Passive and Active Techniques for Resilient Control of Ground Vehicles

Mark A. Minor, PhD

TreadPort Active Wind Tunnel (TPAWT)

Motivating Applications:

Training:

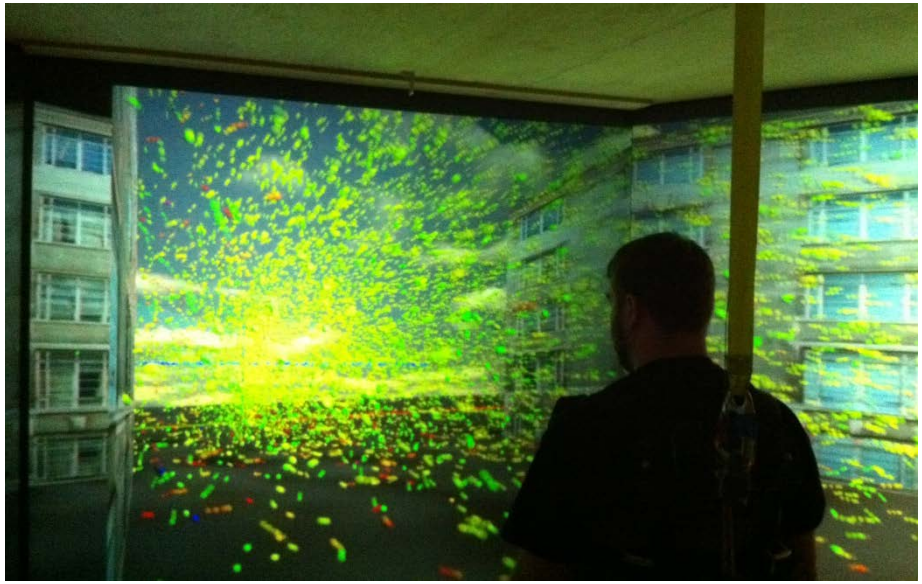
- First response personnel localizing plumes from chemical releases, dirty bombs, etc.

Rehabilitation:

- Provide more realistic environmental factors for people re-learning to walk (post spinal-cord injury or stroke)

Psychology:

- What factors of environmental displays are relevant? Affects on immersion? Accuracy requirements?

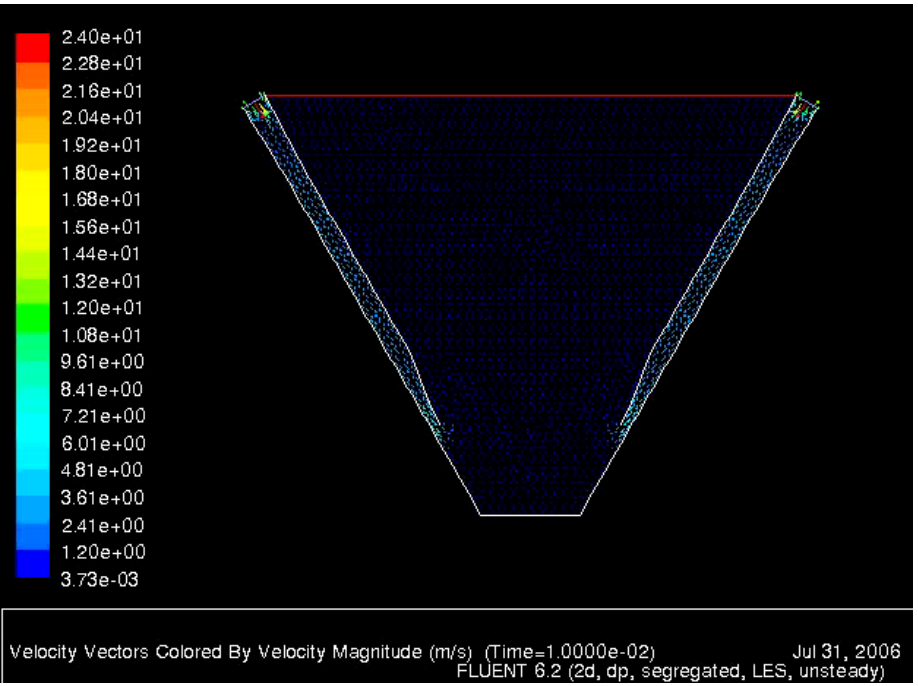


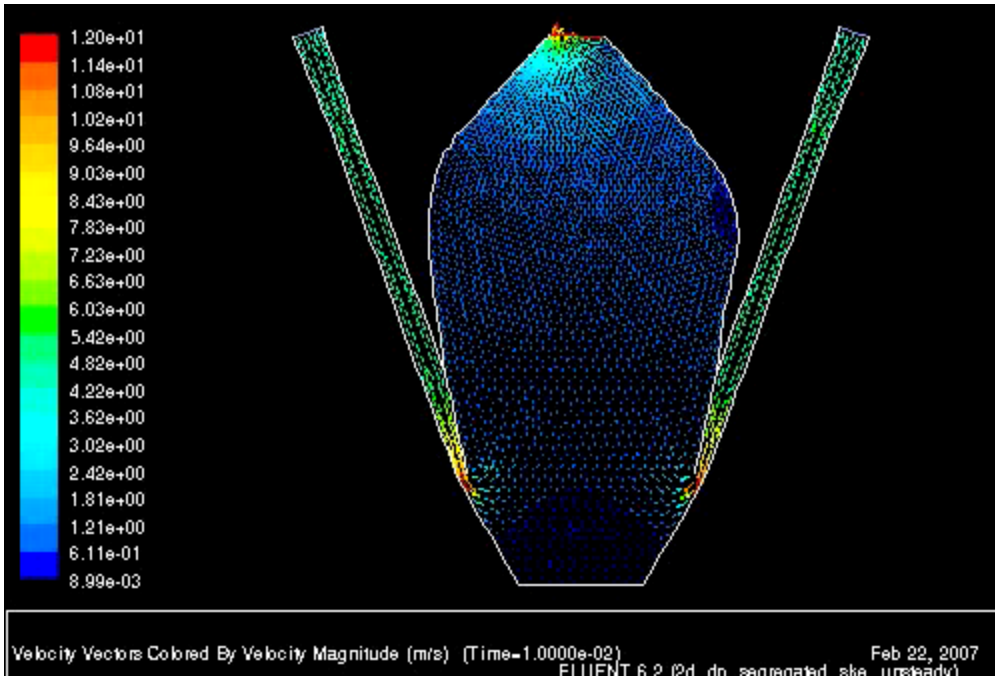
Goal:

Immersive TreadPort ***Atmospheric Display***:

- Wind,
- VR Graphics
- **Heat,**
- **Smell**

Resilient by design…





Outline

- Resilience concepts
- Wheeled mobile robotics
- Ground vehicle trailer parking
- Ground vehicle steering control
- Simultaneous gait design, robot design, and control
- Conclusions

Resilience Concepts

- Passive Resilience:
  - The ability of a system to ***naturally*** continue to operate satisfactorily in spite of disturbances, uncertainty, wear, failures, etc.
  - Not coordinated. Correlations between parts of system not considered.

- Active Resilience:
  - The ability of a system to recognize, characterize, and respond to a disturbance, uncertainty, wear, failure, etc.
  - Features are coordinated,
  - Typically engineered to be highly capable

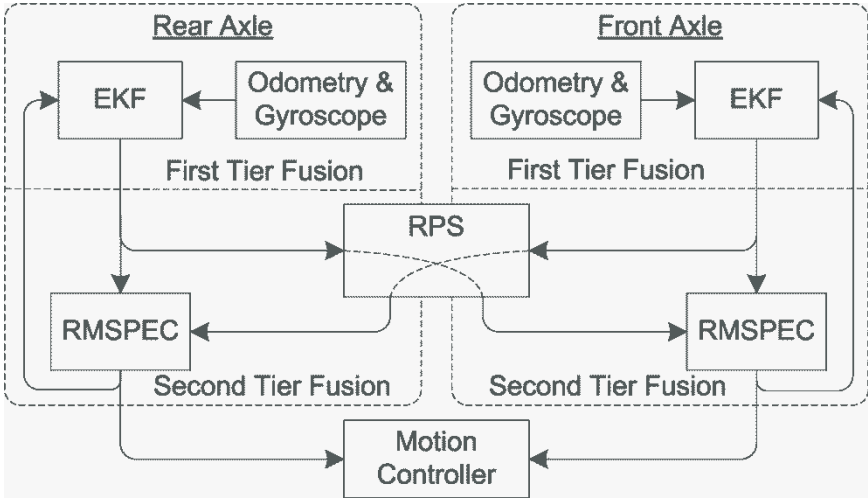
Compliant Framed Modular Mobile Robots

CFMMR Passive Resilience Features

- Frame Compliance: Allows the robot to naturally deform and adapt to terrain shape and disturbances.
- Early odometry based servo controllers provided passive resilience to disturbances.

CFMMR Active Resilience Features

- Data fusion algorithms combine odometry, relative posture estimates derived from the frame deflection, and external sensors to provide reliable estimates of robot state that are used to control the robot.
- Kinematic Controllers consider coordination between modules of the system.



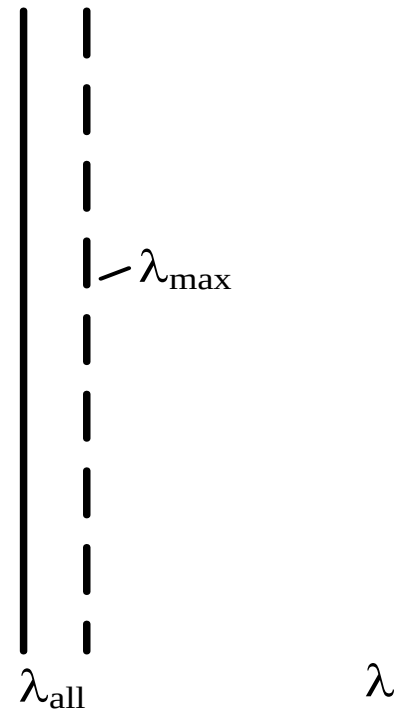
- Dynamic Controllers coupled to kinematics via backstepping provide torque commands to assure overall stability of the system and assure tracking

Active Resilience: Robot Slip Estimation and Control

- Slip ratio, λ, indicates relative motion between ground and a tire.

