Introduction to An MPC/Hybrid System Approach to Traction Control

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Norio Iwabuchi

Outline

Outline

計測と制御 2006 Vol.45 川邊

Period	'80s	'80s～'90s
Trend	**Technology maturity of vehicle mechanism** ➢(Twin calibrator) ➢(Power steering) ➢(Independent suspension) ➢(Disk brake) ➢(Automatic transmission) ➢etc	**Computerization of vehicle** ➢Electronic control engine ➢Anti-lock brake system (ABS) ➢Steering of Four-wheel-drive vehicle ➢Active suspension Semi-active suspension ➢Traction control system (TCS)
Demand		❑Emission gas purification ❑Advancement of mobility ❑Advancement of safety


4WD vehicle


active suspension


Disc break


Independent suspension

Outline

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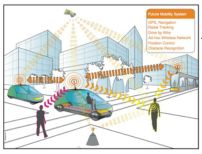
Period	2000s～	
Trend	**Informatization of vehicle** ➢Automated driving ➢Intelligent transport system (ITS) ➢Various drive assist systems •(Car navigation) •Adaptive cruise control •Lane keeping assist system	**Realization of low fuel consumption・Automation of vehicle** ➢Continuously variable transmission (CVT) ➢Hybrid electric vehicle ➢Fuel cell vehicle ➢X-by-wire
Demand		❑Reduction of CO_2 ❑Reduction of traffic accident/traffic victim ❑Ease traffic jam


Steer-by-wire


Informatization of vehicle

Introduction

Vehicle

- Engine
- Traction
- Drivability
- Powertrain
- etc

control a vehicle motion under wheels slip.

Introduction

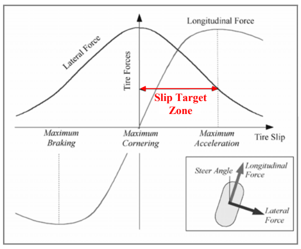
Traction control problems

- ✓ Improve a driver's ability to control a vehicle under adverse external conditions.
- ✓ Prevent the wheel from slipping by maximizing the tractive force .
- ✓ Improve vehicle stability and steerability.

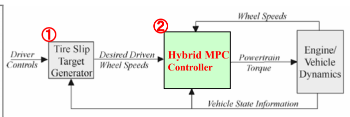
Objective

- ✓ Maximize the tractive torque while preserving the stability of the system

Introduction



Typical behavior of lateral and longitudinal tire forces.



Overall traction control scheme.

①A device that estimates the road surface condition and consequently generates a desire wheel slip

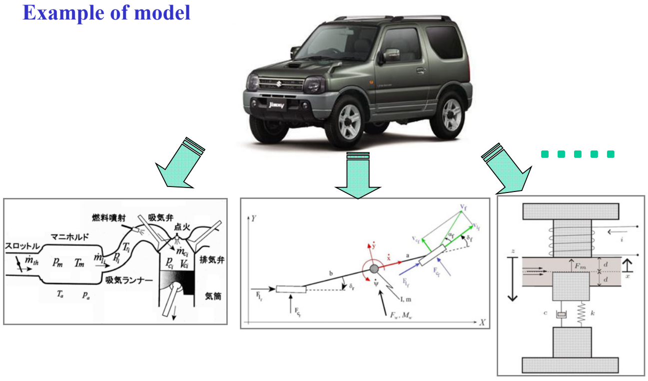
②A traction controller that regulates the wheel slip at the desired value.

1. Outline

1. Introduction
2. Modeling of Vehicle
3. An MPC/Hybrid System
4. Simulations and Experiments
5. Conclusions and Future Works

Modeling of Vehicle

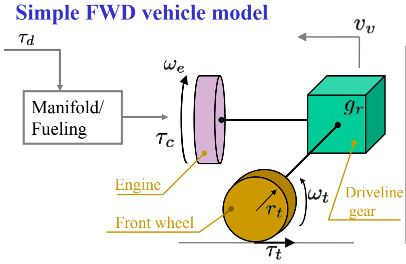
Example of model



Modeling of Vehicle

Simple FWD vehicle model

FWD : Front-Wheel-Driven



- τ_d : Desired combustion torque
- ω_e : Engine speed
- τ_c : Actual combustion torque
- g_r : Total driveline gear ratio between ω_e and v_v
- r_t : Tire radius
- τ_t : Frictional torque on the tire
- v_v : Vehicle speed

