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Detection of Mode Confusion in Human-Machine System Model with Temporal Information on Operations.

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Abstract: In human-machine systems, a user operates a machine using information on machine's behavior displayed at a user interface. If the abstraction of the information is insufficient for the user to anticipate machine's state, mode confusions occur in the human-machine systems. In the case where the machine is a physical system, consistency between the machine's bahaviors and user's knowledge of temporal information on the operations is also important to avoid a mode confusion. Therefore, in this paper, we deal with mode confusion due to the lack of temporal information on machine's dynamics. First, we introduce a model of the human-machine system with temporal information using transition systems. Next, we define a mode confusion including the temporal discrepancy between the machine's behaviors and the user's knowledge formally. Then, we show that the nonexistence condition of the mode confusion is related to an alternating simulation relation and propose a detection algorithm of the mode confusion. Finally, we apply the algorithm to a heating, ventilation and air conditioning system.

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Keywords: Human-machine system, hybrid system, automation surprise, mode confusion, alternating simulation relation

1. INTRODUCTION

In human-machine systems, a user operates a machine using abstracted information on machine's behavior through a user interface. Recently, since the machine tends to be more complicated and large-scale, it is difficult for the user to interpret the complex and much information. Therefore, the user interface must display the abstracted information enough to anticipate machine's state by the user. If the abstraction of the information is insufficient or too much, the user may issue a wrong command for the machine. Such discrepancy between machine's behavior and the user anticipation is called an *automation surprise* (Palmer, 1995; Sarter *et al.*, 1997). Degani and Heymann (2002) classified automation surprises into a blocking state and a mode confusion. A blocking state represents a situation that the user interface does not display the machine's information sufficiently after the internal events of the machine occur. A mode confusion represents a situation that the display mode of the user interface is unexpected for the user after issuing commands.

Formal methods such as model checking is an effective approach verifying that a system satisfies specified properties (Clarke Jr. *et al.*, 1999). Rushby (2001) applied model checking to detecting automation surprises. Moreover, Degani and Heymann (2002) and Degani (1996) proposed a formal verification-based approach to the detection of the automation surprises. In the formal verification approaches, several models of the user and the machine, called a user model and a machine model, have been proposed (Bolton *et al.*, 2013). The user issues commands based on machine's information displayed at the user interface and his/her knowledge of the machine. Then, machine dynamics is affected by the commands and its internal events. In general, the user model and the machine model are described by transition systems (Heymann and Degani, 2002; Degani and Heymann, 2003). Oishi *et al.* (2003) proposed immediate observability in discrete event systems (DESs) and introduced the formalism of the minimization problem for states of a user interface using integer programming. Eskandari and Oishi (2011) derived conditions for user-observability and user-predictability, and Hammond *et al.* (2016) applied these notions to human-machine systems described by transitions systems.

On the other hand, Milner (1989) introduced notions of bisimulation and simulation with respect to equivalence of two systems (Sangiorgi, 2012). Bisimulation based synthesis of supervisors in DESs has been studied (Barrett and Lafortune, 1998; Rutten, 1999). In general, automation surprises occur due to the discrepancy between an actual machine's state and a state anticipated by the user from machine's information. Therefore, in the human-machine systems, the bisimulaiton is related to a nonexistence condition for automation surprises. Adachi *et al.* (2006) showed necessary and sufficient conditions for the nonexistence of automation surprises using (bi)simulation relations. They proposed a bisimulation-based design algorithm of a user model and a user interface without automation surprises for a given machine model. Moreover, Ishii and Ushio (2016) proposed an alert design algorithm based on bisimulation in order to avoid automation surprises. Ishii and Ushio (2015) considered a machine model with real-valued variables and derived a nonexistence condition for the blocking state and the mode confusion, respectively, using approximate simulation and alternating simulation relations. These studies deal with mode confusions focus-

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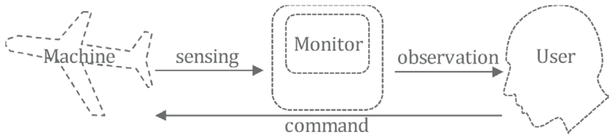

