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A PROPOSAL OF SWITCHING CONTROL SYSTEM BASED ON SPECULATIVE CONTROL AND ITS APPLICATION TO ANTISKID BRAKING SYSTEM

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Abstracts This paper presents a construction method of logic-based switching control system which operates in widely changing environments. The logic-based switching controller is composed of a family of candidate controllers together with a supervisor. The system does not require any identification schemes of environments. Switching from one candidate controller to another is carried out based on monitoring the output of the system. The basic ideas of adaptation are as follows: (1)each candidate controller is prepared for each environment in advance; (2)the supervisor applies a sequence of speculative controls to a plant with candidate controllers just after the control has started and just after the change of the environment has been detected. It is important that each candidate controller can keep the system stable during a sequence of speculative controls, and the most appropriate candidate controller for the environment to which the system is exposed can be selected before the last speculative control is ended. An application to an antiskid braking system clarifies the effectiveness of the proposed method.

Keywords Identification Schemes of Environment, Switching Control System, Robustness, Stability, Responsiveness

1. INTRODUCTION

Increasing attention has been paid to the adaptive control systems which are required to operate in a variety of environments [1]. In recent years, the researches of such systems have been focused on the unexplored area of logic-based switching control systems [2]-[8]. The typical logic-based switching control system consists of a plant to be controlled, a family of candidate controllers(CC's), and a supervisor [2]. A supervisor is a logical element capable of determining in real time which candidate controller should be put in feedback with a plant in order to achieve desired control performance. In the sequel we shall refer to such logic-based switching controllers informally as multiple controllers(MC's).

Approaches using multiple controller can be roughly classified into two categories by information which a supervisor monitors. In the first category, switching from one candidate controller to another is carried out based on monitoring estimated plant parameter values. The work in [3] shows an adaptive fuzzy control approach. A number of fuzzy control laws are obtained for different typical plant models in advance. An appropriate fuzzy control laws are inferred from them based on observing plant parameter values. This approach is successfully implemented in [4] for the cooperation control of several wet pumps. In the second category, switching is carried out based on monitoring observed identification errors between the plant output and multiple identification models. The work in [5] shows an approach using multiple models, where models are switched and tuned based on monitoring identification errors. This approach has been extended in [6] to nonlinear systems with successful experimental results for a two-link direct-drive robot arm using eight adaptive models. In spite of many successes of these approaches, several drawbacks exist. One of the most serious problems is that their performance may degrade, and what is worse, systems may lose their stability in case when the enough accuracy of plant parameter estimators or multiple identification models can't be achieved.

This paper presents a construction method of logic-based switching control systems which does not require any identification schemes of environments. Switching is carried out based on monitoring the output of the system. The basic ideas of adaptation are as follows: (1)each candidate controller is prepared for each environment in advance; (2)the supervisor applies a sequence of speculative controls to a plant with candidate controllers just after the control has started and just after the change of the environment has been detected [7][8]. It is important that each candidate controller can keep the system stable during a sequence of speculative controls, and the most appropriate candidate controller for the environment to which the system is exposed can be selected before the last speculative control is ended. An application to an antiskid braking system clarifies the effectiveness of the proposed method.

2. STATEMENT OF THE PROBLEM

2.1 Assumptions

We consider a feedback system composed of a multiple controller together with a plant whose input-output characteristics change in different environments. Four assumptions concerning environments and a plant are made as follows:

1) The region in which the environment changes during the operation of the system is obtainable in advance. C is a set of an infinite number of environments which belong to the region. $\widetilde{C}(\subset C)$ is a set of a finite number of environments, each of which is representative of each partitioned region. The set $\widetilde{C}$ is given by

$$\widetilde{C} = \{c_i | i \in I_C\}, \tag{1}$$

where $I_C = \{1, 2, \cdots, N_C\}$ and N_C is the number of partitioned regions.