Equation of motion

$$\begin{cases} J'_e\dot{\omega}_e = \tau_c - \dfrac{\tau_t}{g_r} - \omega_e b_e \\ m_v r_t \dot{v}_v = \tau_t \end{cases}$$

- J'_e : Combined engine/wheel inertia
- b_e : Engine damping
- m_v : Vehicle mass

Modeling of Vehicle

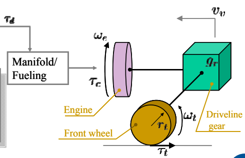
$$\begin{pmatrix}\dot{\omega}_e \\ \dot{v}_v\end{pmatrix} = \begin{pmatrix}-\frac{b_e}{J'_e} & 0 \\ 0 & 0\end{pmatrix}\begin{pmatrix}\omega_e \\ v_v\end{pmatrix} + \begin{pmatrix}\frac{1}{J'_e} \\ 0\end{pmatrix}\tau_c + \begin{pmatrix}-\frac{1}{J'_e g_r} \\ \frac{1}{m_v r_t}\end{pmatrix}\tau_t$$

1. The wheel dynamics under the effect of the combustion toque and of the friction torque
2. Longitudinal motion dynamics of the vehicle

The air intake and fueling model

$$\tau_c(t) = \tau_d(t - \tau_f)$$

- t : time
- τ_f : Fueling to combustion pure delay period



Modeling of Vehicle

Assumption

- The fuel combustion delay is modeled as a pure delay.
- Neglect the intake manifold dynamics.
- Neglect the effect of the speed variation on the torque.
- The clutch is locked.
- The vehicle is a front-wheel-driven.

The intake manifold
(six-cylinder engine)

Modeling of Vehicle

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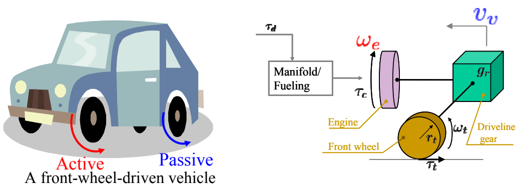

The front wheel : estimate ω_e
The rear wheel : estimate v_v

The slip of the car

$$\Delta\omega = \frac{v_v}{r_t} - \frac{\omega_e}{g_r}$$

$\Delta\omega$: The slip of the car

Modeling of Vehicle

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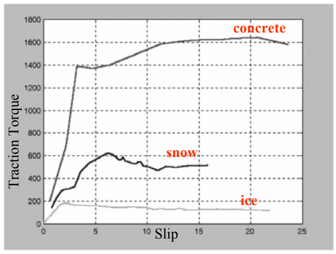

Measured tire traction torque for three different road conditions

The frictional torque

$$\tau_t = f_\tau(\Delta\omega, \mu)$$

μ : coefficient of friction depends on the road-tire conditions
f_τ : nonlinear function of $\Delta\omega$ and μ

Modeling of Vehicle

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Equation of motion

$$\begin{pmatrix}\dot\omega_e \\ \dot v_v\end{pmatrix} = \begin{pmatrix}-\frac{b_e}{J'_e} & 0 \\ 0 & 0\end{pmatrix}\begin{pmatrix}\omega_e \\ v_v\end{pmatrix} + \begin{pmatrix}\frac{1}{J'_e} \\ 0\end{pmatrix}\tau_c + \begin{pmatrix}-\frac{1}{J'_e g_r} \\ \frac{1}{m_v r_t}\end{pmatrix}\tau_t$$

The slip of the car

$$\Delta\omega = \frac{v_v}{r_t} - \frac{\omega_e}{g_r}$$

The frictional torque

$$\tau_t = f_\tau(\Delta\omega, \mu)$$

The air intake and fueling model

$$\tau_c(t) = \tau_d(t - \tau_f)$$

Outline

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An MPC/Hybrid System

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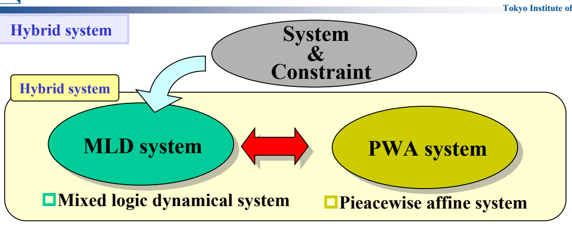
Hybrid system



- ✓Possible to use the HYSDEL compiler and multiparametric programming algorithms.
- ✓Constrains are embedded in the control problem.
- ✓Much less supervision by logical construct than PID controller
- ✓Handle more accurate models and include additional constraint without changing the design flow.

