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UAB THE UNIVERSITY OF
ALABAMA AT BIRMINGHAM.

ARC Project #1

Robust Control of a Single-Wheel Module Operating in an Off-Road Terrain with Uncertain and Stochastic Attributes

Automotive Research Center Phase V

Cooperative Agreement #1.A82

ARC Seminar

01/21/2022



Exploratory and Translational Projects

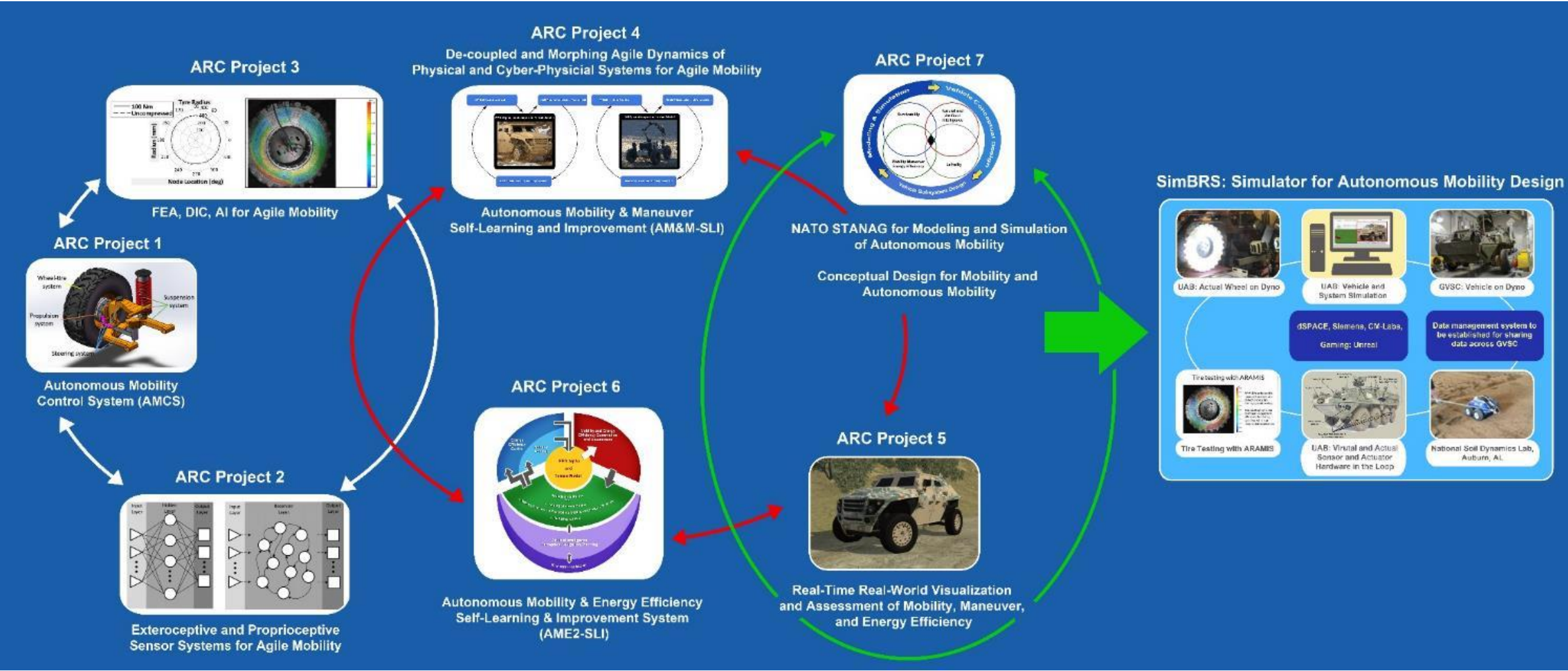


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Quad Members



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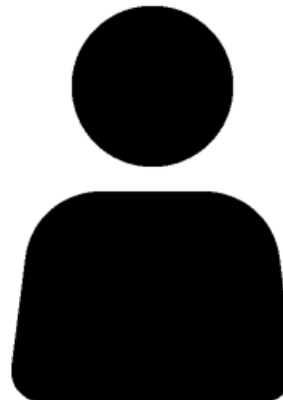
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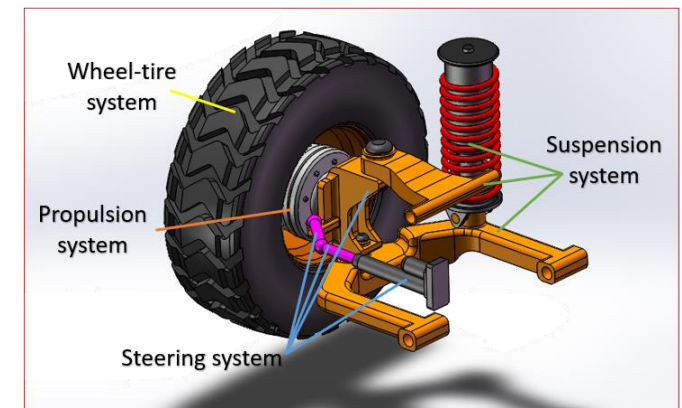
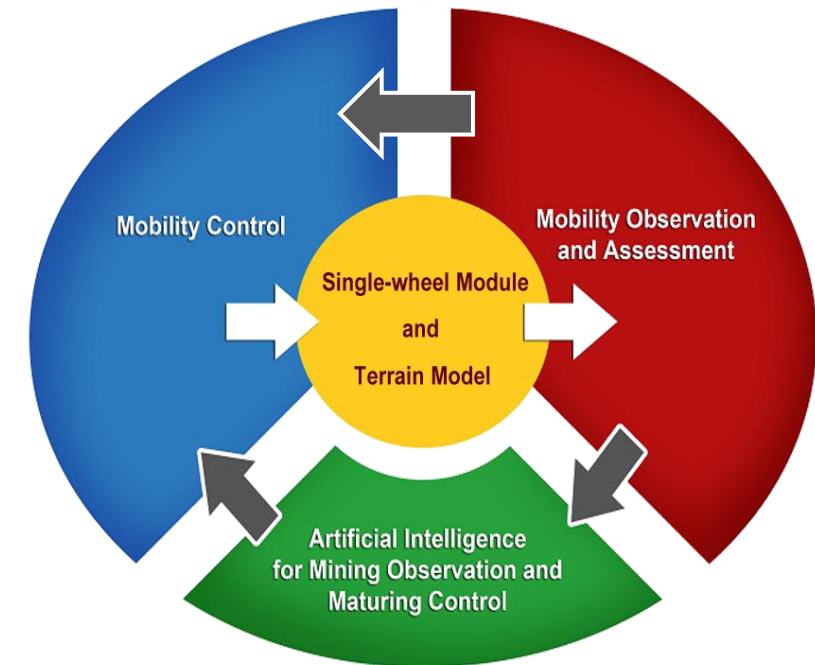
Motivation and Problem Statement

