Activities at the Robotics, Automation, and Mechatronics (RAM) Laboratory

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About Myself

Education background
- Ph.D. (ME), UC Berkeley, 2002
- M.A. (Math), UC Berkeley, 2001
- M.Eng., Tsinghua Univ. (China), 1996
- B.S. (EE) Zhejiang Univ. (China), 1993

Research experience
- Rutgers Univ., 08/2008 -- Now
- San Diego State Univ., 01/2007-08/2008
- Texas A&M Univ., 01/2005-01/2007
- Lam Research Corp., 05/2002/-01/2005

Research Interests

Research areas
- Applied control theory (nonlinear, adaptive, and robust control systems)
- Design and automation
- Dynamic systems

Application areas
- Robotics and vehicle systems
- Biomedical and biological systems
- Civil infrastructural and transportation systems
- Semiconductor manufacturing systems

Recent Research Areas

Autonomous robotic systems:
- Autonomous robot and control
- Human/robot interaction
- Mobile manipulators
- Vision-based navigation

Sensing/actuation systems:
- Contact sensing systems
- Nano-/bio-manipulation
- Energy harvesters

Automation science and engineering
Research Projects

- GOALI: Safety-preserved estimation and control of tire/road interaction (PI, NSF)
- CAREER: Human-inspired safety-preserved vehicle agile maneuvers (PI, NSF)
- Automated nondestructive evaluation and rehabilitation system (ANDERS) for bridge decks (Co-PI, NIST)
- Automated condition assessment of concrete bridge decks using multiple NDE technologies (Task leader, FHWA)
- BIOME - A bio-robotic infrastructure for oceanic microbial ecology (Co-PI, NSF)
- Some other projects

Estimation, Sensing, and Control of Tire/Road Interactions

- Tire/road friction estimation and control
- In situ tire/road friction sensing
- Stability and agility of aggressive maneuvers

Hybrid Tire/Road Friction Models

- A hybrid physical/dynamic friction model
  - Partitioned adhesion/sliding regions (physical model)
  - The adhesive deformation and force is calculated by a LuGre dynamic model
    \[
    \frac{d\delta(z, t)}{dt} = v_R \delta_z(z, t) - \frac{\partial}{\partial v_R} \delta(z, t),
    \]
    \[
    r_a = \int_0^1 \left[ \sigma_1 \delta(z, t) + \sigma_2 \frac{d\delta(z, t)}{dt} + \sigma_3 v_R \right] dz,
    \]

- Resolve the limitations of the existing results in literature
- Bridge the model parameter relationships
- Enable the use of “smart tire” for parameter estimation

Why Need Tire Sensing Systems?

- Tire/road friction modeling and estimation
  - Lack of in situ sensing information
  - Tire tread dynamics neglected
- Tire pressure monitoring system (TPMS)
  - Only monitors inlet pressure and temperature
  - TPMS cannot be used in real-time applications
  - Battery life-time limitation
- Deformation information is critical for
  - Understanding of tire/road interactions
  - Real-time monitoring and control
Deformation Sensing Systems

- Polyvinylidene fluoride (PVDF) sensors
- Custom-built circuits

Sensor Modeling: Bending

- Generated charge due to bending
  \[ q_b(l_x) = \frac{2d_{31}Po_r}{t_S} \left( l_x - \frac{2}{\alpha} e^{\alpha l_x} - 1 \right) \]
- Maximum charge \( q_{bm} \) when \( l_x = l \)

Sensing Modeling: Stretch/Compress

- Physical model: a partition of tire/road contact patch
- Strain/stress distribution on sensors
  \[ \varepsilon(\xi) = \begin{cases} \xi, & 0 \leq \xi < \xi_A, \\ \xi(1 - \xi), & \xi_A \leq \xi \leq 1, \end{cases} \]
  \[ \sigma(\xi) = \begin{cases} \kappa_2 \xi, & 0 \leq \xi < \xi_A, \\ \kappa_2 \xi \left(1 - \frac{\xi}{\xi_A}\right), & \xi_A \leq \xi \leq L, \end{cases} \]
- Maximum charge
  \[ q_{bm} = \frac{1}{2L}d_{31}c_{11}l(l(2L_a - l))\lambda = K\lambda, \]

Sensing Modeling: Summary

- Bending+stretch in sensor output
- Adhesion region size
  \[ L_a = \left(1 - \frac{\bar{c}_x}{3\mu_x F^{-1}_x}\right)L \]
- How to utilize sensor reading?
  - Estimate \( L_a \) by \( \Delta t_a = \frac{l + L - L_a}{\rho_0} \)
  - Estimate sliding friction coeff. \( \mu_x \)
Experimental Setup

- On-board control systems and a sensor suite
- Vision-based computer localization as the global location reference

Sensor Measurements

Wheel encoders

(a) The experimental robot
(b) Various ground conditions
(c) Camera positioning systems

Embedded Rubber Force Sensors

- We design and fabricate a well-structured single-tire test bed
- Pressure-sensitive, electric conductive rubber sensor is embedded inside the tire
- Four sensing cells on one sensor

Sensor Data Analysis

- Left/right wheels: 60/80 rpm; Concrete surface. Sensors embedded in the right front wheel.
- Estimate of sliding friction coefficient on the concrete surface: $\mu_x = 0.47$
Stick-Slip Tire/Road Interaction Sensing

- Simultaneously measure both the normal and frictional forces.
- A multi-cantilever model for stick-slip interaction.