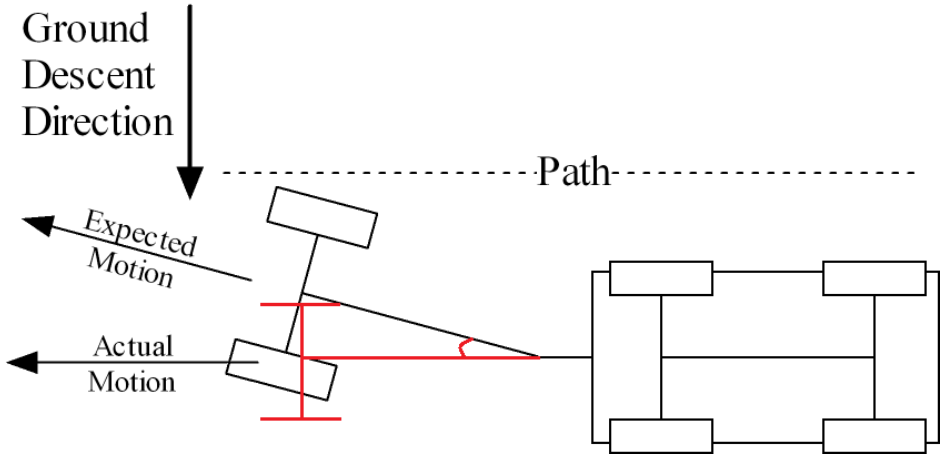
$$\lambda = 1 - \frac{v}{\omega r_w} = \frac{\omega - v/r_w}{\omega}$$

- Slip-curve slope indicates traction stability
- Goals:
  - Establish sensor based estimate of Slip Velocity (new metric, important for low speeds) and correlate to traction stability.
  - Sensor based traction control algorithms
- Real World Application:
  - Robots (exploration, search/rescue)
  - Cars/Trucks/Off-highway vehicles.



Active Resilience: Simple trailer backing control law with side-slope compensation

- Planning and control with parameter uncertainty and external perturbations
- Disturbance Identification and compensation



Vehicle-trailer Kinematics

$$
\begin{aligned}
\dot{x} &= v\cos(\theta_1) \\
\dot{y} &= v\sin(\theta_1) \\
\dot{\theta}_1 &= vF_\kappa(\varphi) \\
\dot{\psi} &= -v(F_\kappa(\varphi) + \frac{\sin(\psi)}{L_2} + \frac{L_1 F_\kappa(\varphi)\cos(\psi)}{L_2})
\end{aligned}
$$

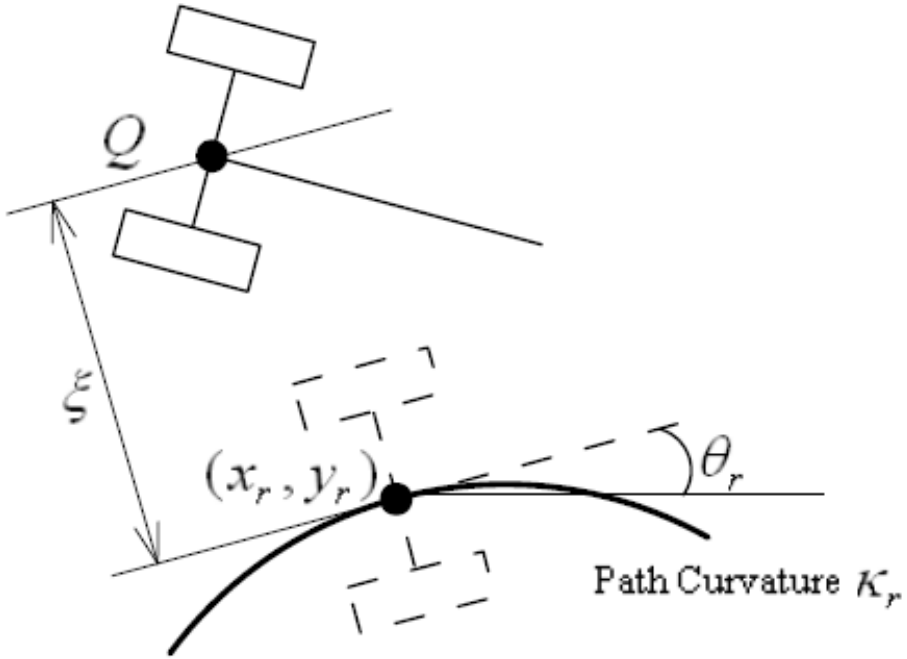
Vehicle-trailer Kinematics

- Curvature of the trailer trajectory can be derived as:

$$\kappa_2 = \frac{\dot{\theta}_2}{v_T} = -\frac{\sin(\psi)/L_2 + L_1 F_\kappa(\varphi)\cos(\psi)/L_2}{\cos(\psi) - L_1 F_\kappa(\varphi)\sin(\psi)}$$

Steering Controller

- Path reference



Steering Controller

- Two-tier controller.
- The first tier calculates the desired trailer trajectory curvature according to tracking errors.
- The second tier translate trailer trajectory curvature to steering wheel angle.
- Can be proven to be asymptotically stable.

Passively Resilient Steering Controller

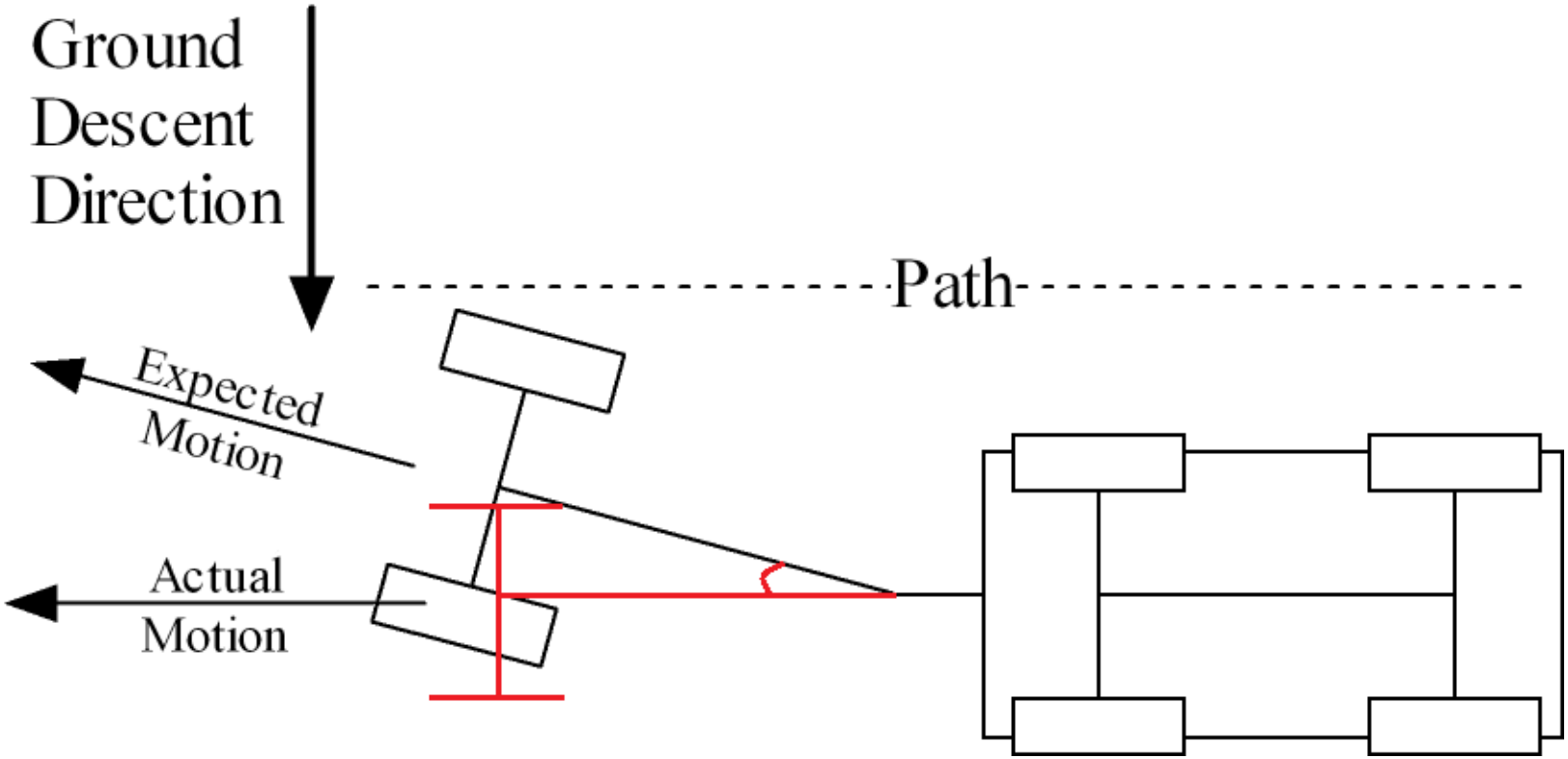
- First Tier – curvature command

$$\kappa_d = \kappa_r + k_\xi \xi + k_\theta(\theta_r - \theta)$$

- Second Tier – steering command

$$\varphi_d = F_\kappa^{-1}\left(\frac{\kappa_d L_2 \cos\psi + \sin\psi}{\kappa_d L_1 L_2 \sin\psi - L_1 \cos\psi}\right)$$

Providing Active Resilience via Side-slope Compensation



Side-slope Compensation

- Gravity disturbance can be revealed by the equivalent hitch angle offset;
  - The gap between the hitch ball and coupler also affect the hitch angle bias
- Least square method can be used in estimating this hitch angle offset.
- This estimation is then substituted into controller.