Fig. 1. Illustration of a human-machine system consisting of a user, a machine, and a user interface.

ing on logical behaviors of the human-machine systems. However, mode confusions occur not only when the machine reaches an unanticipated state by the user , but also when it takes a longer time than he/she anticipates for the machine to reach a state where he/she determines the next command after issuing a command. Therefore, this paper deals with the mode confusion considering how and when the user operates the machine to reach a target machine's state. First, we introduce a human-machine system model where the machine model is described by continuous variables and the user model includes information on not only the change of the user interface but also the timing of issuing commands. Next, we define mode confusion including temporal discrepancy between the machine's behaviors and user's anticipation. We show a nonexistence condition for the mode confusion is related to a notion of a weak alternating simulation relation. Then, we propose a detection algorithm for the mode confusion based on the weak alternating simulation relation. Finally, we apply the proposed algorithm to a heating, ventilation and conditioning system (HVAC system).

This paper is organized as follows. Section II introduces the machine model, the user model, and the user interface. Section III defines a mode confusion including the temporal discrepancy formally and shows that the nonexistence condition for the mode confusion is characterized by a weak alternating simulation relation. Then we propose an algorithm for detection of the mode confusion. Section IV applies the proposed algorithm to an HVAC system. Section V concludes this paper.

2. MODEL OF HUMAN-MACHINE SYSTEM

Human-machine systems consist of three components: a user that operates a system, a machine that has dynamics depending on both user's operations (commands) and its internal events, and a user interface that displays an abstracted representation, which is called a display mode, of machine's current state. Shown in Fig. 1 is an example of the interaction between the user, the machine, and the user interface. Each component of human-machine systems interacts in the following way:

(1) The user's operation is to issue commands based on the current display mode at the user interface.
(2) The commands and the internal events affect machine dynamics.
(3) Through the user interface, the user confirms that the machine exhibits a target behavior. If the machine behaves as expected, he/she can continue the operations.

In general, temporal information is useful for the selection of the commands. For example, we consider the case where the user anticipates that the user interface will be a target display mode when a specified time is elapsed after he/she issues the command. Then, an automation surprise occurs if the display mode is different from the target one when the time is elapsed. To deal with such an automation surprise due to the temporal information, we introduce a timed model of the human-machine systems.

2.1 Machine Model

Dynamics of a controlled physical system, which will be called the machine, is described not only by continuous physical variables but also by the commands issued by the user and the internal events that represent autonomous changes of modes in the machine. Thus, the machine is a dynamical system with several modes where its dynamics are different each other. By representing the commands and the internal events as discrete events, we model the machine $\mathcal{S}$ by the following hybrid system.

$$\mathcal{S} = \langle V, E, \Sigma, x, event, init, inv, flow, guard, reset\rangle, \quad (1)$$

where

- (V, E) is a finite directed graph, where V is a set of vertices (the modes) and $E \subseteq V \times V$ is a set of edges,
- $\Sigma = \Sigma^{com} \cup \Sigma^{int}$ is a set of events, where Σ^{com} is a set of the commands and Σ^{int} is a set of the internal events, and we assume that $\Sigma^{com} \cap \Sigma^{int} = \emptyset$,
- $x := [x_1, x_2, \cdots, x_n]$, and $\dot{x} := [\dot{x}_1, \dot{x}_2, \cdots, \dot{x}_n]$ are n-dimensional real-valued vector of physical variables representing behaviors of the machine and its first derivative, respectively. Denoted by $x' := [x'_1, x'_2, \cdots, x'_n]$ is an updated value of the vector by changing from a mode to another one.
- $init : V \to \Re^n$, $inv : V \to 2^{\Re^n}$, and $flow : V \to \Re^n \times \Re^n$ are vertex labeling functions,
- $event : E \to \Sigma$ and $guard : E \to 2^{\Re^n}$ are edge labeling functions, and
- $reset : E \times \Re^n \to \Re^n$ is a reset function representing an updated value of variables resulting in changing the mode.