Sensor Calibration and Modeling

- Calibration schematic and models.
- Sensor calibration.
- Validation.

Frictional Force Estimation

- Deformation under varying pulling forces.
- Estimated vs. measured friction force distribution.
- The multi-cantilever beam model predicts frictional force distribution on the contact patch during the stick-slip process.
- The model captures the evolution of the stick-slip development over the contact patch.

Estimation, Sensing, and Control of Tire/Road Interactions

- Tire/road friction estimation and control.
- In situ tire/road friction sensing.
- Stability and agility of aggressive maneuvers.
Human-Inspired Aggressive Maneuvers

- Transfer human-inspired driving knowledge to the next-generation “accident-free” vehicle systems
- Advance understanding and control of human-machine-environment (HME) interactions
- Stability and Agility are important characteristics of aggressive maneuvers

Vehicle Maneuver Agility Metrics

- Agility metric 1: lateral jerk (i.e., acceleration derivative)
  \[ A_J(s) = |(\ddot{s} - s^3 \kappa^2) s_B + \text{sign}(\kappa_s)(3s\dot{s}\kappa + \dot{s}^2 \kappa)| \]
  Aggregated over distance
  \[ A_{J_s} = \frac{1}{s} \int_0^s A_J(x)dx \]
- Agility metric 2: relative lateral acceleration
  \[ A_A(\dot{s}) = \frac{[\alpha \dot{\kappa}]}{g \rho_{\text{max}}} \]
  Aggregated over distance
  \[ A_{A_s} = \frac{1}{s} \int_0^s A_A(x)dx \]

Pendulum-Turn Aggressive Maneuver

- A high-speed sharp turning strategy used in rally race driving
- Experiments conducted at Ford facilities by professional racing drivers on a Ford SUV

Typical Human Driver vs. Professional Driver

- Travel time and agility metrics comparison: professional driver vs. typical human driver

<table>
<thead>
<tr>
<th>Performance metrics</th>
<th>Racing car driver</th>
<th>Typical human driver</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Testing</td>
<td>CarSim simulation</td>
</tr>
<tr>
<td>Travel time (s)</td>
<td>13.25</td>
<td>13.30</td>
</tr>
<tr>
<td>Agility (A_{J_s}) (m/s²)</td>
<td>5.18</td>
<td>5.36</td>
</tr>
<tr>
<td>Agility (A_{A_s})</td>
<td>0.442</td>
<td>0.443</td>
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</tbody>
</table>
Comparison: Vehicle Maneuver Stability

- (a) Trajectory stability: professional driver
- (b) Human driver with $\alpha_{\text{max}} = 0.5 \text{ m/s}^2$
- (c) Human driver with $\alpha_{\text{max}} = 3 \text{ m/s}^2$

Summary

- Hybrid physical/dynamic friction model captures the complex tire/road forces in a compact form
- A pendulum-turn aggressive maneuver example has been analyzed for stability and agility comparison
- Vehicle can be operated in “unstable regions” to achieve high agility aggressive maneuvers
- A safety boundary concept is proposed for designing new autonomous aggressive maneuvers

Rider/Bicycle Interactions and “Smart Bicycle”-Based Rehabilitation

- Video 1

IMU/Seat Force Sensor-based Rider/Bicycle Pose Estimation – Preliminary Results

- (a) Rider/bicycle modeling schematic
- (b) Seat force sensor results
- (c) Rider pose estimation results
Automated Nondestructive Evaluation and Rehabilitation Systems (ANDERS) for Bridge Decks*

* Supported by the NIST TIP Award 70NANB10H014 (2010-2015) and FHWA grant (2011-2013).

Bio-robotic Sampler for Rutgers Underwater Gliders

- Development of in-situ onboard biological sampler systems for Slocum autonomous underwater gliders
- Extended work for modeling, localization, planning and control of single- and multi-glider systems

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Semiconductor Manufacturing Automation

- Micro-scale¹:
  - Mechatronic systems for semiconductor manufacturing
- Meso-scale²:
  - In-situ monitoring, diagnosis and control
- Macro-scale³:
  - Cluster tool analysis and scheduling

Individuals
- TAMU: Prof. D. Song, Prof. H. Liang, Prof. R. Langari, J. Zhang, C.-Y. Kim, and B. Mika
- Rutgers: Prof. Gucunski, Prof. Kerkhof, Prof. Shan, Prof. Lin, Prof. Basily, Prof. Li, and the RAM Lab members
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1. Mech’05, ASME IMECE’04
2. ACC’04, IEEE TSM’03, IEEE CSM’08
3. WSC’04, ICRA’04, CASE’04-08, IEEE TSM’04, IEEE TASE’07,08,11
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Thank You!