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HPN MODELING, OPTIMIZATION AND CONTROL LAW EXTRACTION FOR CONTINUOUS STEEL PROCESSING

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ABSTRACT

This paper presents a new modeling and controller design technique for the steel sheet processing line based on Hybrid Petri Nets (HPN), Mixed Logical Dynamical Systems (MLDS) expressions and system identification techniques for hybrid systems. In the steel sheet processing line, the dynamics of sheets is represented by differential equation. On the other hand, some operations such as welding of the steel sheets are described by logical formulas. HPN can harmoniously integrate these two different aspects. The HPN expression can be transformed into a suitable formulation for numerical optimization. Based on this modeling, the closed-loop control can be realized by receding horizon scheme. At the next step, control laws are extracted from the results obtained by receding horizon scheme. The method identifies probability weighted ARX (PrARX) functions as a controller. Some simulations are conducted to demonstrate that the identified controller can achieve fast and near-optimal control.

1 INTRODUCTION

Thin steel sheet, a class of steel products, is widely used for products familiar with the public such that cars, home electronics, cans, and so on. In this paper, processing lines in which several intermediate products are welded and which are subject to some of treatments (e.g., cold rolling or surface treatment) are considered. This class of processing lines is called *continuous processing lines*.

Typical behavior and structure of the continuous processing lines are as follows (see Figure 1): Several intermediate products (steel sheet) are put into the line continuously. New intermediate products are coils of steel and they are arranged on *payoff reels*. A new intermediate product has to be welded to the one that have been already in the line. They are subject to some of treatments in processing facilities. After treatment, they are pulled out from the line as treated (intermediate) products. The treated products are reeled off by *tension reels* and are cut to the proper length.

One of the main objectives is to control the treatment speed since it affects the quality of the final product. This is called as *line pacing*. When a new intermediate product is welded, it is necessary to stop (or slowdown) the welding point. An *entry looper* is equipped in order to absorb the speed difference between the welding point and the processing facility. The looper acts as a buffer between the welding point and the processing facility. Similarly, it is necessary to stop or slow down when the treated products are checked or cut. An *exit looper* is equipped between the processing facility and the tension reels.

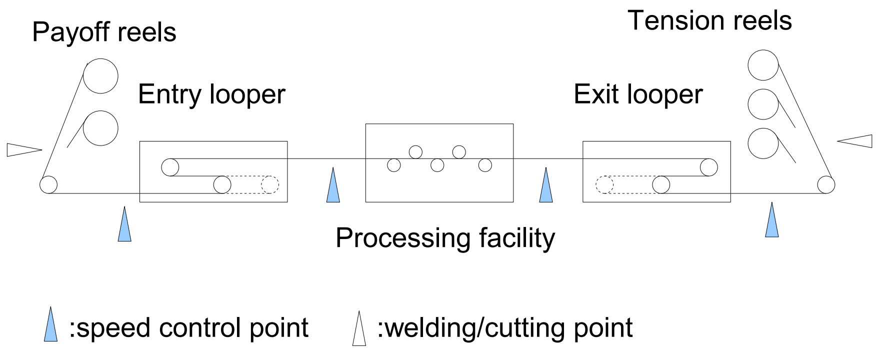


Figure 1: Continuous processing line.

Operators of the process have to control the speed of processing facility and remaining length of the entry and exit looper while predicting the future. The overall objective of control is to maximize the treatment speed while maintaining the constraints of the process. This is, however, a difficult task for the operators due to the following reasons:

- Different constraints are imposed to each facility. For instance, upper and lower bound of the length in the entry and exit loopers, speed constraint on the processing facility, and so on.
- Stop or slowdown operation for specific conditions. For instance, the welding point must be stopped while a new intermediate product is being welding.
- Operators usually takes conservative policy in order to avoid a shutdown due to constraint violation.

Because of these difficulties, the processing capacity has not been fully utilized and no model-based control methods have been applied to the continuous processing lines. This paper proposes a novel modeling and controlling method of the continuous processing lines.