For each mode $v \in V$, $init(v)$ represents an initial value of x if the machine starts from v, $inv(v)$ represents the possible values of x in v, and $flow(v)$ represents possible values of $(x, \dot{x})$ in v. For each edge $e = (v, v') \in E$, $guard(e)$ represents a condition for changing from v to v'. If the machine is in v and does not satisfy $x \in inv(v)$, the machine must change from v to another mode.

The machine $\mathcal{S}$ is a syntax of the machine dynamics. We define a semantics of the machine $\mathcal{S}$ by the following transition system.

$$\mathcal{G}_M = \langle H_M, \Sigma_M, \delta_M, H_{M0}\rangle, \quad (2)$$

where

- $H_M \subseteq V \times \Re^n \times \Re$ is a set of states such that $(v, x, t_M) \in H_M$ represents the current mode, the continuous variable, and the elapsed time from the instant of the latest mode transition,
- $\Sigma_M = \Sigma \cup \Re$ is a set of events, where $\Re$ represents an elapsed time,
- $\delta_M \subseteq H_M \times \Sigma_M \times H_M$ is a transition relation, and
- $H_{M0} \subset H_M$ is a set of initial states.

Each transition $((v, x, t_M), \sigma, (v', x', t'_M)) \in \delta_M$ is defined if one of the following conditions hold:

- $e = (v, v') \in E$, $event(e) = \sigma \in \Sigma$, $t'_M = 0$, $x \in guard(e)$, and $x' \in reset(e, x)$.
- $\sigma \in \Re$, $t'_M = t_M + \sigma$, $v = v'$, and there exists a continuously differentiable function $\xi_x : [0, \sigma] \to \Re^n$ such that $\xi_x(0) = x$, $\xi_x(\sigma) = x'$, and $\xi_x(\tau) \in inv(v)$ and $(\xi_x(\tau), \dot{\xi}_x(\tau)) \in flow(v)$ for any $\tau \in [0, \sigma]$.

Moreover, for any event $\sigma \in \Sigma_M$ and any sequence $s \in \Sigma_M^*$, we extend the transition relation to the set-valued transition function $\delta_M : H_M \times \Sigma_M^* \to 2^{H_M}$ as follows:

$$\delta_M(h_M, \sigma) := \{h'_M \in H_M | (h_M, \sigma, h'_M) \in \delta_M\} \quad (3)$$

$$\delta_M(h_M, s\sigma) := \{h''_M \in \delta_M(h'_M, \sigma) | h'_M \in \delta_M(h_M, s)\} \quad (4)$$

2.2 User Interface and User Model

The user interface displays machine's abstracted state as one display mode. We define a user interface as the following binary relation.

$$\mathcal{I} \subseteq H_M \times H_U, \quad (5)$$

where H_M is the state set of the machine model, and H_U is a set of display modes. A pair $(h_M, h_U) \in \mathcal{I}$ means that machine's state h_M is displayed as the display mode h_U at the user interface. We call the binary relation $\mathcal{I}$ the user interface.

We consider the case where an objective of the user is to change from the current state of the machine to a target state. To achieve this objective, the user repeats the observation of machine's state through the user interface and the operation for the machine. We assume that the user issues a command to the machine based on the machine's information displayed at the user interface, and waits for time $\tau \in [\tau_l, \tau_h]$ until the next command is issued, where the user waits for time τ_l at least and determines the next command followed by the change of the display mode at the user interface before time τ_h is elapsed. A display mode of the user interface is an abstracted or a partially observed state, and a pair of the command and the time interval $[\tau_l,\ \tau_h]$ is an event in the user model since the user's next operation is concerned with a display mode of the user interface when τ is elapsed after issuing the command. Then, we define a user model with his/her temporal knowledge of the machine's dynamics by the following transition system $\mathcal{G}_U$.

$$\mathcal{G}_U = \langle H_U, \Sigma_U, \delta_U, H_{U0} \rangle, \quad (6)$$

where

- H_U is a set of user's states that are associated with display modes,
- $\Sigma_U = \Sigma^{com} \times (\Re \times \Re)$ is a set of events,
- $\delta_U \subseteq H_U \times \Sigma_U \times H_U$ is a transition relation, and
- $H_{U0} \subset H_U$ is a set of initial states.