2) The input-output characteristics of a system are affected by only environments. The system in each environment $c_i \in \widetilde{C}$ is described by a pair of differential equations of the form: $\dot{x}(t) = f_i(x(t), u(t))$ $(i \in I_C)$ and $y(t) = g(x(t))$. $x(t)$, $u(t)$ and $y(t)$ represent respectively the input, state and the output of the system. $f_i(\cdot)$ and $g(\cdot)$ are nonlinear functions and a part of $f_i(\cdot)$ may be unknown. The desired output y_{d_i} $(i \in I_C)$ of the system is determined for each environment $c_i \in \widetilde{C}$ in advance.

3) In the design of a multiple controller, it is possible to apply trial controls to a plant from an arbitrary initial state

in each environment $c_i \in \widetilde{C}$.

4) During the control of a plant, the environment to which the system is exposed can not be identified, but the output of the system $y(t)$ is accessible.

2.2 The Desired Control Performance

We regard continuously changing environments as discretely changing ones. The environment is unchangeable, i.e. the environment belongs to the same environment $c_i \in \widetilde{C}$, for $nT \leq t < (n+1)T$. It is assumed that the control is started at $t=0$ and is ended before $t=NT$. The objective is to construct a logic-based switching control system which achieves the desired control performance as follows:

1) An initial output value of the system is between the lower and upper holding bounds, y_l and y_u (prespecified constants):

$$y_l \leq y(0) \leq y_u. \tag{2}$$

2) Just after the control has started in an environment $c_i \in \widetilde{C}$, the output of the system is kept within the holding bounds for a prespecified constant time $T_s(<T)$. And then the output of the system is kept between the lower and upper settling bounds, $y_{d_i} \pm \epsilon$ ($i \in I_C$, ϵ is a small prespecified positive constant):

$$y_l \leq y(t) \leq y_u \quad (0 \leq t < T_s), \tag{3}$$

$$|y_{d_i} - y(t)| \leq \epsilon \quad (T_s \leq t < T,\ i \in I_C). \tag{4}$$

3) Just after the environment changed to another environment $c_{i'} \in \widetilde{C}$ at $t=nT$ $(n=0,1,\cdots,N-1)$, the output of the system is kept within the holding bounds for a time T_s. After a period of time T_s has passed, the output of the system is kept within the settling bounds $y_{d_{i'}} \pm \epsilon$ ($i' \in I_C$):

$$y_l \leq y(t) \leq y_u \quad (nT \leq t < nT + T_s), \tag{5}$$

$$|y_{d_{i'}} - y(t)| \leq \epsilon \quad (nT + T_s \leq t < (n+1)T,\ i' \in I_C). \tag{6}$$

4) For the rest of time, the output of the system is continuously kept within the settling bounds:

$$|y_{d_i} - y(t)| \leq \epsilon \quad (nT \leq t < (n+1)T,\ i \in I_C). \tag{7}$$

3. SPECULATIVE CONTROL

In this section, the basic ideas of speculative controls are presented. A schematic diagram of the structure of the proposed system is shown in Fig.1.

In order to achieve the desired control performance in different operating environments, we need to address, in general, the design of a multiple controller which can rapidly regulate the output of the system to the corresponding desired output. Since we do not use any identification schemes of environments, the supervisor is required to determine in real time which candidate controller should be put in feedback with a plant based on monitoring the output of the system. We consider a multiple controller in which switching from one candidate controller to another is carried out based on monitoring some of tracking errors $e_i(t) = y_{d_i} - y(t)$.

