and the pressure roller, and the heat dissipation into the air are also considered.

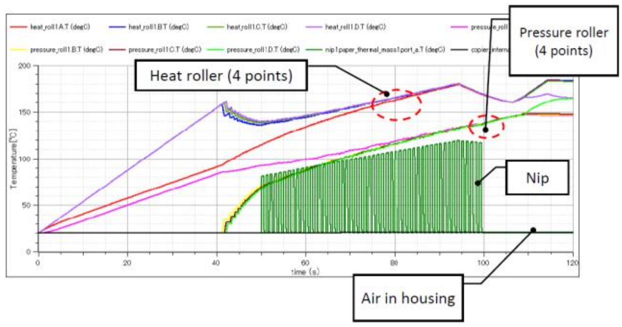

Figure 8. Analysis result of the temperature change at the nip.

Figure 8 shows the analysis results. We considered that the paper conveyance would be repeated from the start time to the end time of the copying process. The roller performs an acceleration motion from the start of the operation until the specified angular velocity is reached. After that, the rotation was continued with a constant angular velocity until the end of the operation. At the end of the operation, the roller performs an equiangular deceleration from the specified angular velocity. In our model, the temperature of the heat roller is correctly controlled, and the changes in the temperature at the nip is accurately reproduced before, during, and after the paper conveyance.

4 Combined Use of Modelica, MATLAB/Simulink and SystemC

In the design of a mechano-electrical product, an analog device was replaced with a digital device for promotional purposes of achieving higher functions of higher quality at low production cost. For similar reasons, the function realization method of the product was changed from a method using hardware to a method using software.

To determine a proper function realization method (analog or digital, hardware or software), the designer must execute the 1D CAE simulation of the product with the mechanical, electrical/controlling, and software components at an early stage of the design. In recent products, use of FPGA (Field-Programmable Gate Array) and custom LSI is emerging as a common trend. Since a longer time is necessary in the development of FPGA and custom LSI, it is necessary to start the function analysis with 1D CAE models earlier. The increased use of IoT technology is further accelerating this trend.

To start the collaboration of the mechano-electrical design and the software design earlier, a suitable method for the combined use of the 1D CAE models of the mechanical, electrical/controlling, and software components is required. For mechanical design, Modelica is emerging as a popular tool for creating 1D CAE models. On the other hand, most electrical as well as controlling engineers use MATLAB/Simulink as a modeling tool. For the software development related to a mechano-electrical product, SystemC is adopted as a standard language for describing a hardware of the electronic circuit to be incorporated in the mechano-electrical product. To realize the 1D CAE simulation of the total mechanism, the method of data sharing between the Modelica models, MATLAB/Simulink models, and SysmteC software must be standardized.

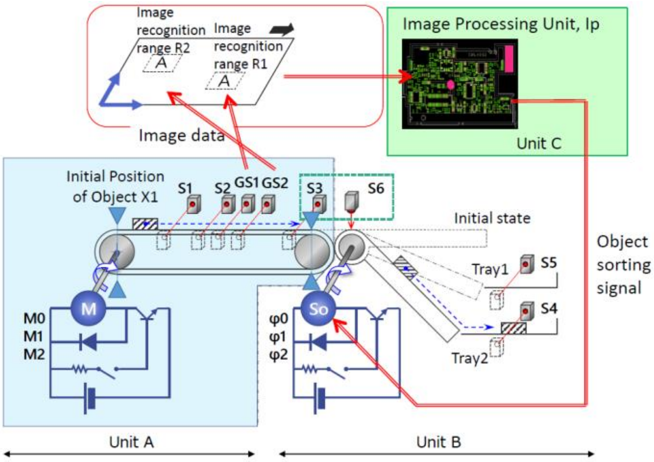

Figure 9. A simple model of the paper transferring mechanism of a copying machine.

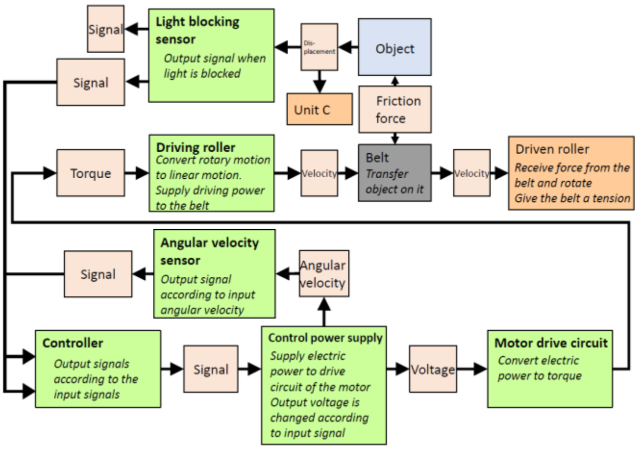

Figure 10. Block diagram of unit A (Object transferring mechanism with a belt).