Denoted by $(\sigma, [\tau_l, \tau_h])$ is an element of Σ_U, where $\sigma \in \Sigma^{com}$, $\tau_l \in \Re$, and $\tau_h \in \Re$. A transition $(h_U, (\sigma, [\tau_l, \tau_h]), h'_U)$ means that, when the display mode is h_U, the user can issue a command σ and anticipates the change of the display mode to h'_U after time $\tau \in [\tau_l, \tau_h]$ is elapsed. Moreover, we denote the transition function as $\delta_U(h_U, \sigma_U) = \{h'_U \in H_U | (h_U, \sigma_U, h'_U) \in \delta_U\}$ for each $\sigma_U \in \Sigma_U$. We denote the human-machine system as 3-tuple $(\mathcal{G}_M, \mathcal{G}_U, \mathcal{I})$.

3. DETECTION OF MODE CONFUSIONS

In this section, we deal with a mode confusion in the human-machine system. Mode confusions represent a phenomenon such that a change of a display mode after the user issues a command is different from that anticipated by him/her. The user may have temporal knowledge for his/her operations such that he/she waits for specified time after the command is issued. Then, the user may have knowledge such that he/she issues the next command at an anticipated dispaly mode changing from the current one at an anticipated time. Therefore, we introduce a formal definition of the mode confusion related to the elapsed time after issuing the command. Moreover, to detect the mode confusion, we introduce a weak alternating simulation relation and derive an algorithm for detecting the mode confusion based on the relation.

3.1 Formal Definition of Mode Confusions

We assume that there is a state $h_U \in H_U$ satisfying $(h_M, h_U) \in \mathcal{I}$ for each state $h_M \in H_M$. Intuitively, this assumption means that any machine's state is displayed as a display mode at the user interface, that is, the user interface always works correctly. The initial states $h_{M0} \in H_{M0}$ and $h_{U0} \in H_{U0}$ satisfy $(h_{M0}, h_{U0}) \in \mathcal{I}$.

Recall that the event set Σ_M of the machine model $\mathcal{G}_M$ includes real numbers representing elapsed times after the occurrences of events. We introduce a function $time : \Sigma_M^* \to \Re$ that represents the accumulation of the elapsed times included in a finite sequence generated by $\mathcal{G}_M$. For any $\sigma \in \Sigma_M$ and any $s \in \Sigma_M^*$,

$$time(\sigma) = \begin{cases} \sigma, & \text{if } \sigma \in \Re, \\ 0, & \text{otherwise,} \end{cases} \quad (7)$$

$$time(s\sigma) = time(s) + time(\sigma). \quad (8)$$

We define the mode confusion in the human-machine system $(\mathcal{G}_M, \mathcal{G}_U, \mathcal{I})$ as follows:

$$\begin{aligned} &{}^\exists h_M \in H_M, {}^\exists h_U \in H_U, {}^\exists (\sigma, [\tau_l, \tau_h]) \in \Sigma_U, {}^\exists s \in \Sigma_M^*, \\ &{}^\forall h'_M \in H_M, {}^\forall h'_U \in H_U, {}^\forall s' \in \bar{s} : \\ &\quad \Big((h_M, h_U) \in \mathcal{I} \land \delta_U(h_U, (\sigma, [\tau_l, \tau_h])) \neq \emptyset \\ &\quad\quad \land \delta_M(h_M, \sigma s) \neq \emptyset \land time(s) = \tau_h \Big) \\ &\land \Big(h_U \xrightarrow{(\sigma, [\tau_l, \tau_h])} h'_U \land h_M \xrightarrow{\sigma s'} h'_M \\ &\quad\quad \land \tau_l \leq time(s') \leq \tau_h \Rightarrow (h'_M, h'_U) \notin \mathcal{I} \Big), \end{aligned} \quad (9)$$

where $\bar{s}$ is the set of all prefixes of the sequence s. The intuitive meaning of the mode confusion defined by the condition (9) is that there exist machine's state h_M and a display mode h_U leading to the following situations:

(1) h_M is displayed as h_U at the user interface.
(2) the user can issue the command σ when the user interface displays h_U.
(3) no machine's state h'_M reachable from h_M in the time interval $[\tau_l,\ \tau_h]$ after issuing the command is displayed as a display mode h'_U anticipated by him/her.