The flow dynamics of steel sheet should be described in model. In this modeling, it is necessary to account that each sheet has different features (e.g., length, thickness, and so on) and they are subject to several operational constraints. Therefore, the continuous processing line is a *hybrid dynamical system (HDS)*, which contains both continuous value (e.g., length, speed) and discrete event (e.g., welding, cutting). Several modeling methodology of HDS, for instance, Hybrid Automata (Henzinger 1996; Branicky, Borkar, and Mitter 1998) and Piecewise Affine (PWA) system (Sontag 1981), have been proposed. In this paper, *Hybrid Petri Nets (HPN)* (Balduzzi, Guia, and Menga 2000; Ghomri and Alla 2007) is used to modeling. HPN is an extension of *Petri Nets (PN)*, then it is suitable for graphical representation. Recently, HPN is used in various fields (Guan, Nakamura, Shikanai, and Okazaki 2008; Febbraro and Sacco 2004; Kaakai, Hayat, and Moundi 2007), but there are no works for continuous processing lines.

HPN helps the designer to intuitively grasp the behavior of the plant since each component of the line directly corresponds to that of HPN, such as places and transitions. Other modeling methods, such as hybrid automata, have not this feature. Therefore, HPN is a good interface to model the line.

However, it is not a suitable model to solve the control problem based on optimization on computers. In Júlves, Bemporad, Recalde, and Silva (2004), it is shown that a class of HPN can be transformed into Mixed Logical Dynamical System (MLDS) form which is suitable for numerical optimization. This paper shows that the continuous processing line can also be transformed into MLDS form. By using this model, a finite horizon optimal control of the continuous processing line can be formulated as a *Mixed Integer Programming Problem (MIP)*. Moreover, *Model Predictive Control (MPC)*-based control can be realized by iteratively solving the MIP.

MIP-based similar applications for other fields are as follows: gas supplying system (Bemporad and Morari 1999), co-generation power plants (Ferrari-Trecate et al. 2002;

Ferrari-Trecate et al. 2004), traction control (Borrelli et al. 2001; Borrelli et al. 2006), hydraulic system (Colmenares et al. 2001), and so on. This method, however, has drawbacks in terms of computation time for implementation since it is necessary to solve a mixed integer programming (MIP) problem on a second time scale.

In order to overcome this problem, this paper proposes the extraction of a control law from the optimization data using the system identification method. Specifically, this method identifies probability weighted autoregressive exogenous (PrARX) model, where the multiple ARX models are composed by the probabilistic weighting functions (Taguchi, Suzuki, Hayakawa, and Inagaki 2009).

The organization of this paper is as follows: The modeling method of the continuous processing line is described in Section 2. In Section 3, HPN model is transformed into MLDS model. In Section 4, a design principle of MPC controller is described. The proposed identification algorithm is explained in Section 5. Some numerical simulations are performed to verify the usefulness of the proposed method. The results are shown in Section 6. Section 7 concludes the paper.

2 HPN MODELING

Figure 1 shows the continuous processing line under study.

This process consists of several facilities such as payoff reels, entry looper, processing facility, exit looper and tension reels. Steel sheet flows from the payoff reels to tension reels. The speed of the sheet is controlled at four speed control points between facilities. The length of entry and exit looper are time-variant in order to absorb the speed difference between previous and next facilities. Each facility has its own constraint on the length of the sheet. Similarly, there are lower and upper bound on speed and acceleration at each speed control point.

2.1 Hybrid Petri Net (HPN)

Petri Net (Peterson 1992) is a class of directed bipartite graph i.e., two types of nodes are contained. These nodes are called places and transitions. The other components of Petri Net are tokens and arcs. They are shown in Table 1.

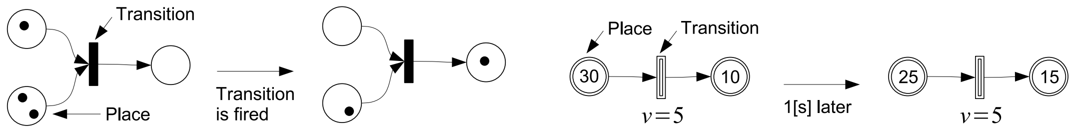
Table 1: Components of (discrete) PN and HPN.

Component	PN	HPN		Component	PN	HPN	
		Discrete	Continuous			Discrete	Continuous
Place	○	○	◎	Transition	▮	▮	▯
Token	●	●	Number	Arc	→	→	

Places are depicted by circle. Nonnegative numbers of tokens are placed on the places. Tokens are depicted by black dots. The configuration of tokens are called marking. Marking represents the state of the system. Transitions are depicted by bold bars. Places and transitions are connected by directed arcs. If a transition is "fired", tokens are moved between places. Figure 2(a) shows an example of Petri Net.