- **Motivation**

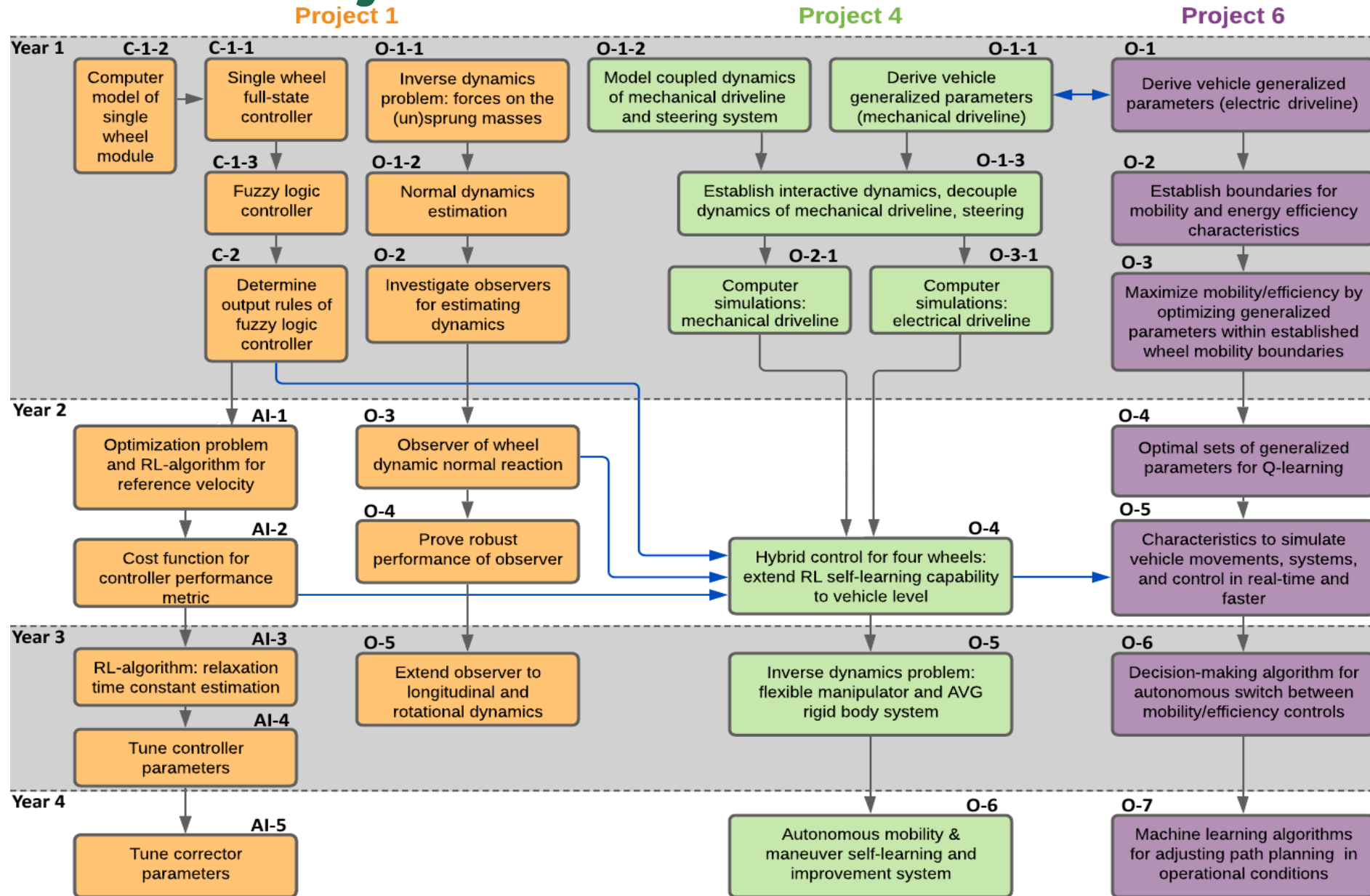
- ❑ The current vehicular control designs (traction control, slippage control, ABS, etc.) are not **agile**
- ❑ The response time of current control designs are more than the **tire relaxation time** (100-250 ms compared to 40-80 ms)
- ❑ The vehicle **mobility** may be lost and wheels start spinning