We consider that a method based on the FMI standard is promising for sharing the data between simulation models using different implementation technologies. To clarify the problems in the data sharing using FMI, we performed several experiments implementing the 1D CAE models with Modelica, MATLAB/Simulink, and SystemC, and combined them using FMI for realizing the total simulation. Figure 9 illustrates a test case. This is a simplified model of a paper transferring mechanism of a copying machine. This model has three basic units that are denoted as unit A, unit B, and unit C.

Figure 10 shows a block diagram of unit A. This unit is an object (paper) transferring mechanism with a belt. This unit changes the motion as an object passes in front of the light blocking sensor S1, S2, and S3.

1. When the power is turned on, the driving motor rotates at speed M0.
2. When the object passes in front of the light blocking sensor at S1, the speed of the drive motor is switched from M0 to M1.
3. When the object is further conveyed and passed in front of the light blocking sensor at S2, the speed of the driving motor is switched from M1 to M2.
4. When the object is transported and passed in front of the light blocking sensor S3, the speed of the drive motor is switched from M2 to M0.

The unit C is a mechanism to identify the image of an object (paper). This mechanism has two devices GS1 and GS2 for capturing an image on the object. GS1 captures the image in a region R1 on the object. Another device GS2 obtains the image in a region R2 on the object. The images captured are processed by an image processing unit Ip. This unit outputs a signal according to the captured image. The output signal is used in the following object sorting operation.

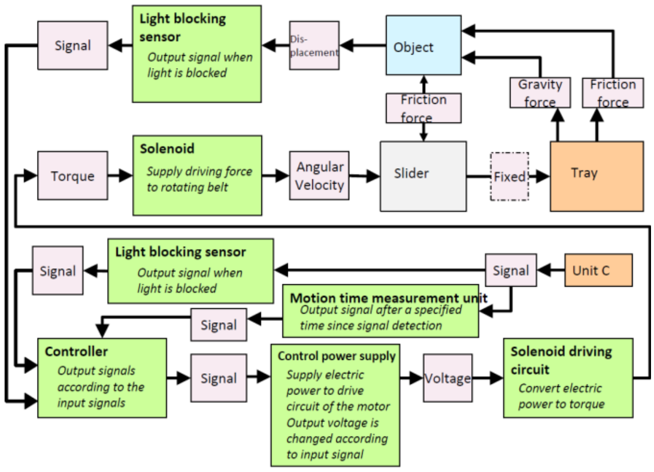

Figure 11. Block diagram of unit B (Object sorting mechanism).

Figure 11 illustrates a block diagram of unit B. This unit is a mechanism to sort the transferred object. It controls the inclination angle of a bridge according to the signal given by the unit C, and it sorts the object to tray1 or tray2. In the initial state, the bridge is in horizontal orientation.

- When the signal is 1, a solenoid S0 is rotated and the bridge is connected to tray1. When the sorted object is passed in front of the light blocking sensor

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S5, the bridge is rotated back to the initial horizontal orientation.

- When the signal is 2, the bridge is connected to tray2. When the sorted object is passed in front of the light blocking sensor S4, the bridge is rotated back to the initial orientation.

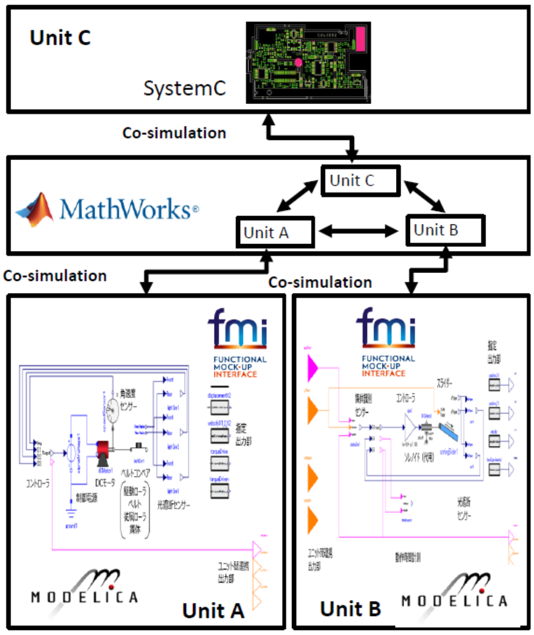

Figure 12. Combined use of Modelica, MATLAB/Simulink, and SystemC for implementing the paper transferring system.

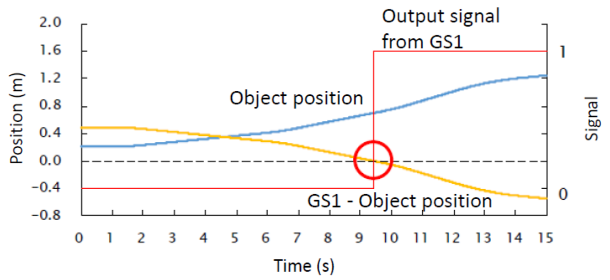

Figure 13. Analysis result of unit A.