Hybrid Petri Net (HPN) (David and Alla 2005) is an extension of Petri Net. In HPN, continuous places and transitions are used to represent the continuous behavior of the system. They are shown in "Continuous" column in Table. 1. Continuous places and its marking represent continuous physical value of the system, e.g., fluid volume in a tank, strip length in each facility, and so on. If a continuous transition is fired, then continuous marking moves between continuous places. Continuous transition has "firing speed" which shows the moving rate of continuous marking. For instance, fluid velocity at an valve between two tanks, processing speed of steel sheet at a facility, are firing speed.

Figure 2(b) shows an example of (continuous part of) HPN. If the continuous transition is fired and its velocity is 5[s^{-1}], then the continuous marking moves and its value is 5 in 1[s].



(a) Petri net (b) Hybrid Petri net

Figure 2: Example of PN and HPN.

2.2 Modeling of the Plant

Figure3 shows the HPN model of the system shown in Figure1.

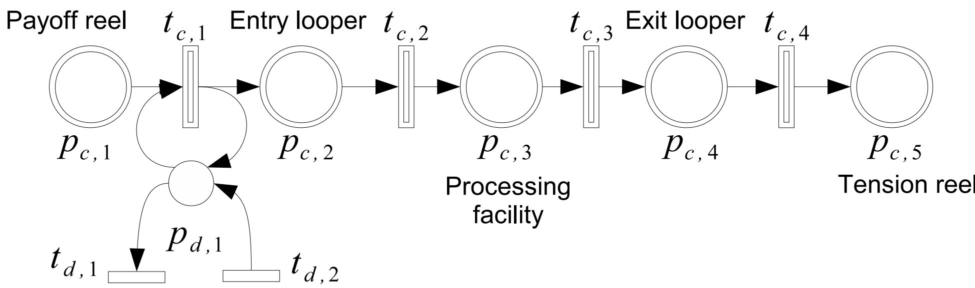


Figure 3: HPN model of steel processing lines.

Continuous places $p_{c,i},\ i = 1, \cdots, 5$ correspond to each facility. $x_{c,i}$ denotes marking of $p_{c,i}$. This value shows the length of steel strip in i-th facility. Continuous transitions $t_{c,i},\ i = 1, \cdots, 4$ correspond to flow of steel sheet between continuous places. $v_{c,i}$ denotes its speed.

Discrete place $p_{d,1}$ and its marking $x_{d,1}$ shows whether the payoff is enabled or not, i.e., $x_{d,1} = 1$ shows that the payoff is enabled, otherwise disabled. Discrete transition $t_{d,1}$ and $t_{d,2}$ changes $x_{d,1}$. Firing of these transitions are denoted by $u_{d,1}$ and $u_{d,2}$.

The connection structure between the continuous places and transitions can capture the behavior of the steel sheet which moves from the payoff reels to the tension reels.

An advantage of HPN modeling is that the model can graphically illustrate the relation of the facilities. In this case, the components of the line correspond to the places of HPN. Similarly, the speed control points correspond to the transitions. This model is very useful interface to MLDS model, which is described in the next section (if MLDS representation can be directly derived, HPN modeling is not necessary).

3 MLDS REPRESENTATION

3.1 Mixed Logical Dynamical System (MLDS)

MLDS is a framework for modeling and controlling hybrid dynamical systems (Bemporad and Morari 1999). General MLDS has the following form:

$$x(k+1) = Ax(k) + B_1 u(k) + B_2 \delta(k) + B_3 z(k), \tag{1}$$
$$y(k) = Cx(k) + D_1 u(k) + D_2 \delta(k) + D_3 z(k), \tag{2}$$
$$E_2 \delta(k) + E_3 z(k) \le E_1 u(k) + E_4 x(k) + E_5. \tag{3}$$

Variables and coefficients of this equations are listed below.

$k \in Z$	discrete time index
$x(k) \in R^n,\ u(k) \in R^p,\ y(k) \in R^l$	continuous state, input, and output variables
$\delta(k) \in \{0,1\}^m,\ z(k) \in R^q$	auxiliary binary and continuous variables
$A, \cdots, E_5$	coefficient matrices have suitable dimension

Note that the inequality in (3) is componentwise. The overlined and underlined variables, such as $\overline{a}$ and $\underline{a}$, means minimum and maximum of the corresponding variable, respectively (in other words, $a \in [\underline{a}, \overline{a}]$).