An MPC/Hybrid System

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Constrained Optimal Control

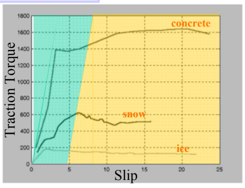
Mixed logic dynamical system	**Pieacewise affine system**
Mixed integer linear program (MILP)	Multi-parametric mixed integer linear program (mp-MILP)
Compute *online*	Compute *offline*
Impossible to solve on standard automotive control hardware at each step.	Control law (piecewise affine form)

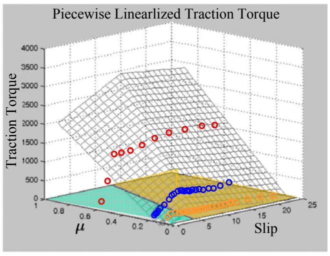
Controller $\tau_c(t) = F_i\theta(t) + g_i \ (= f_{PWA}(\theta(t)))$
Constraint if $H_i\theta(t) \le k_i,\ i = 1, \dots, n_r$
where $\theta(t) = [\omega_e(t)\ v_v(t)\ \tau_c(t-1)\ \mu(t)\ \Delta\omega_d(t)]'$

Parameters : T=5, Q=50, R=1

An MPC/Hybrid System

Hybrid system





$$\tau_t = f_\tau(\Delta\omega, \mu)$$

Hybrid system

$$\tau_t(\Delta\omega, \mu) = \begin{cases} k_{11}\Delta\omega + k_{12}\mu + k_{13}, & \text{if } 0.21\Delta\omega - 5.37\mu \le -0.61 \\ k_{21}\Delta\omega + k_{22}\mu + k_{23}, & \text{if } 0.21\Delta\omega - 5.37\mu > -0.61 \end{cases}$$

$k_{ij},\ i = 1,2,\ j = 1,2,3$:Parameters provided by Ford Research Laboratories

An MPC/Hybrid System

Equation of motion

$$\begin{pmatrix} \dot\omega_e \\ \dot v_v \end{pmatrix} = \begin{pmatrix} -\frac{b_e}{J_e'} & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \omega_e \\ v_v \end{pmatrix} + \begin{pmatrix} \frac{1}{J_e'} \\ 0 \end{pmatrix} \tau_c + \begin{pmatrix} -\frac{1}{J_e' g_r} \\ \frac{1}{m_v r_t} \end{pmatrix} \tau_t$$

The slip of the car

$$\Delta\omega = \frac{v_v}{r_t} - \frac{\omega_e}{g_r}$$

The frictional torque

$$\tau_t(\Delta\omega, \mu) = \begin{cases} k_{11}\Delta\omega + k_{12}\mu + k_{13}, & \text{if } 0.21\Delta\omega - 5.37\mu \le -0.61 \\ k_{21}\Delta\omega + k_{22}\mu + k_{23}, & \text{if } 0.21\Delta\omega - 5.37\mu > -0.61 \end{cases}$$

The air intake and fueling model

$$\tau_c(t) = \tau_d(t - \tau_f)$$

An MPC/Hybrid System

Affine model 1

$$\begin{bmatrix} \dot\omega_e \\ \dot v_v \end{bmatrix} = \begin{bmatrix} -\frac{b_e}{J_e'} - \frac{k_{11}}{J_e' g_r^2} & \frac{k_{11}}{J_e} g_r r_t \\ \frac{k_{11}}{m_v r_t g_r} & -\frac{k_{11}}{m_v r_t^2} \end{bmatrix} \begin{bmatrix} \omega_e \\ v_v \end{bmatrix} + \begin{bmatrix} \frac{1}{J_e'} \\ 0 \end{bmatrix} \tau_c + \begin{bmatrix} -\frac{k_{12}}{J_e' g_r} \\ \frac{k_{12}}{m_v r_t} \end{bmatrix} \mu + \begin{bmatrix} -\frac{k_{13}}{J_e' g_r} \\ \frac{k_{13}}{m_v r_t} \end{bmatrix}$$