- **Problem Statement**

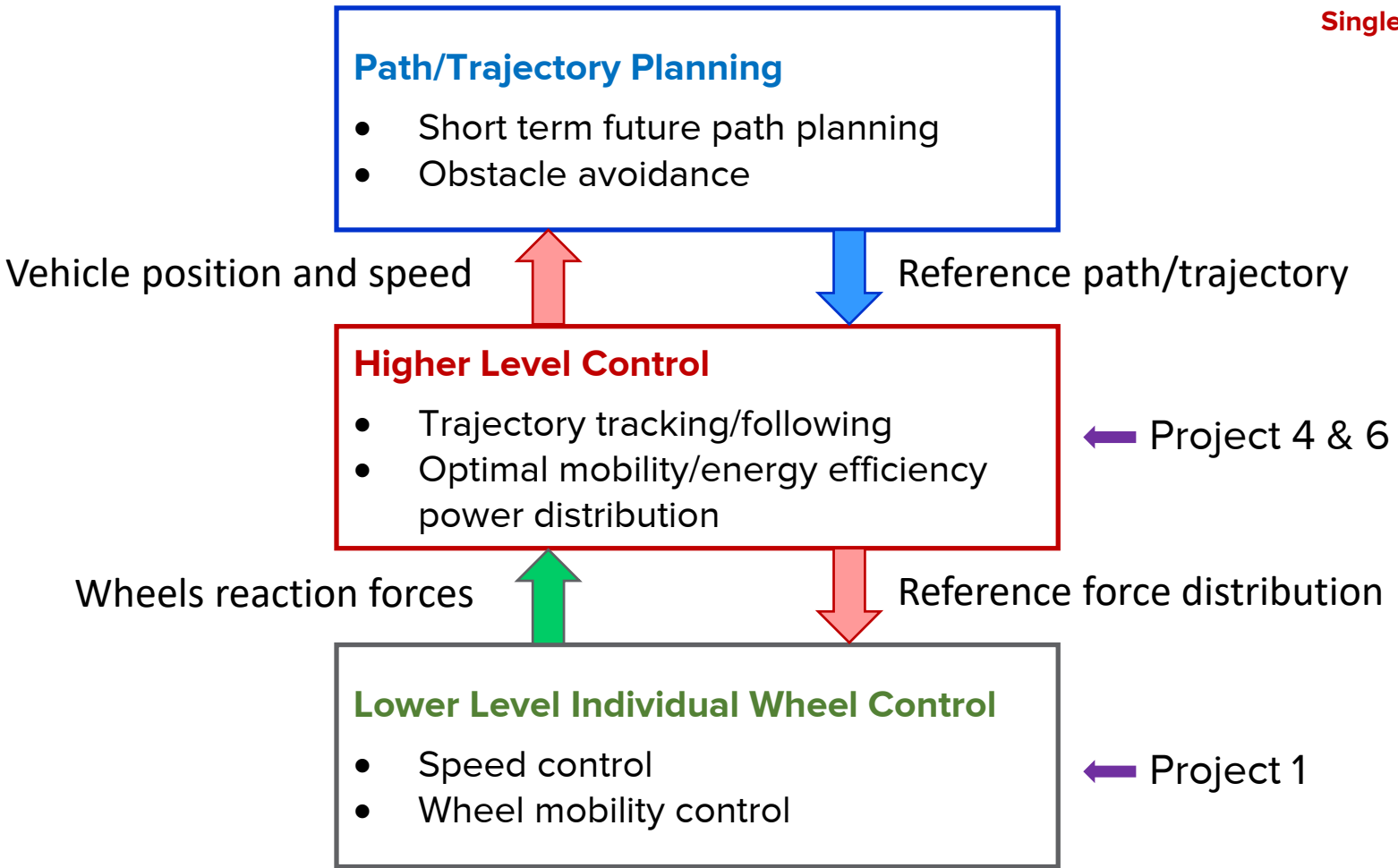
- ❑ Design of an Autonomous Mobility Control System (AMCS)
- ❑ **Part 1:** Superimposed Real-time Mobility Control
 - Full state feedback control
 - Fuzzy logic algorithm to provide reference signal to controller
- ❑ **Part 2:** Mobility Observation and Assessment
 - Estimation of normal, longitudinal, and rotational dynamics
- ❑ **Part 3:** AI-Component
 - Supports the controller with a reinforcement-learning algorithm