MLDS expression is based on "normal" discrete-time state equation. In MLDS expression, two auxiliary variables δ and z are introduced in order to represent logic and/or constraints in the system.

In order to obtain MLDS form, logical formulas are transformed into equivalent inequalities. Auxiliary variables, i.e., δ and z, are introduced in this procedure. Below, a simple example of transformation is explained briefly.

Consider the following logical formula:

$$[f(x) \geq a] \quad \Leftrightarrow \quad [\delta = 1], \tag{4}$$

where a is a constant. This formula is transformed to the equivalent inequalities (5).

$$-f(x) + (a-m)\delta + m \leq 0, \quad f(x) - (M - a + \varepsilon)\delta - a + \varepsilon \leq 0, \tag{5}$$

where $M = \max_x f(x)$, $m = \min_x f(x)$, and $\varepsilon > 0$ is a sufficiently small positive constant. The equivalence between the logical formula (4) and the inequalities (5) is easily verified by substituting 0 or 1 for δ.

Transforming techniques for other logical operators, e.g., $\vee, \wedge, \rightarrow$, are in the references (Bemporad and Morari 1999) (Raman and Grossmann 1991) (Raman and Grossmann 1992).

3.2 MLDS Modeling of the Plant

In this section, the HPN model (Figure 3) is transformed into MLDS form (1)-(3).

3.2.1 Definition of Welding Point

In the HPN model in Section 2, three coils are connected and welding points are ignored (in other words, the HPN model only concerns total strip length). The welding points, however, are important information for operator. Therefore, the welding points are newly defined here.

Let constants c_1 and c_2 denote the welding points and defined as Figure 4. Coils 1 to 3 are connected as in this figure. The tail of Coil 3 is an origin, thus the welding points are defined as the length from the origin. For instance, if Coil 1 to 3 are 700[m], 600[m] and 500[m], respectively, then $c_1 = 1100$[m] and $c_2 = 500$[m].

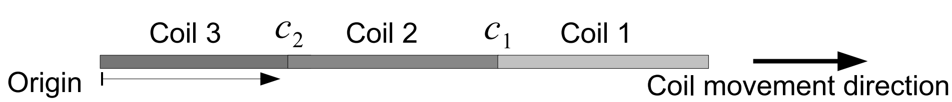


Figure 4: Welding points.

3.2.2 State Equation

The state equation of continuous marking is as follows:

$$\begin{bmatrix} x_{c,1} \\ \vdots \\ x_{c,5} \end{bmatrix}(k+1) = \begin{bmatrix} x_{c,1} \\ \vdots \\ x_{c,5} \end{bmatrix}(k) + T_s \begin{bmatrix} -1 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 1 & -1 & 0 \\ 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_{c,1} \\ \vdots \\ v_{c,4} \end{bmatrix}(k), \tag{6}$$

$$\Leftrightarrow x_c(k+1) = x_c(k) + D_c v_c(k), \tag{7}$$

where T_s[s] is sampling interval and x_c and v_c are vectors with suitable dimensions. This equation can be derived directly from connection between continuous places and transitions of HPN model.

Similarly, the state equation of discrete marking is as follows:

$$x_{d,1}(k+1) = x_{d,1}(k) + \begin{bmatrix} -1 & 1 \end{bmatrix} \begin{bmatrix} u_{d,1} \\ u_{d,2} \end{bmatrix} (k) \Leftrightarrow x_d(k+1) = x_d(k) + D_d u_d, \tag{8}$$

where x_d and u_d are vectors with suitable dimensions. Definitions of $x_{c,i}, v_{c,i}, x_{d,i}$, and $u_{d,i}$ could be found in Section 2.2.

3.2.3 Constraints

The continuous and discrete transitions are enable (i.e., $v_{c,i}, u_{d,i}$ can take nonzero value) if the following conditions are satisfied. These constraints are inherent in HPN model, assuming that the weights of the all arcs are 1.

- continuous transition: Marking of input continuous places are more than zero, marking of input discrete places are 1, and marking of output continuous places are less than maximum value.
- discrete transition: Marking of input discrete places are 1, and marking of output discrete places are 0.

If transitions do not have input/output places, the corresponding condition is ignored.

For example, enable condition of the discrete transitions of this system are as follows:

$$[u_{d,1} = 1] \to [x_{d,1} = 1], \ \ [u_{d,2j} = 1] \to [x_{d,1} = 0]. \tag{9}$$

In addition, the system has several constraints on the capability of the facility and the operational requirements.