Side-slope Compensation

$$\dot{\psi} = -v(F_\kappa(\varphi) + \frac{\sin(\psi + \Delta\psi)}{L_2} + \frac{L_1 F_\kappa(\varphi)\cos(\psi + \Delta\psi)}{L_2})$$

$$\dot{\psi}(t) = \frac{\psi(t+T) - \psi(t-T)}{2T}$$

$$\hat{\dot{\psi}}_i = -v_i(F_\kappa(\varphi_i) + \frac{\sin(\psi_i + \Delta\psi)}{L_2} + \frac{L_1 F_\kappa(\varphi_i)\cos(\psi_i + \Delta\psi)}{L_2})$$

Side-slope Compensation Jacobian based upon N samples

$$J_i = \frac{\partial \hat{\dot{\psi}}_i}{\partial \Delta\psi} = -\frac{v_i}{L_2}(\cos(\psi_i + \Delta\psi) - L_1 F_\kappa(\varphi_i)\sin(\psi_i + \Delta\psi))$$

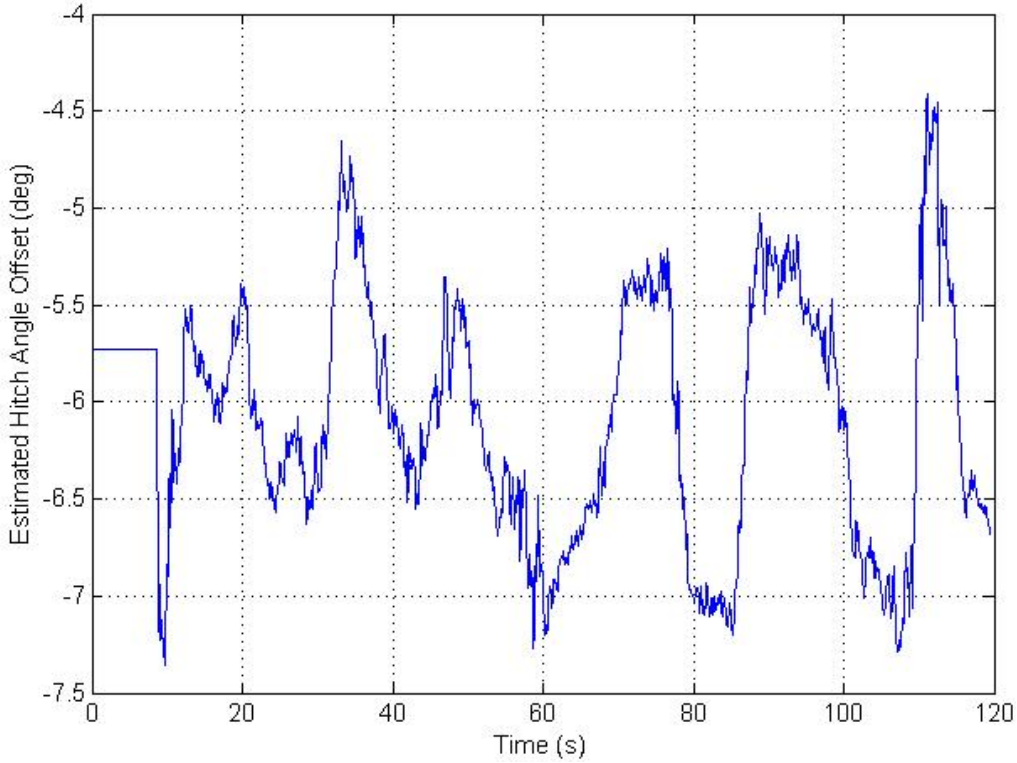
Let $\dot{\Psi}$ be $[\dot{\psi}_1, \dot{\psi}_2, ..., \dot{\psi}_N]^T$, $\hat{\dot{\Psi}}$ be $[\hat{\dot{\psi}}_1, \hat{\dot{\psi}}_2, ..., \hat{\dot{\psi}}_N]^T$ and J be $[J_1, J_2, ...J_N]^T$.

The parameter update can be calculated as:

$$\Delta\psi' = (J^T J)^{-1} J^T (\dot{\Psi} - \hat{\dot{\Psi}})$$

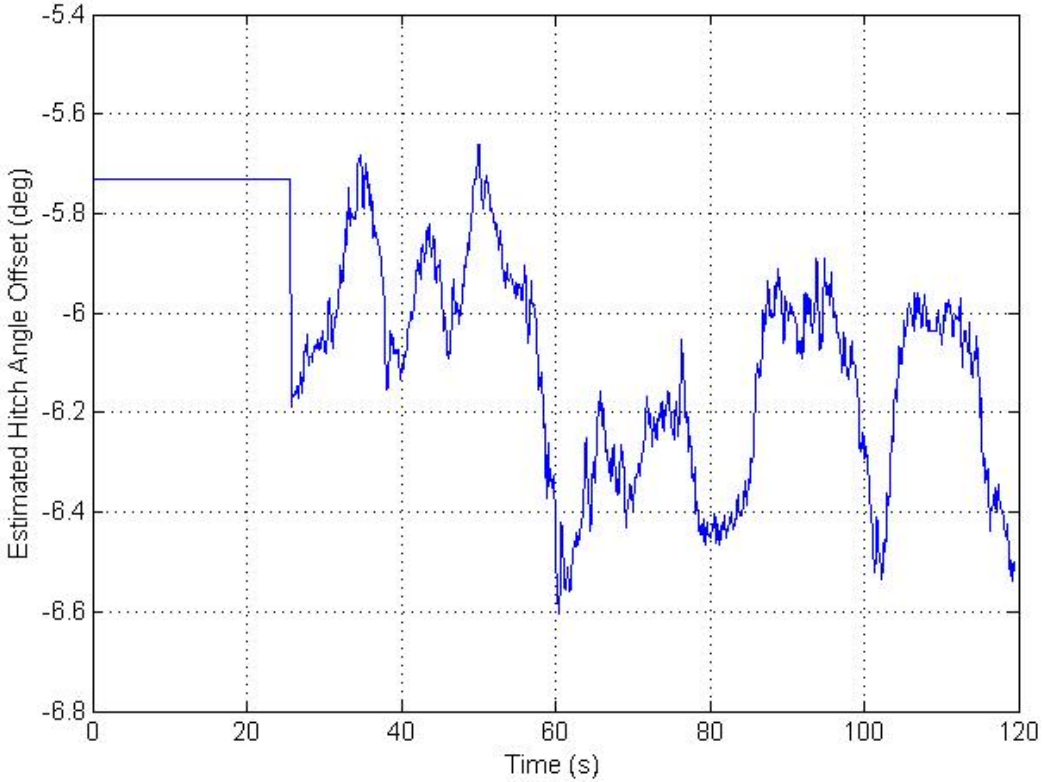
Disturbance Estimation

Identification result with data of 1 meter movement



Disturbance Estimation

Identification result with data of 10 meter movement



Active Resilience - Side-slope Compensation

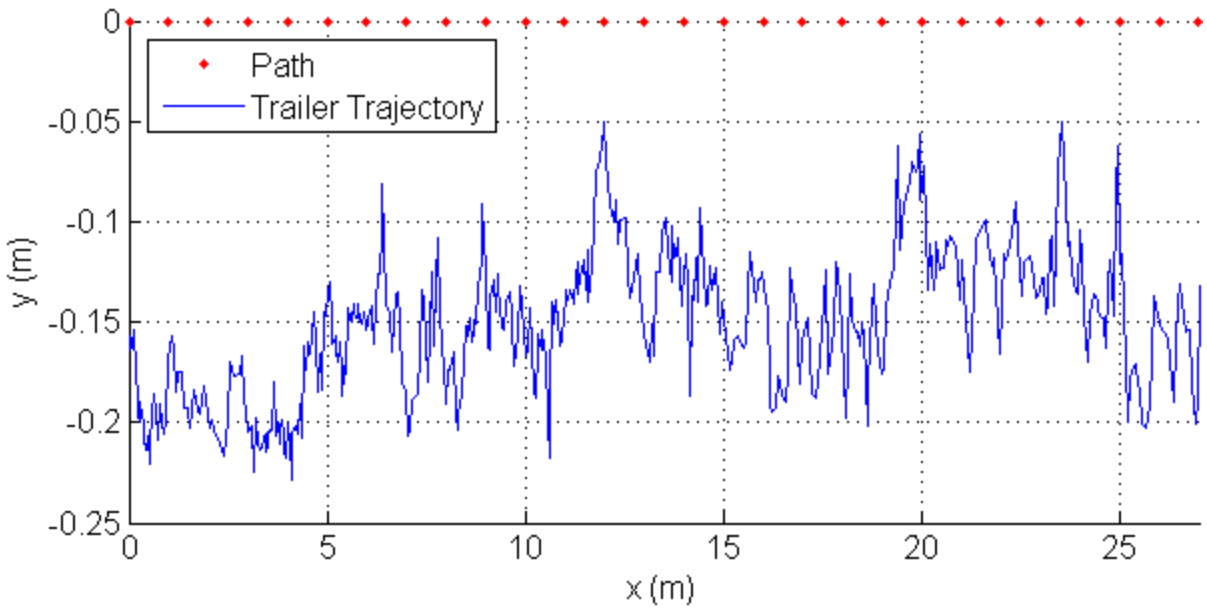
- Controller Revision

$$\kappa_d = \kappa_r + k_\xi \xi - k_\theta(\theta_r - \theta_2 - \Delta\psi)$$

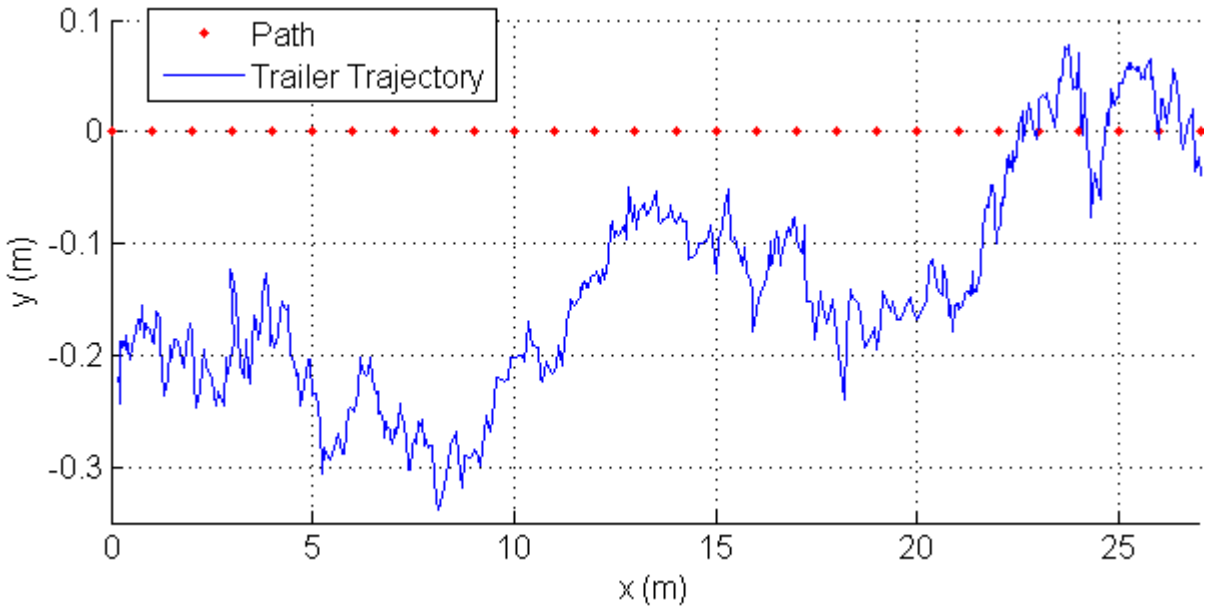
$$\varphi_d = F_\kappa^{-1}\left(\frac{\kappa_d L_2 \cos(\psi + \Delta\psi) + \sin(\psi + \Delta\psi)}{\kappa_d L_1 L_2 \sin(\psi + \Delta\psi) - L_1 \cos(\psi + \Delta\psi)}\right)$$

Test Results

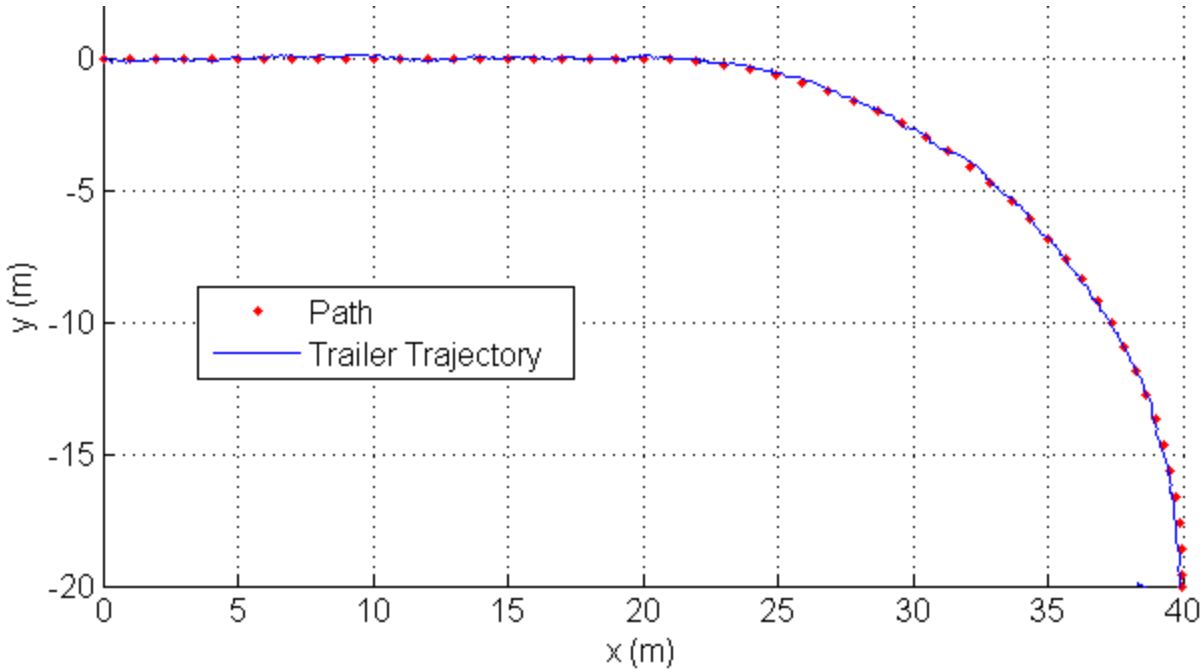
Test Result: w/o compensator



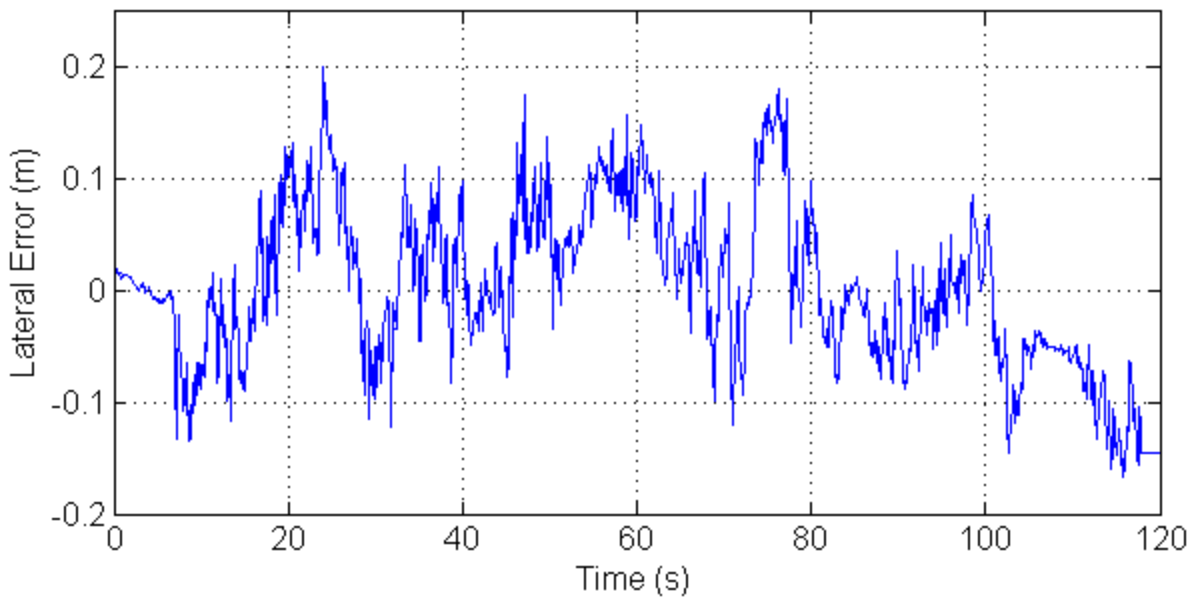
Test Results: w/ compensator



Test Results: w/ compensator



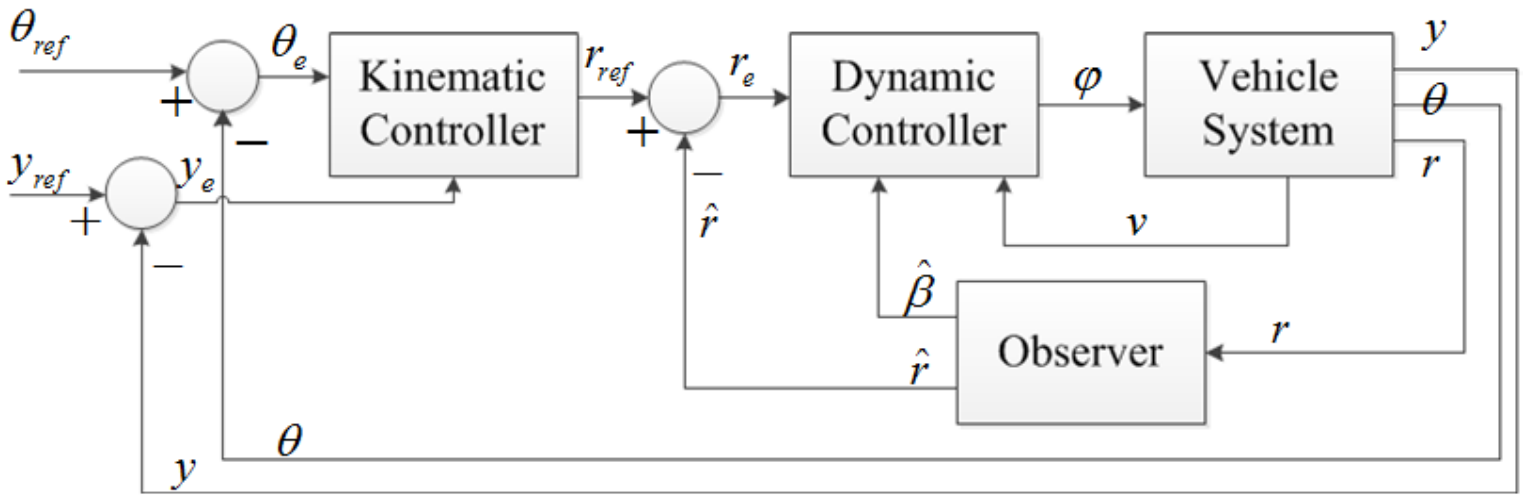
Test Results: w/ compensator



About resilience…

- Passive Resilience:
  - Provides modest resilience to external disturbances
- Active Resilience:
  - Disturbance estimates augment passively resilient controller to make actively resilient
  - Side-slope compensator improves the performance of trailer backing.