In advance, candidate controllers are constructed, so that in each environment the output of the system can be kept within either pair of bounds from an arbitrary initial state,

$$y_l \leq y(t) \leq y_u \quad (0 \leq t < T_r), \tag{8}$$

$$|y_{d_i} - y(t)| \leq \epsilon \quad (T_r \leq t < NT,\ i \in I_C), \tag{9}$$

or

$$y_l \leq y(t) \leq y_u \quad (0 \leq t < T_r), \tag{10}$$

$$y_l \leq y(t) \leq y_u \text{ and } |y_{d_i} - y(t)| > \epsilon \quad (T_r \leq t < NT,\ \forall i \in I_C), \tag{11}$$

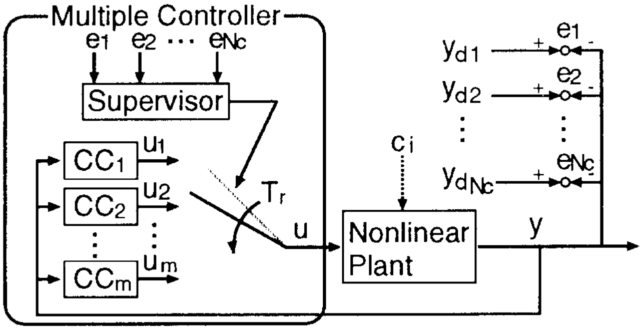

Fig.1. Structure of the proposed logic-based switching control system.

where T_r is a prespecified constant satisfying $0 < T_r \leq T_s$ and we call such T_r a regulation time. Because of this property, the supervisor can judge whether the candidate controller is appropriate or inappropriate for the operating environment, and the candidate controller can at least keep the system stable even if inappropriate. $m(\leq N_C)$ candidate controllers are selected for the construction of a multiple controller, so that a sequence of speculative controls can be ended in less than T_s, and an appropriate candidate controller for the operating environment can be selected before the last speculative control is ended.

Let CC_k be the kth candidate controller in a multiple controller. Just after the control has started, the supervisor simply repeats to switch from CC_1 to CC_2, $\cdots$, CC_m at a constant time T_r intervals but stops switching when an appropriate candidate controller CC_k is selected. Similarly, just after the change of the environment has been detected, the supervisor repeats to switch from CC_k to CC_{k+1}, $\cdots$, CC_m, CC_1, $\cdots$, CC_{k-1}. Whether the switched candidate controller is appropriate or inappropriate is judged as follows. Tracking errors are measured at the time when a constant time T_r has passed after the start of a speculative control. If a tracking error is smaller than ϵ, such candidate controller is appropriate for the operating environment. Else if every tracking error is larger than ϵ, such candidate controller is inappropriate. On the other hand, the change of the environment is detected as follows. The tracking error which has been kept smaller than ϵ is measured at all times after the candidate controller had been judged appropriate. If the tracking error has become larger than ϵ again, it is judged that the environment has already changed.

4. CONTROL PERFORMANCE CRITERIA

In order to construct candidate controllers, a holding set C_H of a robust performance criterion for stability, a settling set C_S and non-settling set C_N of robust performance criteria for responsiveness are introduced. These sets are defined by a set of holding criteria τ_H^i ($\forall i \in I_C$), settling criteria τ_S^i ($\forall i \in I_C$) and non-settling criteria τ_N^i ($\forall i \in I_C$) respectively.

4.1 Criteria of Stability and Responsiveness

We consider stability and responsiveness of the system. In an environment $c_i \in \widetilde{C}$, stability and responsiveness for each candidate controller are evaluated for the same set $\widetilde{X}_0$ of initial states given by

$$X_0 = \{x(0) | x(0) = g^{-1}(y(0)),\ y_l \leq y(0) \leq y_u\}, \tag{12}$$

$$\widetilde{X}_0 = \{x_0^j | x_0^j \in X_0,\ j \in I_{X_0}\}, \tag{13}$$

where $I_{X_0}=\{1,2,\cdots,N_{X_0}\}$ and N_{X_0} is the number of partitioned state regions.