- Maximum/minimum capability of each equipment. This class of constraints are given as upper and lower bounds on $x_{c,i}$ and $v_{c,i}$.
- Maximum/minimum acceleration. This class of constraints are given as upper and lower bounds on time subtraction on $v_{c,i}$, i.e., $v_{c,i}(t) - v_{c,i}(t-1)$.
- Constraint on processing facility. The sheet length in the processing facility $x_{c,3}(k)$ should be constant. This leads $v_{c,2}(k) = v_{c,3}(k)$.
- Constraint on welding and checking at payoff reel. When the coil length on the payoff reel is in interval $[c_i + \underline{c_{po}}, \ c_i + \overline{c_{po}}]$ $(i = 1, 2)$, paying off from payoff reel should be stopped in order to weld to the next coil and check its quality . The stop time interval is τ[s].
  If welding and checking is necessary, $t_{d,1}$ is fired and payoff to entry looper is stopped. After τ[s], $t_{d,2}$ is fired and payoff is enabled. This operation is expressed by the following logical formula.

$$\begin{aligned}&\left[x_{c,1}(k) - \overline{c_{po}} \le c_i \le x_{c,1} - \underline{c_{po}}\right] \wedge [x_{d,1}(k) = 1] \to [[u_{d,1}(k) = 1] \to [u_{d,2}(k+\Delta) = 0]], \\ &i = 1, 2, \ \Delta = 1, 2, \cdots, \tau\end{aligned} \tag{10}$$

- Constraint on quality check at welding point. The welding points are cut and visually checked between the exit looper and the tension reel. Thus, the speed $v_{c,4}$ should be down to $\overline{v_{c,4,check}}$.

$$\left[c_i + \underline{c_{check}} \le \textstyle\sum_{j=1}^{4} x_{c,k}(k) \le c_i + \overline{c_{check}}\right] \to \left[0 \le v_{c,4}(k) \le \overline{v_{c,4,check}}\right], \tag{11}$$

  where $[c_i + \underline{c_{check}}, \ c_i + \overline{c_{check}}]$ $(i = 1, 2)$ denotes the visually checked interval.

These constraints are also expressed by linear inequalities by introducing auxiliary variables, if necessary.

Thus, by combining these linear-transformed constraints and state equations (6) and (8), MLDS model of the system can be obtained.

4 RECEDING HORIZON MPC

4.1 Design of Performance Index

Well-designed performance index is essential when someone wants to obtain suitable control policy using numerical optimization.

The desired behavior of the system is to maximize the processing speed while suppressing deleterious effect for the system facilities and products. In order to meet this requirement, in this paper, the following performance index is used .

$$J = T_s \sum_{k=0}^{K-1} (v_{c,2}(k) + \alpha v_{c,1}(k) + \beta v_{c,4}(k)) - \gamma T_s \sum_{k=0}^{K-1} (|\Delta v_{c,2}(k)| + |\Delta v_{c,1}(k)| + |\Delta v_{c,4}(k)|), \tag{12}$$

where $\Delta v_{c,i}(k) = v_{c,i}(k+1) - v_{c,i}(k)$. This index is *linear* since it could be optimized much faster than quadratic ones. This index is composed as follows: $v_{c,2}, v_{c,1}, v_{c,4}$ are the processing speed, the input speed to the entry looper, and the output speed of the exit looper, respectively. K is a prediction horizon in Model Predictive Control, which will be mentioned in the next subsection. α, β and γ are weights.

The former term of each performance index is a weighted sum of each speed. It is associated with the maximization of the processing speed. On the other hand, the latter term is a penalty for acceleration and deceleration. It is associated with the suppression of acceleration and deceleration, which may cause deleterious effect for the system facilities and products.

4.2 Model Predictive Control (MPC)

The behavior of controlled variable can be predicted if the dynamic model of the system is available. *Model Predictive Control (MPC)* exploits this fact. The prediction interval are defined as *prediction horizon*. In this case, it is possible to obtain the control input which can drive the state to the desired one. If the model is suitable for numerical optimization, e.g., linear state equation with linear constraints, the desired control input can be obtained via numerical optimization technique.

In this case, the performance index is linear and the MLDS model includes binary variables. Therefore, the optimal processing speed $v_{c,i}$ can be obtained by solving the following MIP problem.

$$\text{find } v \text{ which minimize } J \text{ subject to MLDS model}(1),(2),(3) \tag{13}$$

5 CONTROL LAW EXTRACTION USING SYSTEM IDENTIFICATION

In this section, it is proposed that the simulation results using receding horizon MPC scheme is identified as PrARX form in order to achieve a real-time implementation.