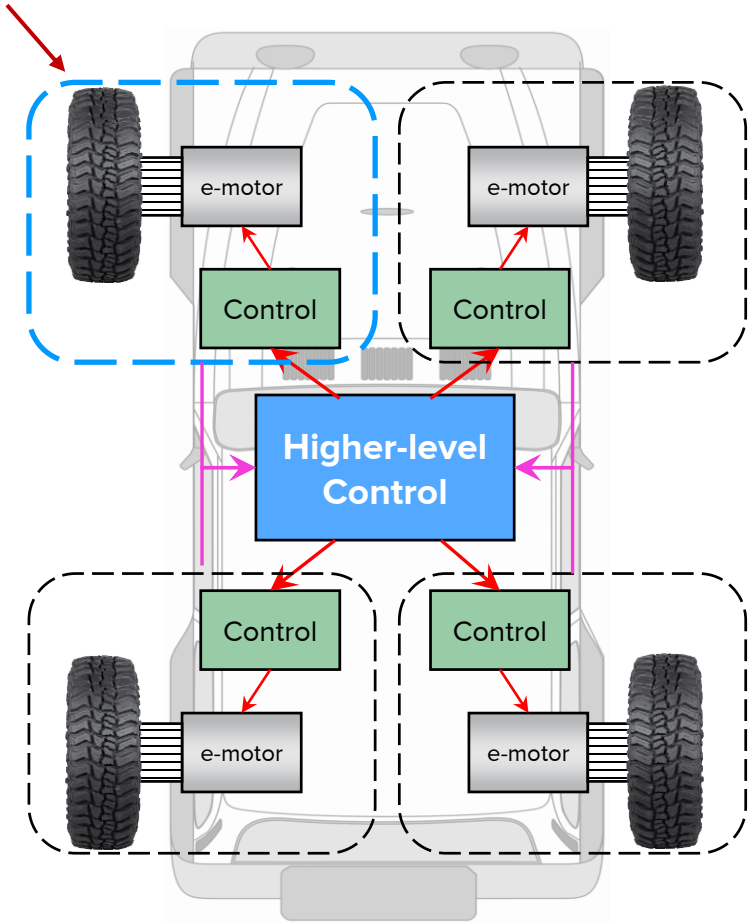
Projects 1-4-6 Tasks Flowchart



Vehicle Control System Architecture

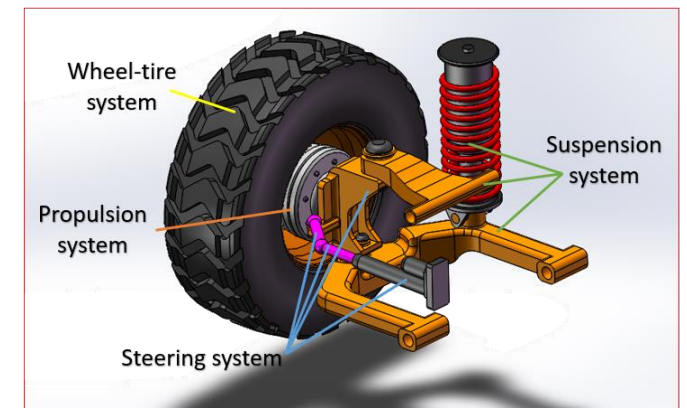
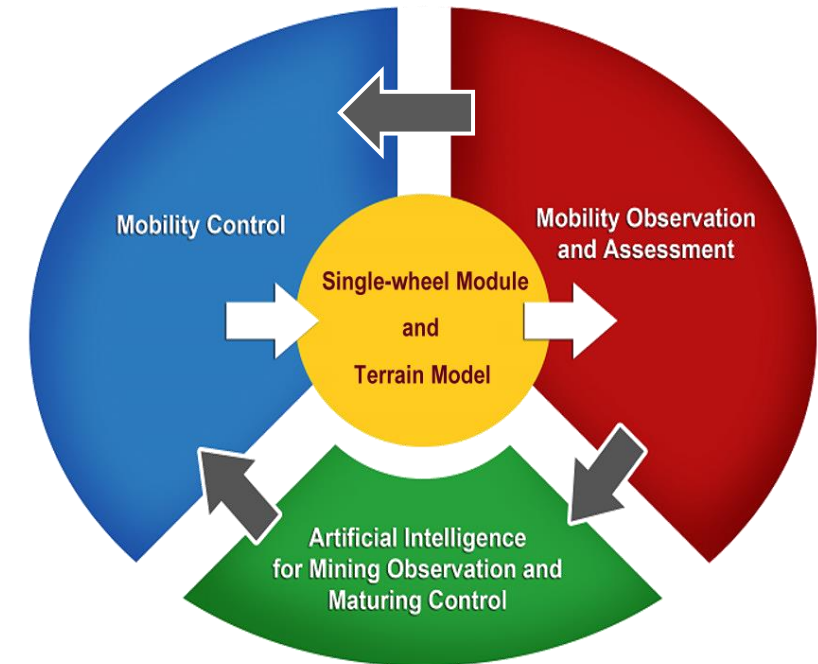