A Holding criterion τ_H^i $(\forall i\in I_C)$ is introduced as a measure of stability for a candidate controller in an environment $c_i\in\widetilde{C}$, and a settling criterion τ_S^i $(\forall i\in I_C)$ and a non-settling criterion τ_N^i $(\forall i\in I_C)$ are introduced as as measures of responsiveness for a candidate controller in an environment $c_i\in\widetilde{C}$. These criteria, τ_H^i, τ_S^i and τ_N^i, are respectively defined by

$$\begin{aligned}\tau_H^i &= \min_{j\in I_{X_0}} t_H^{i,j}, &(14)\\ \tau_S^i &= \max_{j\in I_{X_0}} t_S^{i,j}, &(15)\\ \tau_N^i &= \max_{j\in I_{X_0}} t_N^{i,j}, &(16)\end{aligned}$$

where $t_H^{i,j}$, $t_S^{i,j}$ and $t_N^{i,j}$ are a holding time, a settling time and non-settling time respectively given by

$$\begin{aligned}t_H^{i,j} &= \sup_{t\in[0,NT)}\{t|c_i\in\widetilde{C},\ x_0^j\in\widetilde{X}_0,\\ &\qquad y_l\leq y(t')\leq y_u,\ \forall t'\in[0,t)\}, &(17)\\ t_S^{i,j} &= \inf_{t\in[0,NT)}\{t|c_i\in\widetilde{C},\ x_0^j\in\widetilde{X}_0,\\ &\qquad y_l\leq y(t')\leq y_u,\ \forall t'\in[0,t),\\ &\qquad |y_{d_i}-y(t')|\leq\epsilon,\ \forall t'\in[t,NT)\}, &(18)\\ t_N^{i,j} &= \inf_{t\in[0,NT)}\{t|c_i\in\widetilde{C},\ x_0^j\in\widetilde{X}_0,\\ &\qquad y_l\leq y(t')\leq y_u,\ \forall t'\in[0,t),\\ &\qquad y_l\leq y(t')\leq y_u \text{ and } |y_{d_{i'}}-y(t')|>\epsilon,\\ &\qquad \forall i'\in I_C,\ \forall t'\in[t,NT)\}. &(19)\end{aligned}$$

We set a large value to the number N_{X_0} of partitioned state regions as to guarantee stability and responsiveness for each candidate controller.

4.2 Criteria of Robust Performance

We consider robustness of the system for the changes of the environment. A holding set C_H is introduced as a measure of robustness for stability, and a settling set C_S and non-settling set C_N are introduced as as measures of robustness for responsiveness. These sets, C_H,C_S and C_N, are respectively defined by

$$\begin{aligned}C_H &= \{c_i|c_i\in\widetilde{C},\ \tau_H^i+\delta=NT,\ \delta>0\}, &(20)\\ C_S &= \{c_i|c_i\in C_H,\ \tau_S^i<T_r\}, &(21)\\ C_N &= \{c_i|c_i\in C_H,\ \tau_N^i<T_r\}, &(22)\end{aligned}$$

where δ is a small prespecified positive constant. we also define a subset $C_H\cap(\overline{C_S\cup C_N})$ as $C_{\overline{SN}}$.

5. MULTIPLE CONTROLLER

In order to construct a multiple controller, we select m candidate controllers. Let C_H^k, C_S^k and C_N^k be the holding set, the settling set and the non-settling set for the kth candidate controller, and let $C_{\overline{SN}}^k$ be $C_H^k\cap(\overline{C_S^k\cup C_N^k})$. The selected candidate controllers must satisfy the following conditions.