Robust Multi-tiered Kinematic and Dynamic Steering Control



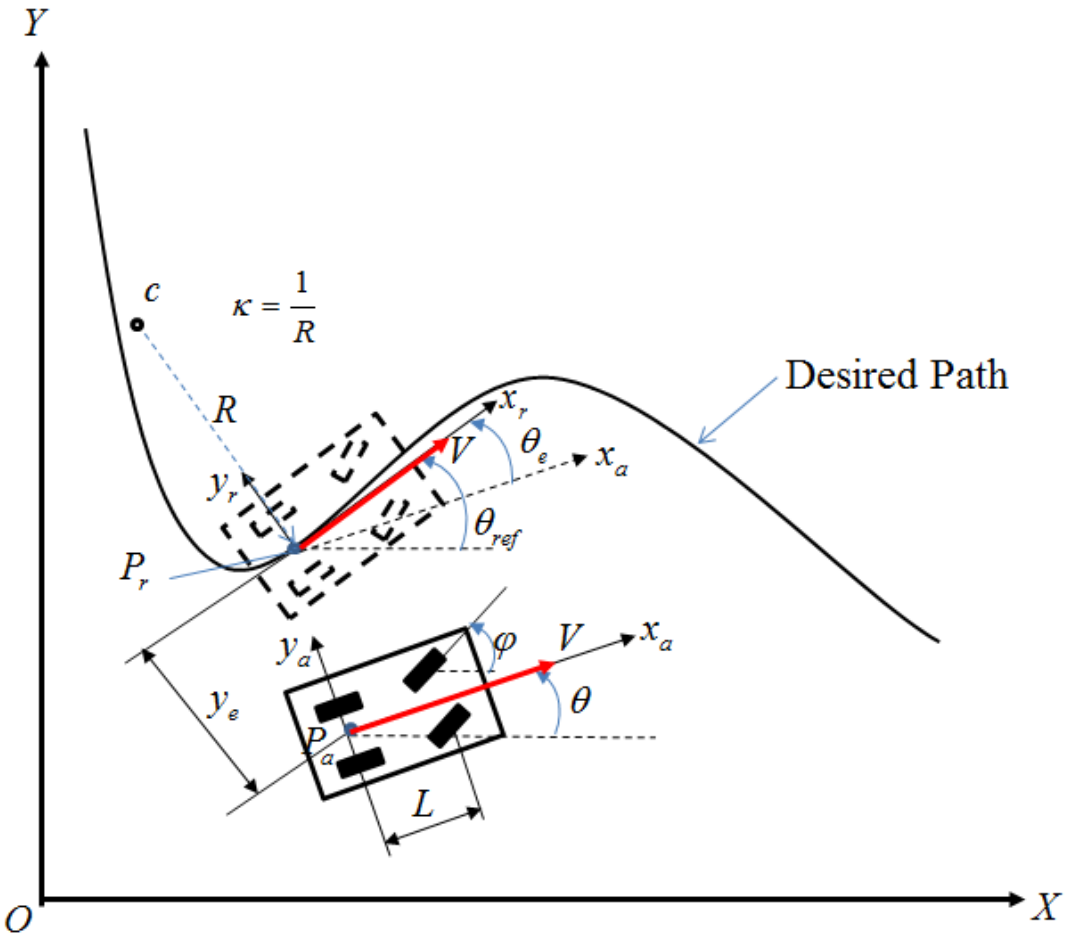
θ_{ref} :Reference heading angle
θ_e :Heading angle error
θ :Actual heading angle
y_{ref} :Reference lateral position
y_e :Lateral position error
y :Actual lateral position

r_{ref} :Reference yaw rate
r_e :Yaw rate error
r :Actual yaw rate
$\hat{r}$:Estimated yaw rate
$\hat{\beta}$:Estimated side slip angle
φ :Steering angle
v :Vehicle forward speed

Kinematic Controller Features:

- Path following kinematic controller
- Uses curvature and velocity based path specification.
  - Typical of real roadway characteristics.
- Provides yaw rate commands based upon tracking performance
  - Robust to kinematic model uncertainty,
  - Smooth and continuous commands reduce jerk
  - Robust surfaces tuned to be appropriate for vehicle capability and passenger comfort.

Kinematic Model – Path Following



Key features:

- The reference point P_r is the closest point to the rear wheel center P_a
- Path-following based kinematics modeling

In bicycle model:

$$\dot{x} = V\cos\theta$$

$$\dot{y} = V\sin\theta$$

$$\dot{\theta} = \frac{V}{L}\tan\varphi = r$$

$$\dot{\varphi} = \omega$$

r: yaw rate
L: vehicle wheel base

Modeling

- Kinematics
  - Goals: Path following
  - Assuming the steering rate is fast enough

  Thus, vehicle kinematics in the form of tracking error:

$$\dot{\theta}_e = r - \kappa V$$

$$\dot{y}_e = V \sin \theta_e$$

θ_e: vehicle heading error
y_e: vehicle lateral error
V : vehicle forward speed
r : vehicle yaw rate
κ : desired path curvature

Kinematic Controller

– Apply SMC for AGV kinematics to have desired yaw rate, *r*.

1. Choose a sliding surface:

$$S_{kin} = \arcsin\left(\frac{c_1 y_e}{v}\right) + \theta_e = 0$$

2. Apply Lyapunov theory to prove asymptotic stability

$$V = \frac{1}{2} S_{kin}^2 \qquad \dot{V} = S_{kin}\dot{S}_{kin} = S_{kin}\left(-\kappa v + \frac{c_1 \sin(\theta_e)}{\sqrt{1-\left(\frac{c_1 y_e}{v}\right)^2}} + r\right)$$

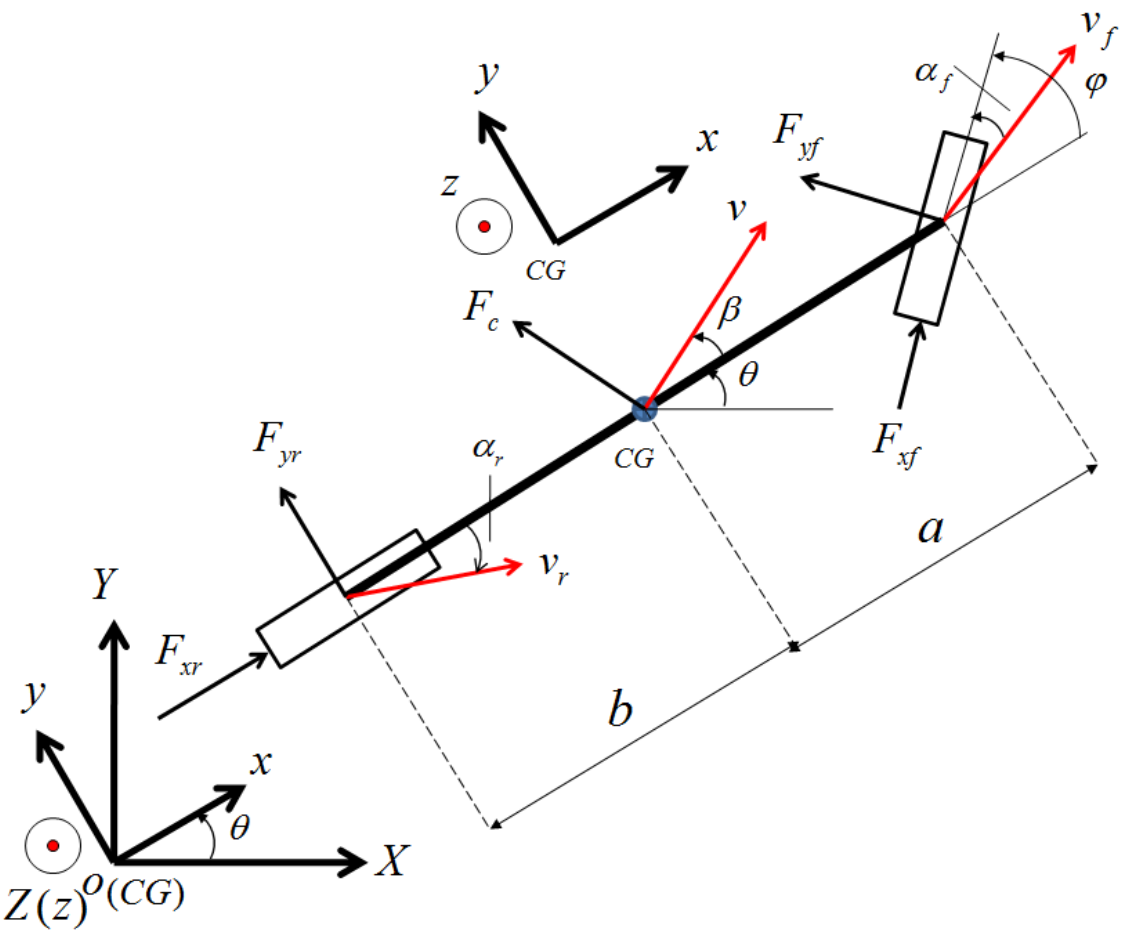
3. Kinematic Control Law provides yaw rate, *r*, commands

$$r = -(\rho_{kin} + \psi_{kin})\tanh\left(\frac{S_{kin}}{\varepsilon_{kin}}\right) \qquad \rho_{kin} \geq \left|-\kappa v + \frac{c_1 \sin\theta_e}{\sqrt{1-\left(\frac{c_1 y_e}{v}\right)^2}}\right|$$

Dynamic Controller Features:

- Dynamic model based upon:
  - Yaw Rate: correlates well with kinematic model and sensing,
  - Side Slip Angle: appropriate for characterizing vehicle handling (lateral motion) and inspired by human proprioception
- Provides smooth and robust steering commands to achieve commanded yaw rate.
  - Robust to modeling error, parameter uncertainty, and external disturbances
  - Smooth robust control reduces jerk and is believed to improve passenger comfort