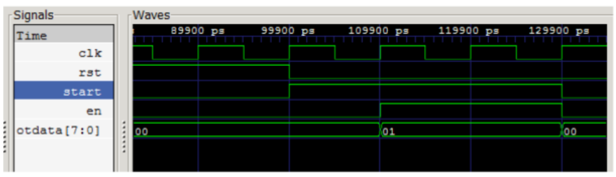

Figure 14. Analysis result of unit C.

In the implementation of the models, Modelica is used for modeling the unit A and unit B. Behavior of the electronic circuit of the image capturing and processing unit (unit C) is implemented using SystemC. The control softwares of the three units are realized using MATLAB/Simulink. Using the export function of FMI, unit A and unit B are incorporated into the control software. Since FMI is not supported by SystemC, the image capturing and processing software is integrated with the control software using the S-function of the MATLAB/Simulink. Figure 12 illustrates the relationships between Modelica, MATLAB/Simulink, and SystemC in our implementation.

By using the combined models, the engineers can analyze the effect of the change of the design parameters of the units on the behavior of the mechanism. The following three issues were detected in the verification result of our model.

1. Management of the simulation step time: Figure 13 shows the analysis result of the unit A. The three curves in the graph represent the object displacement (blue curve), distance between image sensor GS1 and object (yellow curve), and signal output from GS1 (red curve). Figure 14 shows the simulation result of the operation of the unit C. As shown in the two graphs, the time step of the simulations is much different between the unit A (time step is in s) and unit C (ns). When the total simulation is executed following the time step of the unit A, the high frequency behavior of the unit C cannot be detected. The simulation of the unit A must be repeated a number of times when the total simulation is executed according to the time step of the unit C. The latter case causes an increase in the computation time and the accumulation of the computation errors. In the co-simulation of the mechanical system (unit A) and the electronic circuit (unit C), the designer must pay attention to the validity of the time step in the simulation. Similar problem was discussed in (Centomo 2016).

2. Signal transmission between the models: In the control process of the paper transferring mechanism, various parameters of the physical quantities are exchanged between the components and the FMUs. In addition to the physical quantities, the signals that trigger the events are also exchanged. For example, the start and end of the operation of the units in our model are triggered by mutual sending and receiving of the signals. In our experiments, the signals were not successfully transmitted between the software components written in SystemC and the controlling unit performed by MATLAB/Simulink. This problem is expected to be resolved by incorporating the SystemC unit into the controlling unit by using FMI.

3. Selection of proper design parameters: The central purpose of the combined simulation is to determine the optimal design parameters by executing various simulations with different design parameters. In the design of the electrical/electronic system, the clock frequency is usually selected as a design parameter in the time domain. On the other hand, the processing time is usually adopted as a design parameter of the mechanical system. In our demonstration of the paper transferring model, the processing time is selected as a common parameter in the time domain. The design parameter of the electrical/electronic system is given by converting the processing time to the time steps counted in the clock frequency. An incorrect selection of the design parameters would necessitate cumbersome parameter conversions and thereby affect the work efficiency in the simulation. Therefore, it is necessary to the select the design parameters carefully.

5 Conclusions

To realize an efficient design of a mechano-electrical product, it is important to utilize the 1D CAE simulations effectively in the early functional and performance consideration stage. In the automobile and aerospace industry, the use of the 1D CAE model is already a common practice. The model is considered to be effective for assisting the functional and performance design of the mechano-electrical products; however, it has not been adopted as a design method for these products in the past.

To promote the use of the 1D CAE model in the mechano-electrical industry, it is necessary to resolve the issues associated with the use of the model as much as possible. In this paper, we propose the guidelines for creating a proper 1D CAE model. In the guidelines, the desirable steps in the modeling process as well as the important points to be noted in each step are mentioned. By following the guidelines systematically, we can minimize the modeling cost.

In the 1D CAE simulation of a mechano-electrical product, Modelica, MATLAB/Simulink, and SystemC are used as the modeling tools. We investigated to consolidate the important points to consider in the combined use of these three tools. Through the development of simplified models of the plain paper copying machine, we found that there are three critical issues in their combined use: 1) management of simulation step time, 2) signal transmission between the models, and 3) selection of proper design parameters.

It is a difficult task to quantify the effectiveness of the developed guidelines and the points learnt in the combined use of Modelica, MATLAB/Simulink, and SystemC, but we strongly believe that these results are helpful in creating the models without mistakes. We plan to distribute our research results to the member companies of the Standardization Committee of New Digital Verification Technology so as to evaluate its applicability thoroughly.

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