PrARX model, proposed in (Taguchi, Suzuki, Hayakawa, and Inagaki 2009), is a class of hybrid system model and defined as the multiple ARX models are composed by the probabilistic weighting function. The general PrARX model can be expressed by the following equation.

$$y(k) = f_{Pr}(r(k)) + e(k), \quad f_{Pr}(r(k)) = \sum_{i=1}^{s} P_i \theta_i^T [r(k)^T \ 1]^T, \quad P_i \propto \exp\left(\eta_i^T [r(k)^T \ 1]^T\right), \tag{14}$$

where $r(k)$ is the regressor vector composed of the past inputs and outputs, s is the number of modes, and P_i is the probability that the corresponding regressor vector r_k belongs to the mode i, respectively. The main advantage of this model is that the model identifies continuous function. If the identified controller has discontinuity, it might cause excessive switching around the discontinuous point.

The identification of PrARX model is reduced to the problem finding the parameters θ_i and η_i, $(i = 1, \cdots, s)$. In (Taguchi, Suzuki, Hayakawa, and Inagaki 2009), an identification algorithm based on the steepest descent method is proposed. This algorithm is used in this paper.

6 SIMULATION

6.1 Receding Horizon MPC

The speed $v_i(k)$ is obtained by numerical optimization. The solver is NUOPT ver. 10.1. The specification of the PC is CPU: Intel Xeon 3[GHz] and Memory: 3.25[GB].

Table 2 shows the arrangement of coil length and the fixed parameters, respectively. The sampling interval used in this simulation is determined based on the sampling interval of real line pacing plant. γ is determined by several preliminary simulations.

Table 2: Coil length and parameters (MPC).

Initial	$x_{c,1}$	$x_{c,2}$	$x_{c,3}$	$x_{c,4}$	$x_{c,5}$
Coil 1	0	0	113	100	467
Coil 2	300	300	200	0	0
Coil 2	354	0	0	0	0

Subsequent	
Coil 3 to 8	600, 700, 650, 700, 600, 700
Sampling interval T_s[s]	1
Weights (α, β, γ)	$(1, 1, 0.01)$

Figure 5 shows the representative result. Simulation condition of Figure 5 is as follows: 35 [s] future is predicted and input sequence is obtained per one optimization. First 5 [s] input sequence is applied to the line. New optimization is performed after 5 [s].

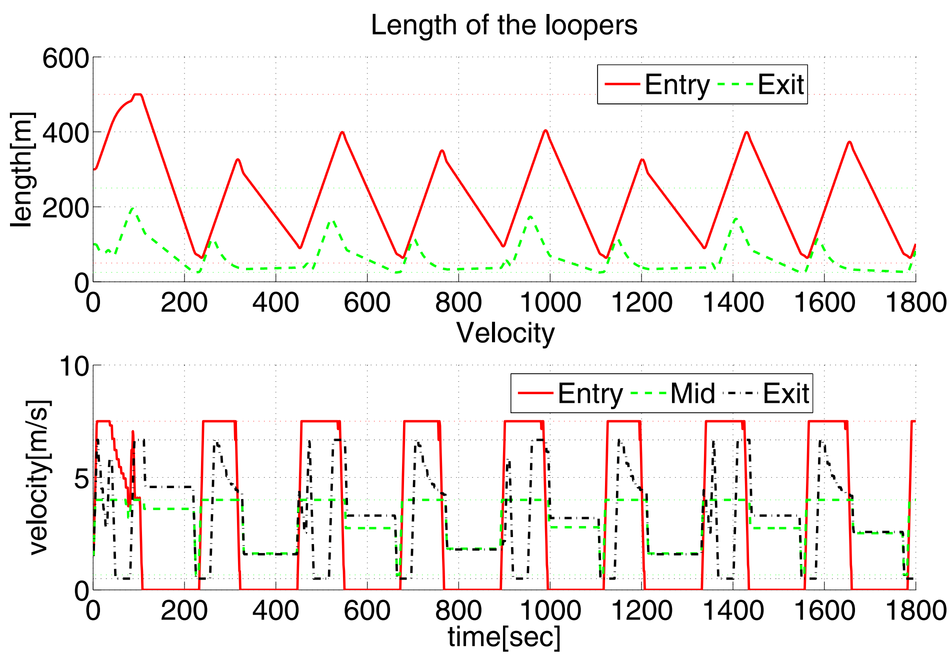


Figure 5: Result (MPC, horizon:35, input interval: 5).