Modeling



F_{yf} / F_{yr} :Front/Rear tire lateral force

F_{xf} / F_{xr} :Front/Rear tire longitudinal force

F_c :vehicle centripetal force

α_f / α_r :Front/Rear tire slip angle

β :side slip angle

CG :center of gravity

a / b :distance from CG to front/ rear wheel center

v :vehicle forward speed

v_f / v_r :vehicle front/rear tire speed

θ :vehicle heading angle

φ :vehicle steering angle

Modeling

- Dynamics
  - Only consider the lateral dynamics in the form of tire-ground interaction:

$$F_{yf}\cos\varphi + F_{yr} + F_{xf}\sin\varphi = F_c\cos\beta + m\dot{v}\sin\beta$$

$$F_{xf}\sin\varphi\cdot a + F_{yf}\cos\varphi\cdot a - F_{yr}\cdot b = J\cdot\ddot{\theta}$$

  - Assumptions:
    - If $\beta \le 11^\circ$, then $V \approx v$
    - Lateral tire forces are only provided by vehicle cornering forces, i.e.

$$F_{yf} = \mu C_f \alpha_f, F_{yr} = \mu C_r \alpha_r$$

    - Steering angle and side-slip angle is small
    - Operating speed of vehicle is not zero

Modeling

- Dynamics
  - simplification
    - the lateral components of the longitudinal tire forces are much less than the lateral tire force

Thus, the linearized dynamic model is:

$$\dot{\beta} = -\frac{\mu(C_f + C_r)}{mv}\beta - (1 + \mu\frac{C_f \cdot a - C_r \cdot b}{mv^2})r + \frac{\mu C_f}{mv}\varphi$$

$$\dot{r} = -\frac{\mu(C_f \cdot a - C_r \cdot b)}{J}\beta - \mu(\frac{C_f \cdot a^2 + C_r \cdot b^2}{Jv})r + \frac{\mu C_f \cdot a}{mv}\varphi$$

which is represented as:

C_f / C_r :Front / rear tire cornering stiffness; μ:Road coefficient

m :Vehicle mass; J:Vehicle inertia

$$\dot{\beta} = a_{11}\beta + a_{12}r + b_{11}\varphi$$

$$\dot{r} = a_{21}\beta + a_{22}r + b_{21}\varphi$$

Dynamic Controller

– Goal: realize the reference yaw rate r_{ref} from kinematic controller

1. Choose a sliding surface: $S_{dyn} = r_e = r - r_{ref} = 0$
2. Replace *r* with *re*: $\dot{r}_e = a_{21}\beta + a_{22}\dot{r}_e + (a_{22}r_{ref} - \dot{r}_{ref}) + b_{21}\varphi$
3. Apply Lyapunov theory to prove stability
   - set Lyapunov function as: $V = \frac{1}{2}S_{dyn}^2$, where $V > 0, \forall S_{dyn} \in \Re, S_{dyn} \neq 0$
     i.e. *V* is positive definite
   - Design steering angle φ such that $\dot{V} < 0, \forall S_{dyn} \in \Re, S_{dyn} \neq 0$
     i.e. $\dot{V}$ is negative definite, where $\dot{V} = S_{dyn} \cdot \dot{S}_{dyn} = r_e \cdot \dot{r}_e$

   Thus, the model based non-negative boundary term ρ_{dyn} is

$$\rho_{dyn} = \left| \frac{a_{21}\beta + a_{22}\dot{r}_e + a_{22}r_{ref} - \dot{r}_{ref}}{b_{21}} \right| \geq 0$$

Dynamic Controller

- Control law is proposed here:

$$\varphi = -(\rho_{dyn} + \psi_{dyn}) sign(S_{dyn})$$

  - ρ_{dyn} is designed by steering angle φ, such that nonlinearity is able to cancelled
  - φ_{dyn} is a small positive number
  - Sign function guarantees that $\dot{V}$ is negative definite
- Control law improvement
  - Uses continuous and smooth hyperbolic tangent function to replace discontinuous sign function

$$\varphi = -(\rho_{dyn} + \psi_{dyn}) \tanh(\frac{S_{dyn}}{\varepsilon_{dyn}})$$

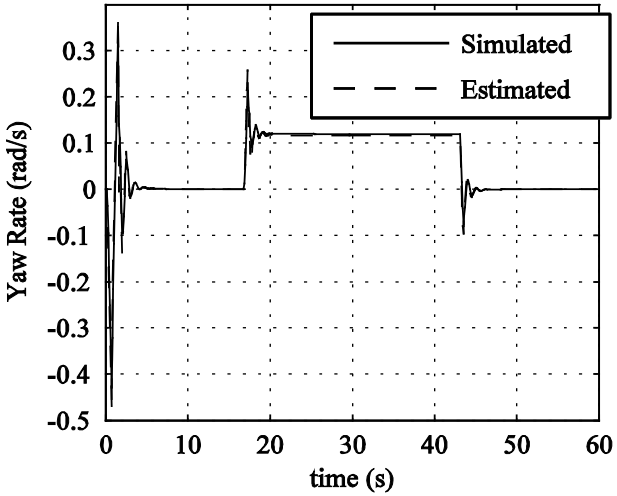
Observer Features

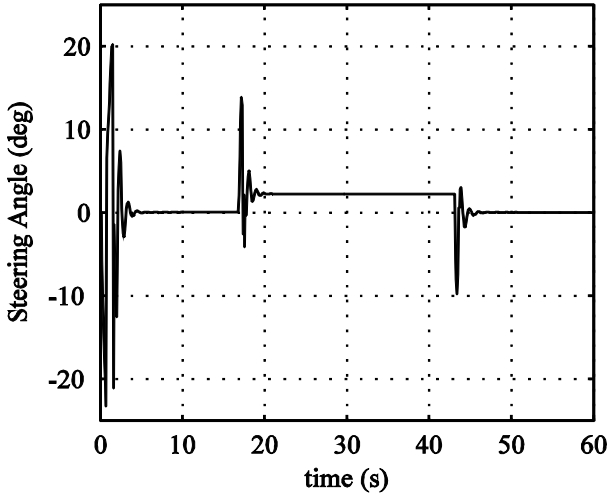
- Provides estimates of dynamic model states
  - Slip angle not directly measurable
  - Based upon yaw rate measurements and steering commands
- High gain feedback
  - Provides some robustness to uncertainty, parameter error, and external disturbances
- Allows output feedback control!