Affine model 2

$$\begin{bmatrix} \dot\omega_e \\ \dot v_v \end{bmatrix} = \begin{bmatrix} -\frac{b_e}{J_e'} - \frac{k_{21}}{J_e' g_r^2} & \frac{k_{21}}{J_e} g_r r_t \\ \frac{k_{21}}{m_v r_t g_r} & -\frac{k_{21}}{m_v r_t^2} \end{bmatrix} \begin{bmatrix} \omega_e \\ v_v \end{bmatrix} + \begin{bmatrix} \frac{1}{J_e'} \\ 0 \end{bmatrix} \tau_c + \begin{bmatrix} -\frac{k_{22}}{J_e' g_r} \\ \frac{k_{22}}{m_v r_t} \end{bmatrix} \mu + \begin{bmatrix} -\frac{k_{23}}{J_e' g_r} \\ \frac{k_{23}}{m_v r_t} \end{bmatrix}$$

The air intake and fueling model

$$\tau_c(t) = \tau_d(t - \tau_f)$$

An MPC/Hybrid System

Combustion torque delay

The air intake and fueling model

$$\tau_c(t) = \tau_d(t - \tau_f)$$

Controller

$$\tau_c(t) = f_{PWA}(\theta(t))$$

Time delay of sampling intervals

$$\sigma = \tau_f / T_s = 12$$

T_s : Sampling time

Kalman filter

$$\tau_d(t) = \tau_c(t + \sigma) = f\left(\hat\theta(t + \sigma)\right)$$

Where $\hat\theta(t+\sigma)$ is the σ-step ahead predictor of $\theta(t)$

The frictional torque

$$\tau_t(\Delta\omega, \mu) = \begin{cases} k_{11}\Delta\omega + k_{12}\mu + k_{13}, & \text{if } 0.21\Delta\omega - 5.37\mu \le -0.61 \\ k_{21}\Delta\omega + k_{22}\mu + k_{23}, & \text{if } 0.21\Delta\omega - 5.37\mu > -0.61 \end{cases}$$

Constraint

$$-20 \le \tau_c \le 176 \text{ Nm}$$

$$\dot\tau_c \approx \frac{\tau_c(t) - \tau_c(t-1)}{T_s} \le 2000 \text{ N/s}$$

$$\Delta\omega \ge 0$$

Differentiate τ_t → **Additional states** $\dot\tau_t$

An MPC/Hybrid System

Linear model 3

$$\begin{bmatrix} \dot\omega_e \\ \dot v_v \\ \dot\tau_t \end{bmatrix} = \begin{bmatrix} -\frac{b_e}{J_e'} & 0 & -\frac{1}{J_e' g_r} \\ 0 & 0 & \frac{1}{m_v r_t} \\ -\frac{k_{11} J_e'}{g_r b_e} & 0 & -k_{11} J_e' - k_{11} m_v \end{bmatrix} \begin{bmatrix} \omega_e \\ v_v \\ \tau_t \end{bmatrix} + \begin{bmatrix} \frac{1}{J_e'} \\ 0 \\ 0 \end{bmatrix} \tau_c$$

Linear model 4

$$\begin{bmatrix} \dot\omega_e \\ \dot v_v \\ \dot\tau_t \end{bmatrix} = \begin{bmatrix} -\frac{b_e}{J_e'} & 0 & -\frac{1}{J_e' g_r} \\ 0 & 0 & \frac{1}{m_v r_t} \\ -\frac{k_{21} J_e'}{g_r b_e} & 0 & -k_{21} J_e' - k_{21} m_v \end{bmatrix} \begin{bmatrix} \omega_e \\ v_v \\ \tau_t \end{bmatrix} + \begin{bmatrix} \frac{1}{J_e'} \\ 0 \\ 0 \end{bmatrix} \tau_c$$

Simulations and experiments

Simulations

- ✓Simulate four linear MPC controllers and a Hybrid controller
- ✓Nonlinear model of the vehicle
- ✓On a polished ice surface (μ =0.2)
- ✓Vehicle stands initially with the wheels slipping