This result shows that the processing capacity of the line is fully utilized by the proposed method: Once the new coil is welded, the entry velocity is accelerated at maximum rate and kept at high level. On the other hand, it is slowing down at maximum rate preparing the welding. This control could achieve high-level throughput.

Figure 6 shows the optimization time to get the result in Figure 5. This figure shows that in almost of all cases the optimization has been finished within 5[s], that is input interval. Excessively long-time situation is limited. Only five optimizations exceed 5[s]. All of these are just after the payoff is stopped in order to weld the new sheet.

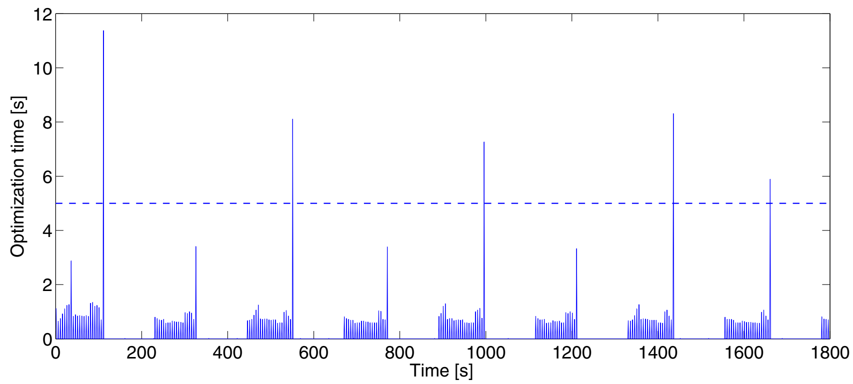


Figure 6: Optimization time (MPC).

6.2 PrARX Identification

Figure 6 shows that the optimization-based MPC sometimes requires large amount of computations. Therefore, the control law is extracted as PrARX model from the simulation result of Figure 5.

Assume that the velocities are expressed by PrARX model.

$$v_{c,j}(k) = f_{Pr,j}(r_j(k)) + e(k), \;\; f_{Pr,j}(r_j(k)) = \sum_{i=1}^{s_j} P_{i,j}\theta_{i,j}^T [r_j(k)^T \;\; 1]^T, \;\; P_{i,j} \propto \exp\left(\eta_{i,j}^T [r_j(k)^T \;\; 1]^T\right), \;\; j = 1,2,4, \tag{15}$$

where $r_j(k)$ is the regressor vector for $v_{c,j}$ defined as follows: $r_1(k) = [x_{c,1}(k), x_{c,2}(k), v_{c,1}(k-1)]^T$, $r_2(k) = [x_{c,2}(k), x_{c,4}(k), v_{c,2}(k-1)]^T$, and $r_4(k) = [x_{c,4}(k), x_{c,5}(k), v_{c,4}(k-1)]^T$. These regressor vectors are selected based on preliminary simulations. The parameters $\theta_{i,j}$ and $\eta_{i,j}$ are calculated using the algorithm proposed in (Taguchi, Suzuki, Hayakawa, and Inagaki 2009) and MATLAB package OH-Pack (Okuda 2011).

This identification algorithm is basically interpolation, therefore this method cannot clearly identify "hard" constraints such as the length limitations $x_{c,i} \in [\underline{x_{c,i}}, \overline{x_{c,i}}]$. Therefore, the velocities calculated by (15) should be modified. For example, in order to satisfy the constraint $x_{c,1} \geq \underline{x_{c,1}}$, (16) and (17) are imposed.

$$v_{c,2}(k) \leftarrow \underline{v_{c,2}} \quad \text{if } \hat{x}_{c,1}(k+1) < \underline{x_{c,1}} + B_{\text{ent}}^l, \tag{16}$$

$$v_{c,1}(k) \leftarrow v_{c,2}(k) \quad \text{if } (\hat{x}_{c,1}(k+1) < \underline{x_{c,1}} + B_{\text{ent}}^l) \wedge (v_{c,1}(k) < v_{c,2}(k)), \tag{17}$$

where B_{ent}^l is the lower margin for the entry looper constraint. $\hat{x}_{c,1}$ denotes the estimate of $x_{c,1}$ calculated using the model and the identified control law. Similar procedures are carried out for the other constraints. The detailed description can be found in (Konaka, Suzuki, Asano, and Iijima 2012). Table 3 lists the parameters used in this simulation. The initial arrangement and the length of coils are the same as Table 2.