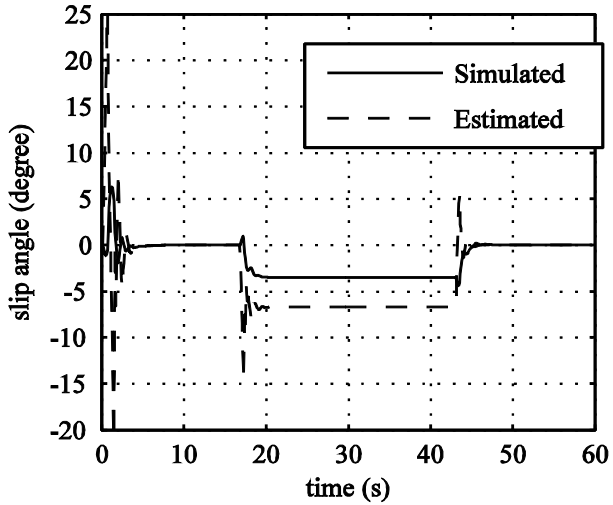
Simulations

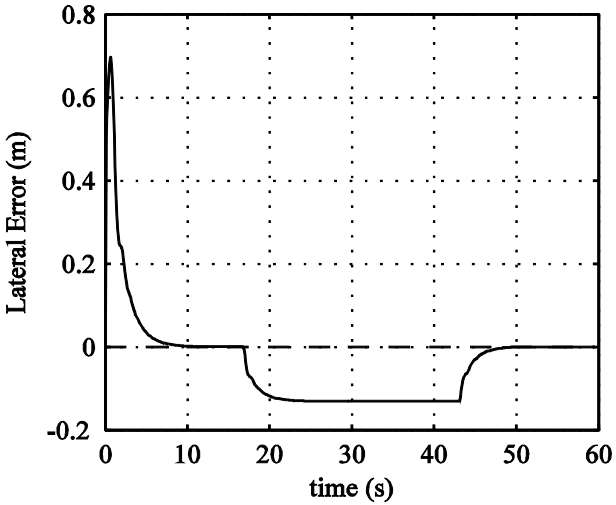
Slippery road, $\mu = 0.1$

Low speed, 6 *m/s*





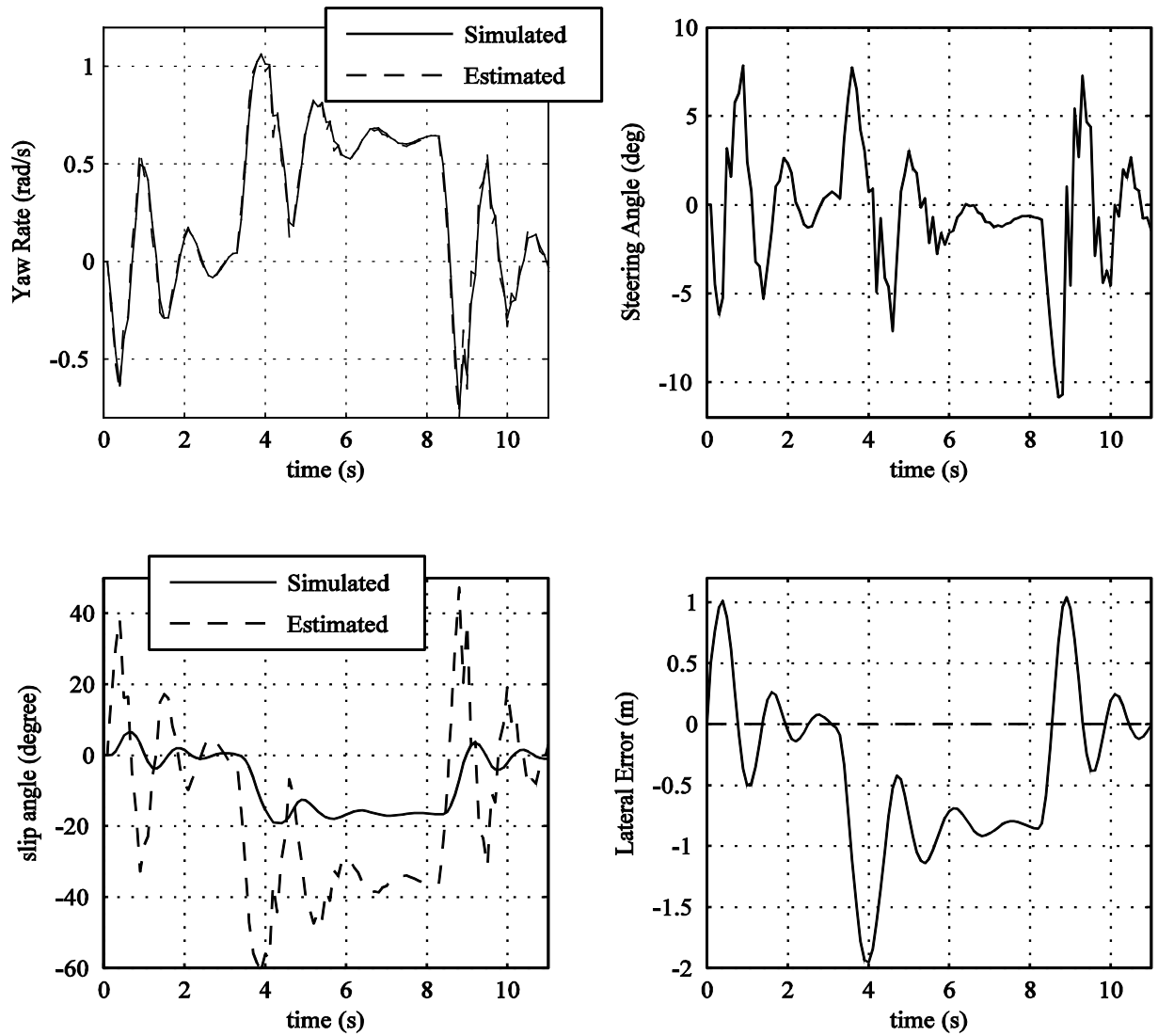




Simulations

Dry road, $\mu = 0.8$

High speed, 32 *m/s*



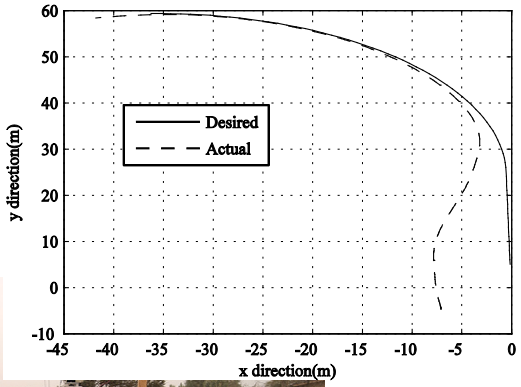
Experiments

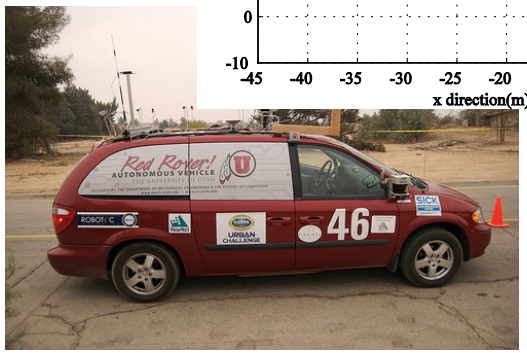
Dry road, $\mu = 0.8$

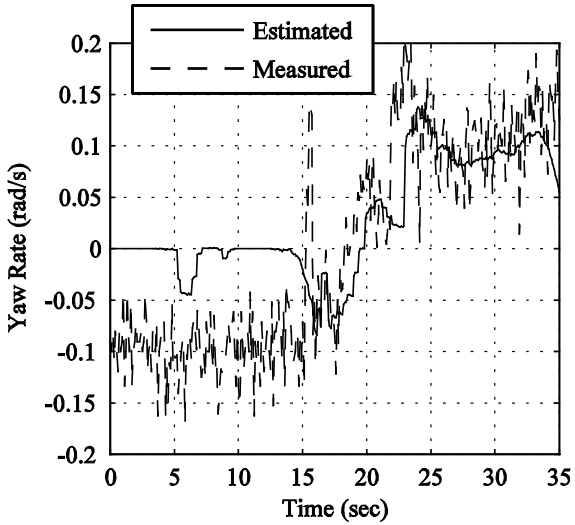
Low speed, 6 *m/s*

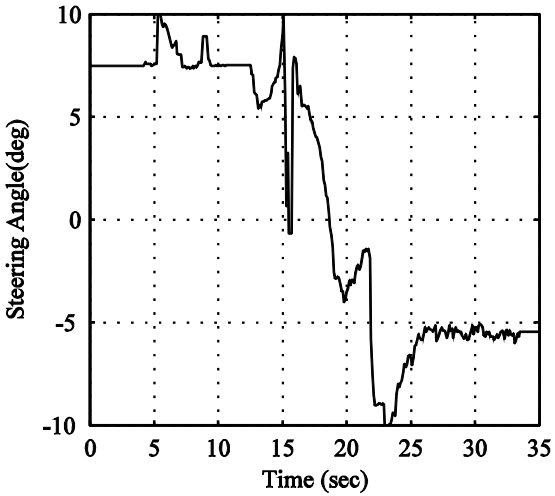
(limited by site)

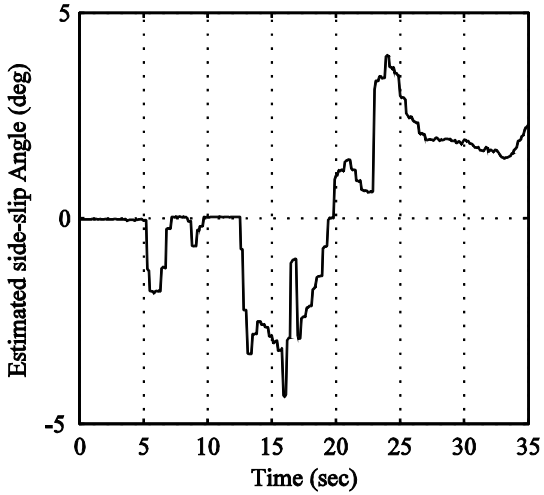
Disturbance: 10% slope

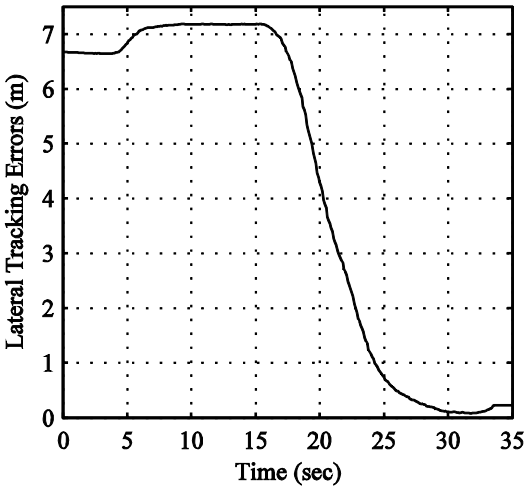








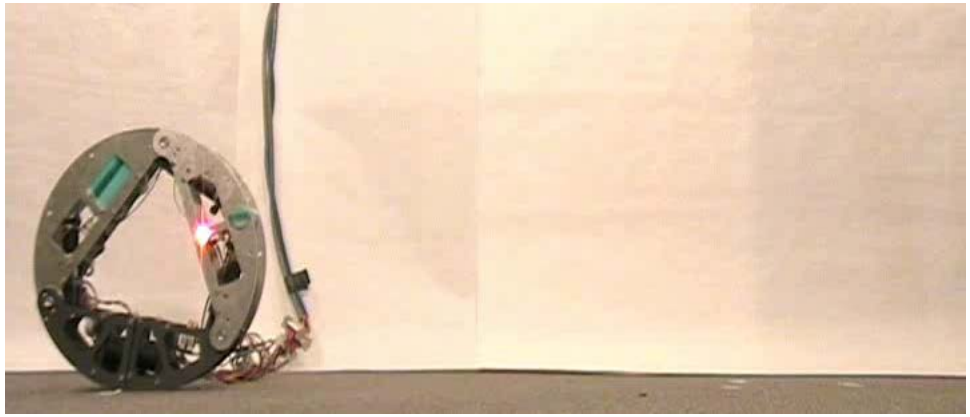




What is Resilience?

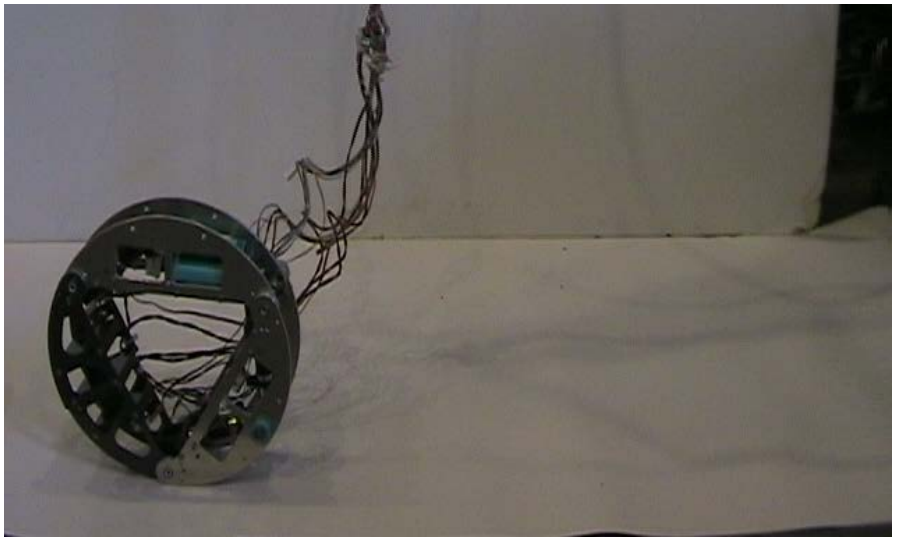
- Robust controllers are individually **Passively Resilient**.
  - They are able to independently deal with uncertainty and disturbances in their part of the system with some Margin of Maneuver.
- Tiered control *can be* ***Actively Resilient***, but communications and cooperation between layers needs to be provided.
  - Backstepping control is *one* aspect of this!
  - *Higher level agents are important for assuring the framework is resilient!*
- *Active Resilience needs to be improved by actively analyzing the systema and adapting control.*
  - *Variable structure control – surfaces change based upon operating conditions*
  - *Application of Artificial Intelligence – controller is adaptively tuned based upon performance and degradation of the system.*

Towards resilience by design...