Single-Wheel Module



Single-wheel Module Control

- **Superimposed Full state feedback control (SMC + Fuzzy Logic Corrector)**
 - ❑ Provide an **agile** control of the SWM with response time **faster** than the **tire relaxation time**
 - ❑ Maintain **mobility** throughout the process that is the **slippage** stays below **critical level** at all time
- **Control and Observation Method Novelties**
 - ❑ Utilizes the **force/torque field estimation** obtained through **observers** (differentiators)
 - ❑ **Decouples** suspension and forward dynamics and thus provides a **simplified** control design solution
 - ❑ Addresses modeling **matched/mismatched** uncertainties as well as disturbances due to **stochastic** terrain profile
 - ❑ Integrates the forward **linear** dynamics to control linear speed
 - ❑ Provides an **agile** solution and maintains **slippage** within a limited range



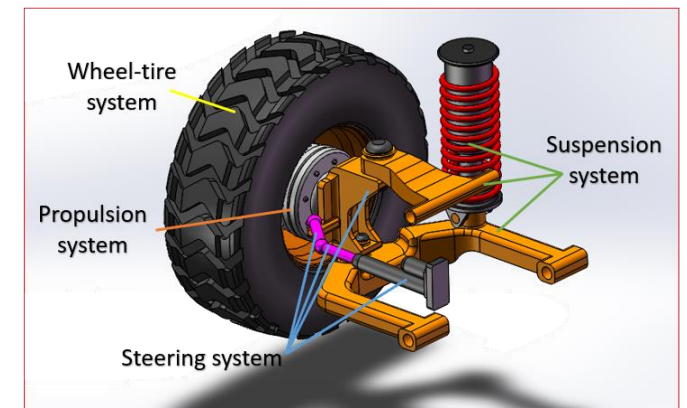
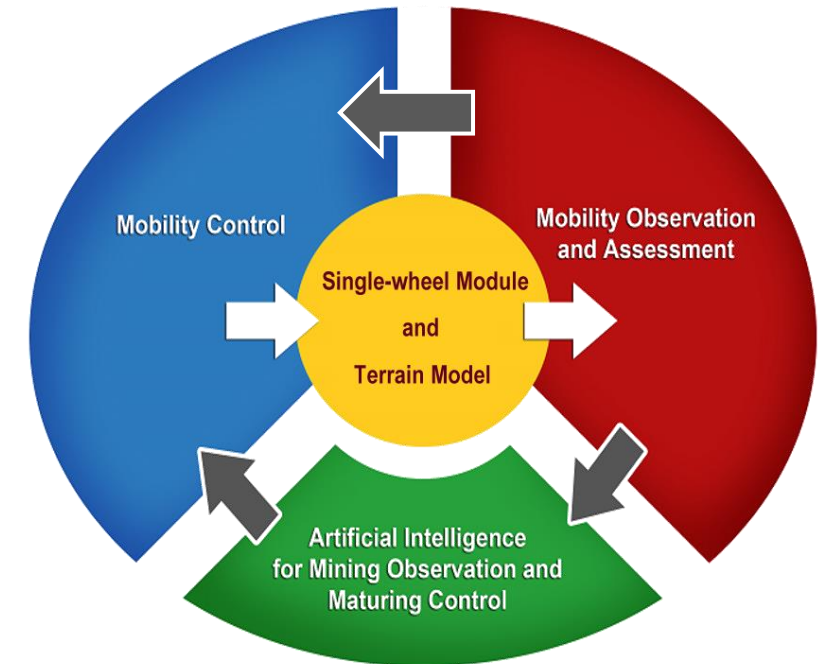
Single-wheel Module Control