Thus, the condition (9) represents a mode confusion with respect to not only the logical interaction between the user and the machine but also user's temporal knowledge about it. It is noted that the previous work (Adachi*et al.*, 2006; Ishii and Ushio, 2016) imposes two assumptions on human-machine systems but this paper does not. So, the condition (9) is also a generalization of the previous work from the logical behavior's point of view.

3.2 $(\Sigma^{com}, \Re)$-*Weak Alternating Simulation Relation*

This section characterizes a human-machine system without the mode confusion. From the condition (9), the mode confusion never occurs if the system satisfies the following condition:

$$\begin{aligned}
&{}^{\forall} h_M \in H_M, {}^{\forall} h_U \in H_U, {}^{\forall} (\sigma, [\tau_l, \tau_h]) \in \Sigma_U, {}^{\forall} s \in \Sigma_M^*, \\
&{}^{\exists} h'_M \in H_M, {}^{\exists} h'_U \in H_U, {}^{\exists} s' \in \bar{s} : \\
&\quad \Big((h_M, h_U) \in \mathcal{I} \wedge \delta_U(h_U, (\sigma, [\tau_l, \tau_h])) \neq \emptyset \\
&\qquad\qquad \wedge \delta_M(h_M, \sigma s) \neq \emptyset \wedge time(s) = \tau_h \Big) \\
&\Rightarrow \Big(h_U \xrightarrow{(\sigma,[\tau_l,\tau_h])} h'_U \wedge h_M \xrightarrow{\sigma s'} h'_M \\
&\qquad\qquad \wedge \tau_l \leq time(s') \leq \tau_h \wedge (h'_M, h'_U) \in \mathcal{I} \Big). \qquad (10)
\end{aligned}$$

The Intuitive meaning of the condition (10) is that, for any machine's state h_M, the user can issue a command σ if his/her user model allows to do so at the display mode h_U corresponding to h_M and no matter which behavior the machine exhibits after issuing the command, the machine reaches a state h'_M such that he/she anticipates that the user interface displays a display mode h'_U corresponding to h'_M after time $\tau \in [\tau_l,\ \tau_h]$ is elapsed and continues his/her operations. In other words, for each pair of machine's state and the corresponding display mode, any command the user can issue at the display mode, and any behavior of the machine after issuing the command, the user can determine the next command until the machine reaches a target state. Thus, the condition (10) is a relation on the product of the sets $H_M \times \Sigma_M^* \times H_U \times \Sigma_U$, which is a kind of alternating simulation relations. Since Σ_U includes the commands and the times elapsed from issuing the commands, and the relation is not related to Σ_M but to Σ_M^*, we will call the condition (10) a $(\Sigma^{com}, \Re)$-*weak alternating simulation relation*. Thus, the nonexistence of the mode confusion is characterized by the $(\Sigma^{com}, \Re)$-weak alternating simulation relation. In the previous work (Adachi *et al.*, 2006; Ishii and Ushio, 2016), the existence condition for a mode confusion is based on a simulation relation because two assumptions are imposed on human-machine systems. By removing the assumptions, the nonexistence condition is not based on a simulation relation but on an alternating simulation relation.

From the above discussion, a design method of a user interface and a user model for a given machine model such that mode confusions do not occur in the obtained human-machine system is related to the computation of the alternating simulation relation. But, the relation depends on Σ_M^*. So, it is future work to propose an efficient design algorithm for both a user interface and a user model.