Quasi-static Roll

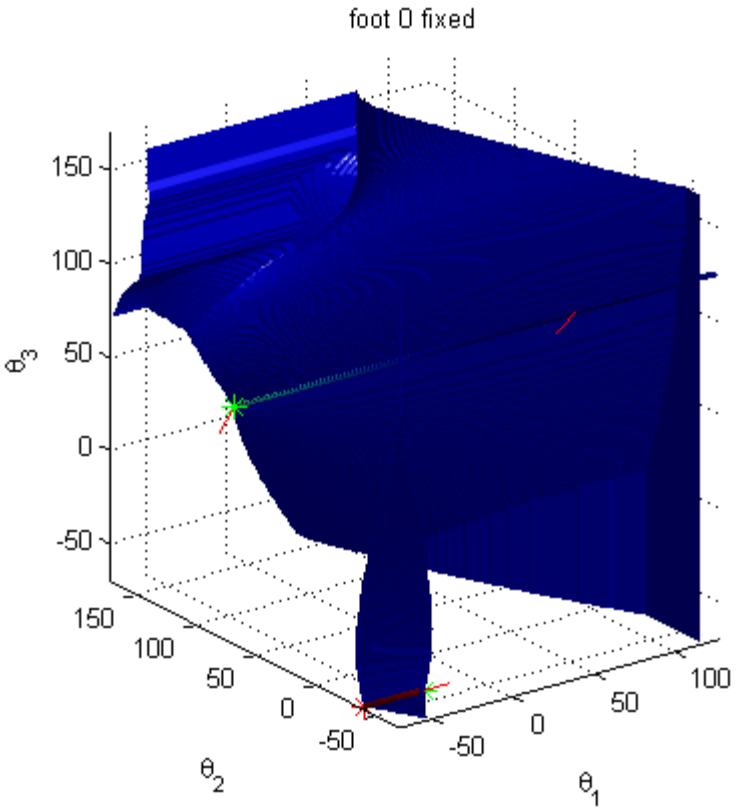
Phipps, Shores, Floyd, Minor

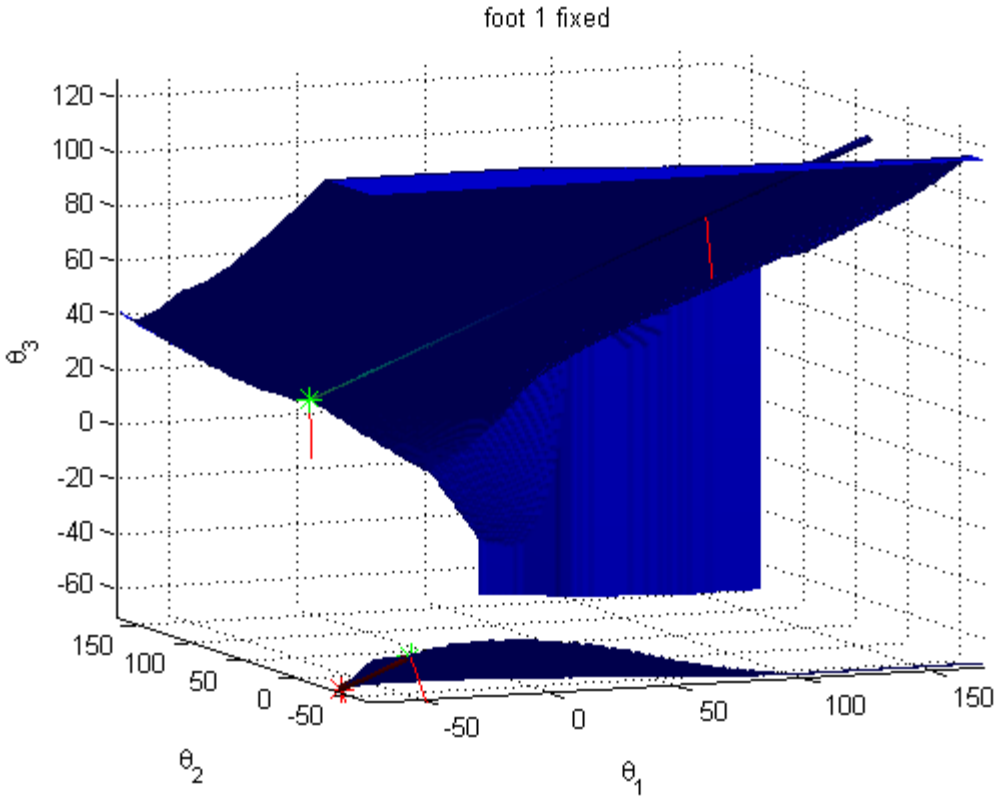


Dynamic Impulse Roll

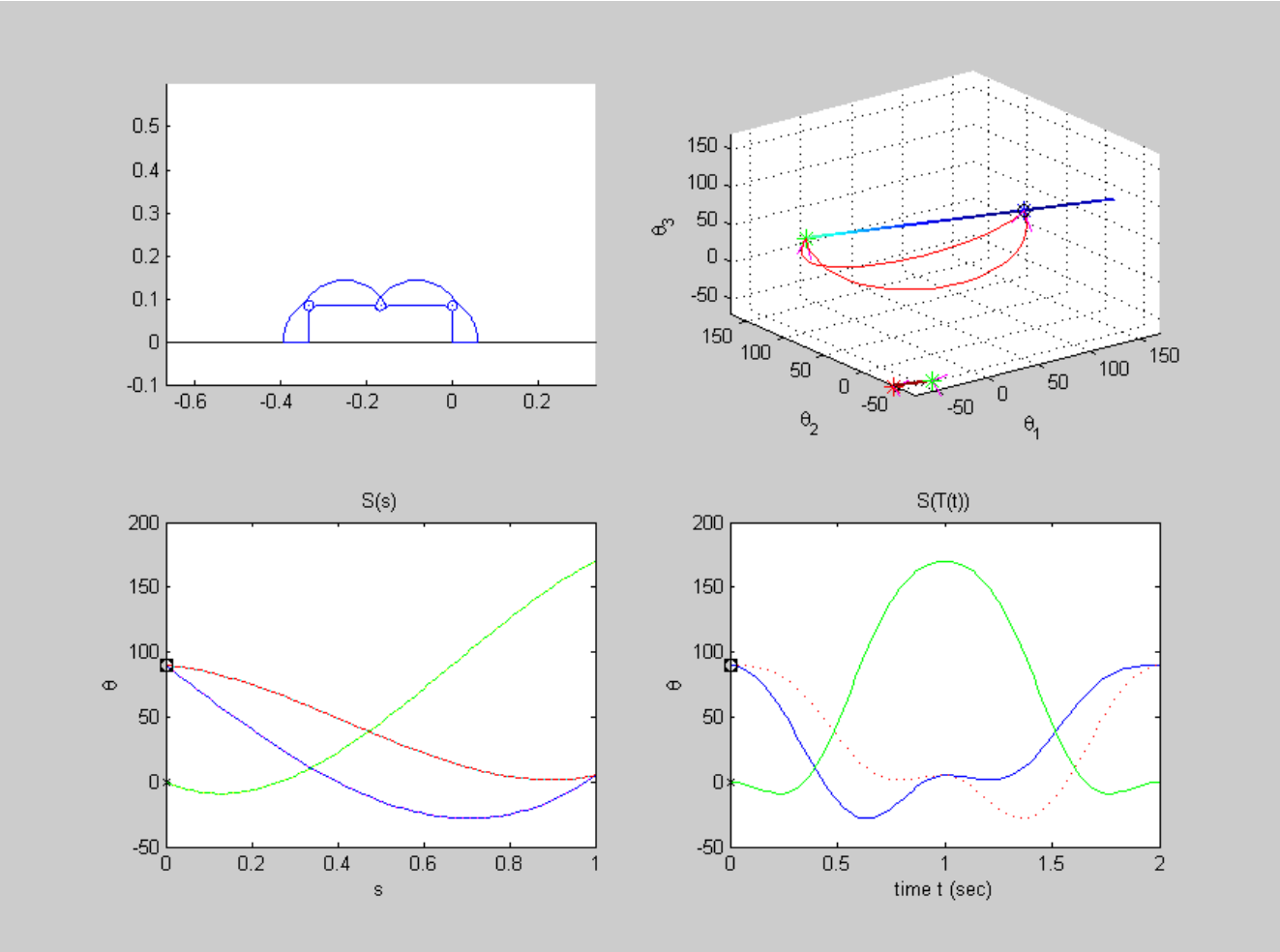
Floyd, Minor

Joint Space analysis: Normal vectors (red) to collision surface (blue).





Non-symmetric, 3D, exaggerated high step gait.



Goal: Simultaneous Robot Design, Gait Generation, and Control. Robots should be as passively resilient as possible, by design.

- Gait Generation:
  - Develop tools that allow designers to automatically generate gaits for robots that allow improved walking, climbing, rolling.
  - Gaits can be kinematic or dynamic for slow or fast motion
- Robot Design: Provide tools that allow designers to easily evaluate the impact of actuator selection and placement, robot geometry, and mass distribution on robot performance.
- Control: Allow engineers to simulate different scenarios and evaluate the ability of their controller design to adapt to uncertainty, dynamic gaits, actuator limitations, sensor placement, etc.
- Applications: New computational tools for robot (product) design for realizing improved mobility and adaptability.

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