1) Detect the change of the environment:

$$\begin{aligned}C_H^1 &= C_S^1\cup C_N^1\ \ (C_{\overline{SN}}^1=\phi), &(23)\\ C_H^2 &= C_S^2\cup C_N^2\ \ (C_{\overline{SN}}^2=\phi), &(24)\\ &\ \vdots\\ C_H^m &= C_S^m\cup C_N^m\ \ (C_{\overline{SN}}^m=\phi). &(25)\end{aligned}$$

2) Terminate a sequence of speculative controls in less than T_s:

$$(m+1)\times T_r \ \leq\ T_s. \qquad (26)$$

3) Keep the system stable during a sequence of speculative controls:

$$C_H^1=C_H^2=\cdots=C_H^m=\widetilde{C}. \qquad (27)$$

4) Select an appropriate candidate controller before the last speculative control is ended:

$$C_S^1\cup C_S^2\cup\cdots\cup C_S^m \ =\ \widetilde{C}. \qquad (28)$$

6. VEHICLE ANTISKID BRAKING SYSTEM

To illustrate the effectiveness of the proposed method, we apply it to the ABS in a simulation.

6.1 Control Criteria

The objective of the vehicle antiskid braking control is both to provide the vehicle with the minimal stopping distance and to maintain adequate vehicle stability and steerability. In general, there are two major difficulties involved in the design of a antiskid braking controller: (1)the vehicle/brake system is highly nonlinear; (2)during braking, it is very difficult to identify the road surface condition which strongly affects the dynamics of the vehicle/brake system [9].

When the brakes on a vehicle are applied, longitudinal and lateral tire forces are generated at the interface between the wheel and the road surface. The former slows the vehicle. The latter directs the vehicle in accordance with steering inputs from the driver or in response to other lateral forces such as side wind. Wheel slip for braking is defined as the difference between the vehicle speed and the wheel speed normalized by the vehicle speed. The longitudinal and lateral tire forces are dependent upon the wheel slip. The longitudinal tire force increases rapidly near 0 wheel slip. However, after reaching the peak value, the longitudinal tire force decreases with increasing wheel slip. One the other hand, the lateral force decreases substantially as wheel slip increases. Since the lateral forces decrease with wheel slip, the ability to steer a vehicle decreases substantially with increasing wheel slip. From the above characteristics, we determine the control criteria as: (1)to regulate the wheel slip where the longitudinal tire force attains its peak value; (2)to at all times keep the wheel slip less than a value, which is slightly larger than the value giving the peak longitudinal tire force.

6.2 Simulation Results

Here, we construct a multiple controller for four types of road surface conditions. The inputs to each candidate controller are the vehicle velocity v, the wheel angular velocity ω and the wheel slip λ. The output from each candidate controller is the braking torque T_b. Fig.2 shows relationships between the longitudinal adhesion coefficient (the ratio between the longitudinal tire force and the normal load) and wheel slip(μ_{Lo}-λ curves) in each road surface condition [10]. Let $\widetilde{C}=\{c_i|i\in I_C\}$ ($I_C=\{$ 1 : dry asphalt, 2 : wet asphalt, 3 : loose gravel, 4 : glare ice$\}$) be the set of the road surface conditions. The parameters used for the construction method are $T=1.0$, $\lambda_l=0.05$, $\lambda_u=0.30$, $\epsilon=0.01$, $T_s=1.0$, $T_r=0.2$ and $N=25$. The desired wheel slips in road surface conditions are determined as $\lambda_{d_1}=0.20$, $\lambda_{d_2}=0.10$, $\lambda_{d_3}=0.25$ and $\lambda_{d_4}=0.15$. In order to understand symbols of environment easily, we shall refer to c_1, c_2, c_3 and c_4 as D, W, L and G respectively.

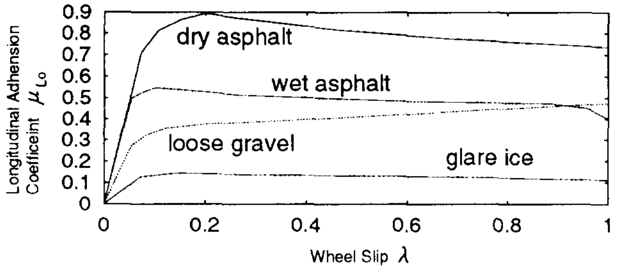

Fig.2. μ_{Lo}–λ curves for four types of road surfaces.