Figure 7 shows the simulation result using the identified controller. This result shows that the identified PrARX controller can operate the pacing line while keeping several constraints. The most notable difference is payoff behavior for the first coil. In Figure 5, the first coil was paid-off around 100[s] (the entry velocity stops). On the other hand, in Figure 7, the payoff slows around 100[s] and the payoff is finished around

Table 3: Parameters (PrARX).

Sampling interval T_s[s]	1
Number of modes s_j	4, 3, 4

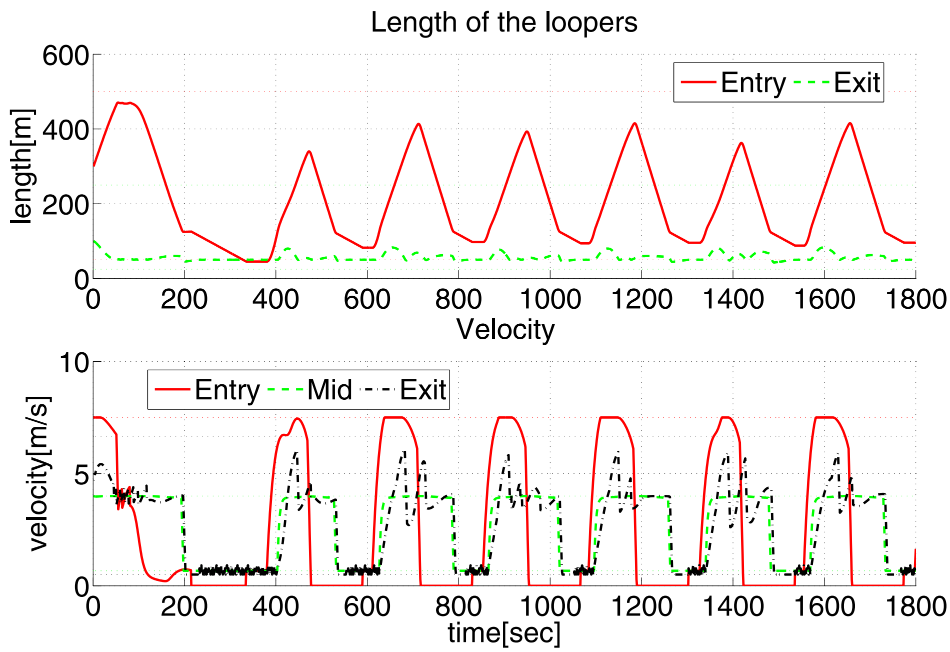


Figure 7: Result (identified PrARX controller).

200[s]. This is mainly due to the learning data. In Figure 5, the control behavior for the coil is different from the other coils. Therefore, suitable control behavior for the first coil cannot be identified by PrARX model.

Table 4 shows the throughput (i.e., $\sum v_{c,4}(k)$) of the both results. This table also shows the result that is obtained from the simulations for various initial arrangement of coils, i.e., $x_{c,i}(0)$. The average and standard deviation are calculated from 1000 trials. In every trials, calculation of control input by the identified PrARX model has finished within 1[ms].

Table 4: Throughputs.

MPC (Figure 5)	5572
PrARX (Figure 7)	4807

	Average	Max.	Min.	STDev
PrARX	4964	5386	4703	200.7

This table shows that MPC achieves a better performance than identified PrARX controller. The identified PrARX controller, however, has robustness for various initial conditions.

7 CONCLUSION

This paper has presented a new modeling and controller design techniques for the steel sheet processing line based on Hybrid Petri Nets (HPN), Mixed Logical Dynamical Systems (MLDS) expressions and system identification techniques for hybrid systems.

HPN can harmoniously integrate continuous and logical aspects of the line. And it acts as a bridge between the control lines and mathematical model for numerical optimization. The HPN expression can be transformed into a suitable formulation for numerical optimization, i.e., MLDS. Based on this modeling, the closed-loop control can be realized by receding horizon scheme. At the next step, control laws are extracted from the results obtained by the receding horizon scheme. The method identifies PrARX functions as a controller.

Some simulations are conducted to demonstrate that the identified controller can achieve fast and near-optimal control.

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