3.3 *Detection Algorithm of Mode Confusions*

We assume the following condititons to propose a detection algorithm for the mode confusion.

- A set of display modes H_U is a finite set.
- For each display mode h_U, a set of machine's states h_M satisfying $(h_M, h_U) \in \mathcal{I}$ is computable within a finite time.

Algorithm 1 is a detection algorithm for the mode confusion based on the $(\Sigma^{com}, \Re)$-weak alternating simulation relation. First, the algorithm calculates a 2-tuple consisting of a display mode and a set of machine's states displayed by the display mode. Next, the algorithm calculates a set of commands issued by the user for each display mode. Finally, the algorithm calculates a set Dsp of machine's states corresponding to the display modes anticipated by the user model after issuing the command. If there is a state trajectory of the machine such that it crosses no state of Dsp in the time interval anticipated by the user model, then the mode confusion occurs.

4. APPLICATION TO HVAC SYSTEM

In this section, we apply the proposed detection algorithm of the mode confusion to a heating, ventilation and air conditioning system (HVAC system) (Arguello-Serrano and Velez-Reyes, 1999; Chiang and Fu, 2006). The HVAC system is used for conditioning environmental comfort in a room such as temperature and humidity. Shown in Fig. 2 is an example of the HVAC system configuration. In this paper, the HVAC system controls temperature, humidity, and CO_2 concentration in a room by the following way:

(1) The outside air flows into the HVAC system and it is mixed with the recirculated air that is a part of the outlet air from the room.
(2) A heat exchanger controls the temperature of the mixed air by a chiller flushing water to a cooling coil.

Algorithm 1 Checking $(\Sigma^{com},\Re)$ - weak alternating simulation relation

Require: $\mathcal{G}_M = \langle H_M, \Sigma_M, \delta_M, H_{M0} \rangle$, $\mathcal{G}_U = \langle H_U, \Sigma_U, \delta_U, H_{U0} \rangle$
Ensure: True or False

$Stt = \emptyset$
for display mode h_U in H_U **do**
  $Stt \Leftarrow Stt \cup (\{h_M \in H_M \mid (h_M, h_U) \in \mathcal{I}\}, h_U)$
end for
for state pair (Stt_M, h_U) in Stt **do**
  $Evnt_U = \{(\sigma,[\tau_l,\tau_h]) \in \Sigma_U \mid \delta_U(h_U,(\sigma,[\tau_l,\tau_h])) \neq \emptyset\}$
  for event $(\sigma,[\tau_l,\tau_h])$ in $Evnt_U$ **do**
    $Stt'_M = \{h'_M \in Stt_M \mid {}^{\exists} s \in \Sigma_M^*,$
      $h'_M \in \delta_M(h_M, \sigma s) \wedge \tau_l \leq time(s) \leq \tau_h\}$
    $Stt'_U = \{h'_U \in H_U \mid \delta_U(h_U,(\sigma,[\tau_l,\tau_h]))\}$
    $Dsp = \bigcup_{h'_U \in Stt'_U} \{h'_M \in Stt'_M \mid (h'_M, h'_U) \in \mathcal{I}\}$
    if ${}^{\exists} h_M \in Stt_M, {}^{\exists} s \in \Sigma_M^*, {}^{\forall} s' \in \bar{s},$
      $time(s) = \tau_h \wedge \delta_M(h_M, \sigma s') \nsubseteq Dsp$ **then**
      return False (detect mode confusion)
    endif
  end for
end for
return True

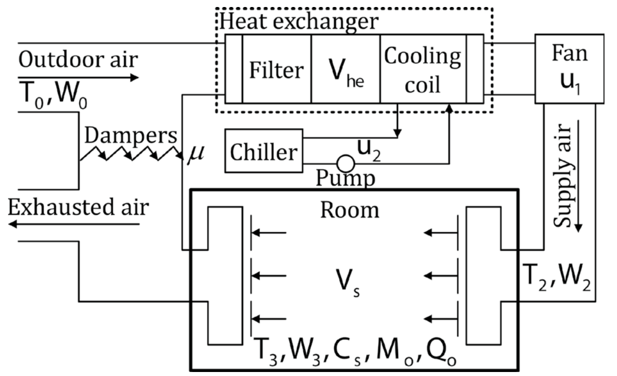

Fig. 2. HVAC system.