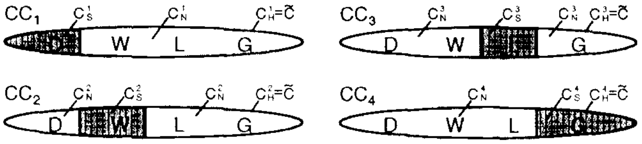

Fig.3. Holding, settling and non-settling sets for selected candidate controllers.

Fig.3 shows holding, the settling and non-settling sets for the selected four candidate controllers. Fig.4 shows the switching results, the braking torque T_b, the vehicle velocity v, the wheel velocity $R\omega$ (R is the radius of the wheel), the wheel slip λ, the vehicle position x and the theoretical vehicle position in case when the road surface condition changes from G to W at the time when five seconds have passed after the start of braking. During a simulation, the wheel slip λ is kept at all times within the holding bounds, and the vehicle position x is nearly equal to the the theoretical vehicle position. This implies the following. The constructed multiple controller can achieve the minimal stopping distance and can maintain adequate vehicle stability and steerability.

7. CONCLUSIONS

A construction method of switching control systems based on speculative control was proposed. The system does not require any identification schemes of environments. An application to an antiskid braking system clarifies the effectiveness of the proposed method.

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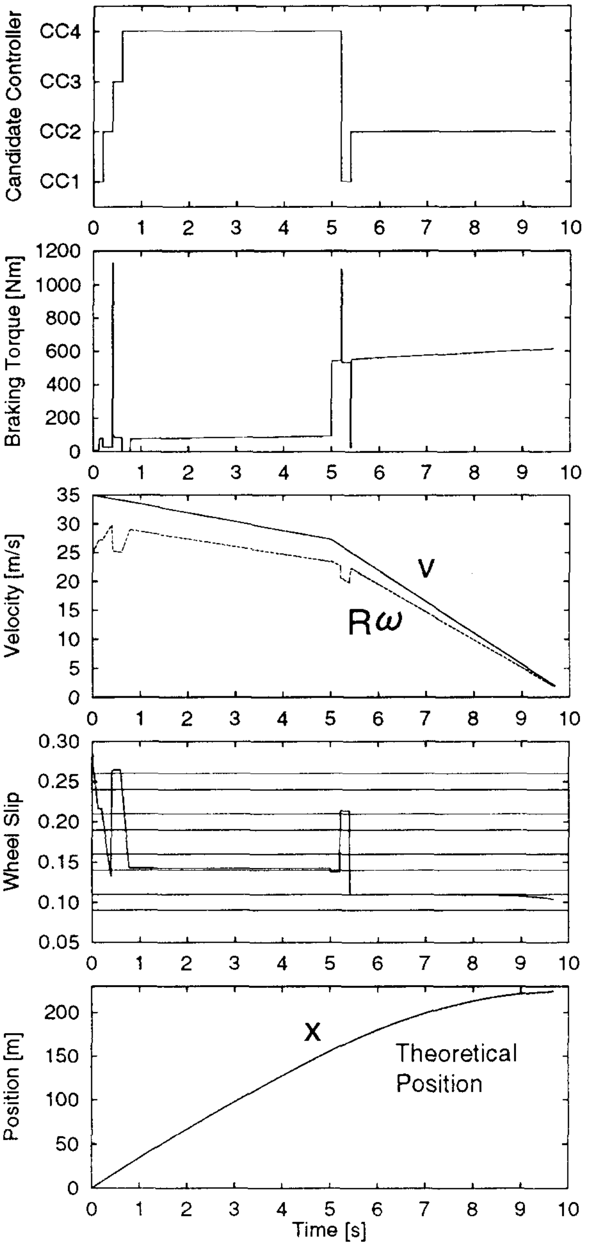

Fig.4. Results for a transition from G to W on braking.

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