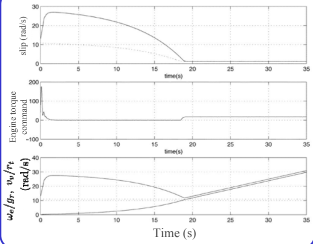
  $\omega_e(0) = 180.6$ rad/s

  $v_v(0) = 0$ m/s

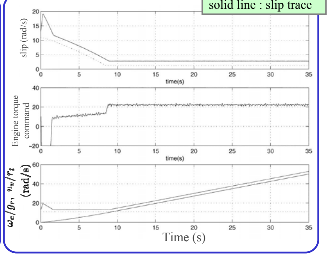
Simulations and experiments

dot line : desired slip
solid line : slip trace

Affine model 1



Affine model 2



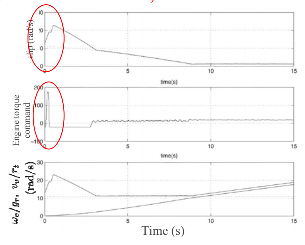
- Very bad performance independently of the MPC tuning
- Find in the large model mismatch

- The performance improves compared to affine model 1
- Generate a steady-state error

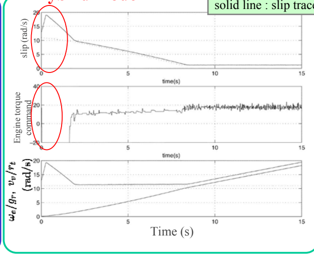
Simulations and experiments

dot line : desired slip
solid line : slip trace

Linear model 3, Linear model 4



Hybrid model



- These two cases lead to similar performance
- Good performance
- Very sensitive to the frictional torque model

- About 21% lower initial spin
- Additional engine torque pulse in the initial phase

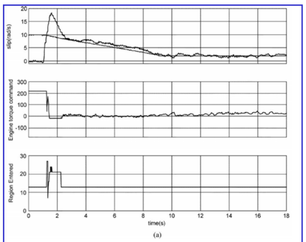
Simulations and experiments

Experiments

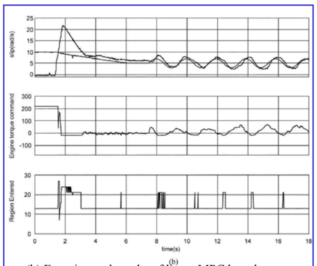
- ✓ The vehicle tested on a polished ice surface. (indoor ice arena, $\mu \approx 0.2$)
- ✓ The controller was tested in a small (1390kg) fornt-wheel-drive passenger vehicle with manual transmission.
- ✓ The overall system latency from issuance of the torque command to production of the actual torque by the engine was relatively large. (0.25 [s])
- ✓ Control intervention was initiated when the average driven wheel speed exceeded the reference wheel speed for the first time.

Simulations and experiments

Experiments



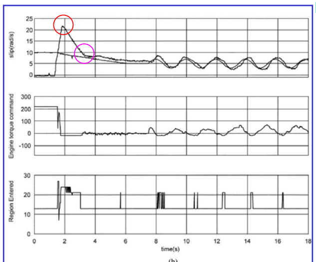
(a) Experimental results of linear MPC based on linear model4(ramp and slip reference)



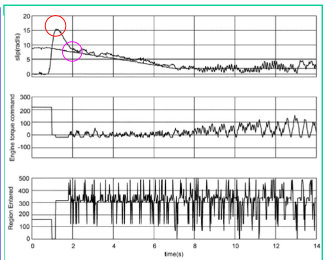
(b) Experimental results of linear MPC based on linear model4 (sinusoidal slip reference)

- The Bandwidth is around 0.5 [Hz]

Simulations and experiments



(b) Experimental results of linear MPC based on linear model4 (sinusoidal slip reference)



Experimental result of hybrid controller

- About 20% lower initial slip peak.
- Faster containment of the first spin.
- The oscillations can be observed

Conclusions and Future Works

Conclusion

- Good and robust performance is achieved on polished ice with hybrid controller.

Future Work

- Survey the thesis using a hybrid system and MPC system.
- More Study MPT.