(3) A fan sends the conditioned air to the room and the CO_2 concentration is controlled by the ventilation.

Denoted by u_1 is the volumetric flow rate of the supply air, u_2 is the flow rate of the chilled water, and μ is the recirculation rate of the outlet air from the room in the HVAC system. These parameters affect the dynamics of the temperature, the humidity, and the CO_2 concentration in the room. The HVAC system is modeled by the following differential equations:

$$
\begin{aligned}
\frac{dT_3}{dt} &= \frac{60u_1}{V_s}(T_2 - T_3) - \frac{60h_{fg}u_1}{c_pV_s}(W_s - W_3) \\
&\quad + \frac{1}{(1-\mu)\rho_a c_p V_s}(Q_o - h_{fg}M_o), \\
\frac{dW_3}{dt} &= \frac{60u_1}{V_s}(W_s - W_3) + \frac{M_o}{\rho_a V_s}, \\
\frac{dT_2}{dt} &= \frac{60u_1}{V_{he}}(T_3 - T_2) + \frac{60(1-\mu)u_1}{V_{he}}(T_0 - T_3) \\
&\quad - \frac{60h_w u_1}{c_p V_{he}}((1-\mu)W_0 + \mu W_3 - W_s) - \frac{6000u_2}{\rho_a c_p V_{he}}, \\
\frac{dC_s}{dt} &= \frac{C_q}{V_s} - (1-\mu)C_s,
\end{aligned}
$$

where c_p is the specific heat of air at constant pressure, ρ_a is the air mass density, V_{he} is the volume of the heat exchanger, V_s is the volume of the room, W_0 is the humidity ratio of the outdoor air, W_s the humidity ratio of the supply air, W_3 is the humidity ratio of the room, T_0 is the temperature of the outdoor, T_2 is the temperature of the heat exchanger, T_3 is the temperature of the room, M_o is the moisture load, Q_o is the sensible heat load, h_{fg} is the enthalpy of the water vapor, h_w is the enthalpy of the liquid water, C_s is the CO_2 concentration of the room, and C_q is the amount of CO_2 generated in the room. We assume that u_1 and μ are updated by the following conditions every 0.015 time and 0.01 time, respectively.

$$
u_1 = \begin{cases} 10000\,(\text{cfm}) & \text{if the room humidity is larger than } 0.008\,(\text{lb/lb}), \\ 20000\,(\text{cfm}) & \text{otherwise}, \end{cases}
$$

$$
\mu = \begin{cases} 0.15 & \text{if } CO_2 \text{ concentration is larger than } 1000\,(\text{ppm}), \\ 0.85 & \text{otherwise.} \end{cases}
$$

The user interface displays either cold, normal, hot, or very_hot. Display mode cold, normal, hot, and very_hot

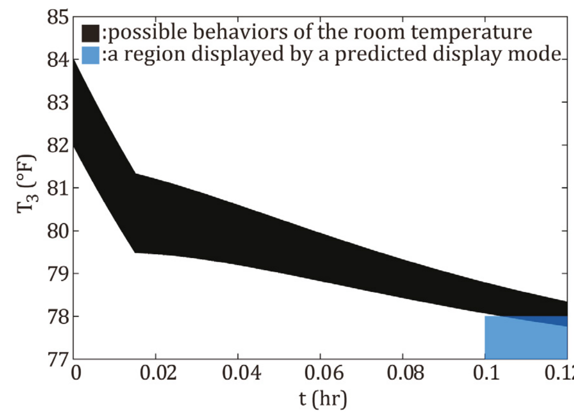

Fig. 3. Time response of the room temperature T_3. If there is no trajectory of T_3 that crosses the region anticipated by the user, then a mode confusion occurs.

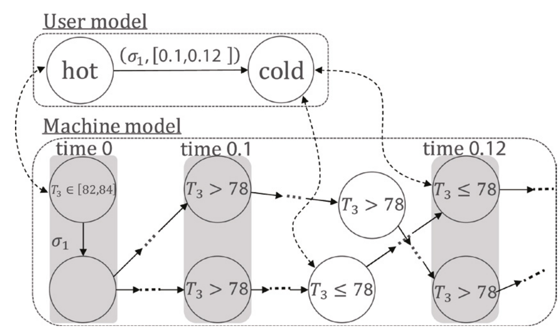

Fig. 4. An example of the mode confusion. A dotted arrow represents apair of a display mode and its corresponding machine state.

represents the abstracted machine's state satisfying $T_3 \leq 78$, $78 < T_3 < 82$, $82 \leq T_3 \leq 84$, and $84 < T_3$, respectively. Moreover, we consider the following user model:

- The initial display mode is hot.
- If the display mode is hot and the command σ_1 meaning that u_2 is set to 70(gpm) is issued, then the user interface displays cold anticipated by the user after time $\tau \in [0.1, 0.12]$ is elapsed.

We detect the following mode confusion using Algorithm 1. Let an initial value of the room temperature, the room humidity, the heat exchanger temperature, and the CO_2 concentration in the room be $T_3 \in [82, 84]$(°F), $W_3 = 0.0092$(lb/lb), $T_2 \in [53, 56]$(°F), and $C_s \in [1100, 1200]$(ppm), respectively. The HVAC system parameters are given by (Zhang and Cai 2002), i.e., $c_p = 0.24\,(\text{Btu/lb} \cdot^\circ \text{F})$, $\rho_a = 0.074\,(\text{lb/ft}^3)$, $V_{he} = 60.75\,(\text{ft}^3)$, $V_s = 58464\,(\text{ft}^3)$, $W_0 = 0.018\,(\text{lb/lb})$, $W_s = 0.070\,(\text{lb/lb})$, $T_0 = 85\,(^\circ\text{F})$, $M_o = 166.06\,(\text{lb/hr})$, $Q_o = 289897.52\,(\text{Btu/hr})$, $h_{fg} = 1087.1\,(\text{Btu/lbm})$, $h_w = 23.0\,(\text{Btu/lbm})$, $C_q = 5000$. We use Flow* (Chen *et al.*, 2012) to calculate the continuous dymanics of the HVAC using the i5-4570 3.2GHz CPU with 8GB RAM. Shown in Fig. 3 is behaviors of the room temperature. Fig. 3 presents the case where the room temperature is not less than 78(°F) between time interval [0.1, 0.12]. In this case, the mode confusion occurs since the user interface does not display cold but normal. Fig. 4 shows an example of the mode confusion illustrated by transition systems. The occurrence of this mode confusion is due to user's insufficient temporal knowledge about the system behavior. The user may be worry about his/her operations if the user interface does not turn into an anticipated display mode by an anticipated time. The proposed algorithm can deal with such a case.

5. CONCLUSION

In this paper, we considered a mode confusion due to user's insufficient knowledge of temporal characteristics of the machine in a human-machine system. First, we defined the user model and the machine model by transition systems, and the user interface by the binary relation over the state sets of the transition systems. User's temporal knowledge of the machine's dynamics is represented by transitions of the user model, and the selection of commands is represented by states of the user model. Next, we defined a mode confusion that occurs due to not only logical knowledge of the machine but also its temporal one. Moreover, we characterized a human-machine system without mode confusions by the $(\Sigma^{com}, \Re)$-weak alternating simulation relation. The weak alternating simulation relation represents the situation that the user can observe machine's state as expected during a time interval after issuing commands. Finally, we proposed a detection algorithm of the mode confusion based on the relation. We applied the algorithm to an HVAC system and detected the mode confusion such that the room temperature does not go down as anticipated by the user.

It is future work to propose a design method of a user interface and a user model using the $(\Sigma^{com}, \Re)$-weak alternating simulation relation when a machine model is given.

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