- **Fuzzy Logic Corrector**

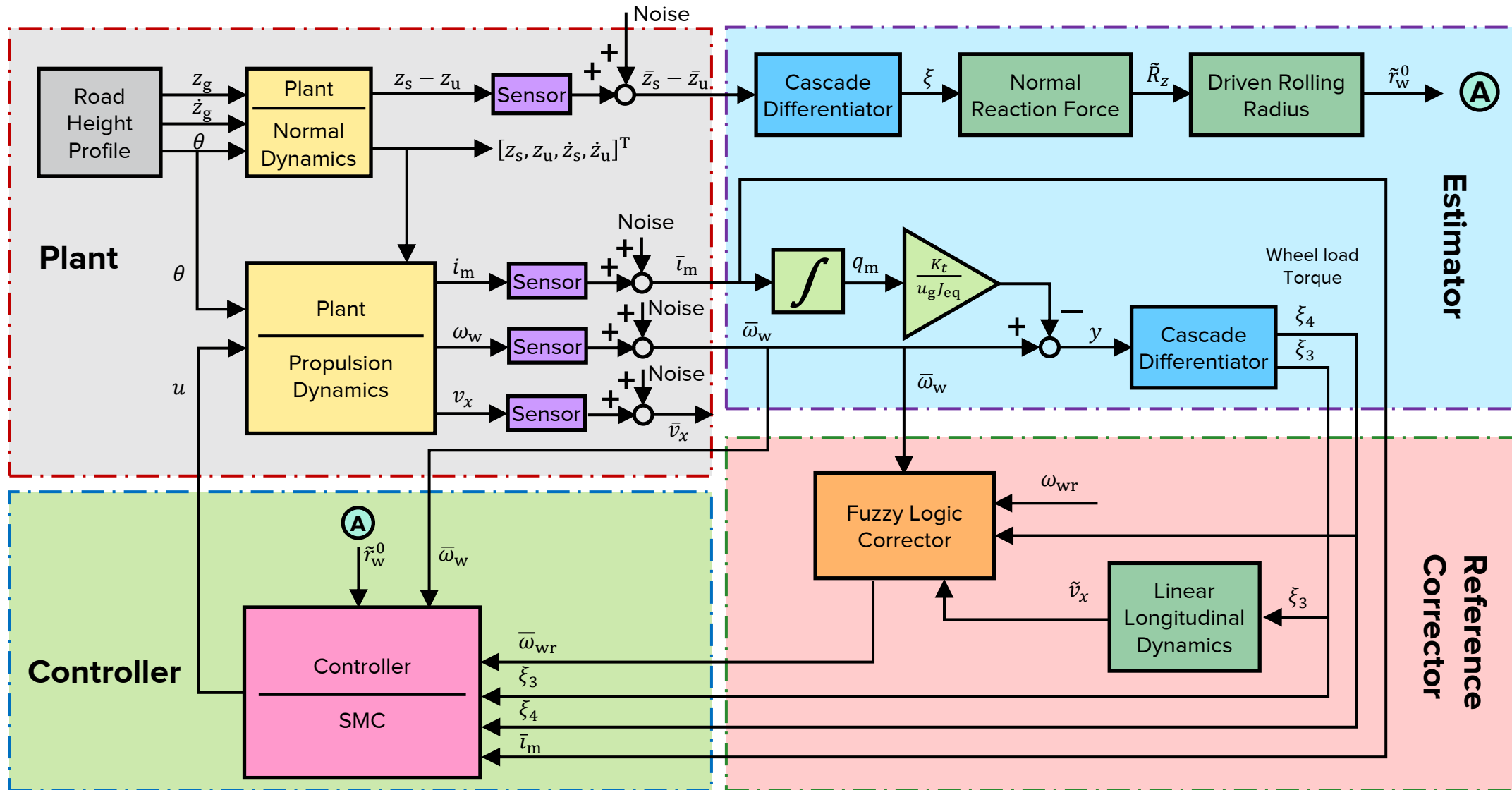
- ❑ Utilizes **linguistic approach** to translate system behavior to meaningful **slippage limiting reference signal**
- ❑ Easily **integrated/superimposed** with the feedback control blocks without impairing its **stability**

- **Vehicle dynamics/mobility Novelties**

- ❑ Method to estimate the **wheel dynamic normal** reaction based on suspension dynamics
- ❑ **Inverse dynamics** approach to link the wheel normal reaction to trafficability prediction
- ❑ Make **critical values** of the normal reaction on various terrains available as an AI database for observation-AI-control to maintain mobility



Block Diagram of the Closed-loop Control System



Force/Torque Field Estimation

- **Estimation Using Physical Sensors**

- ⇒ ARC Project 2

- **Virtual Sensors or Observation-Based Methods**

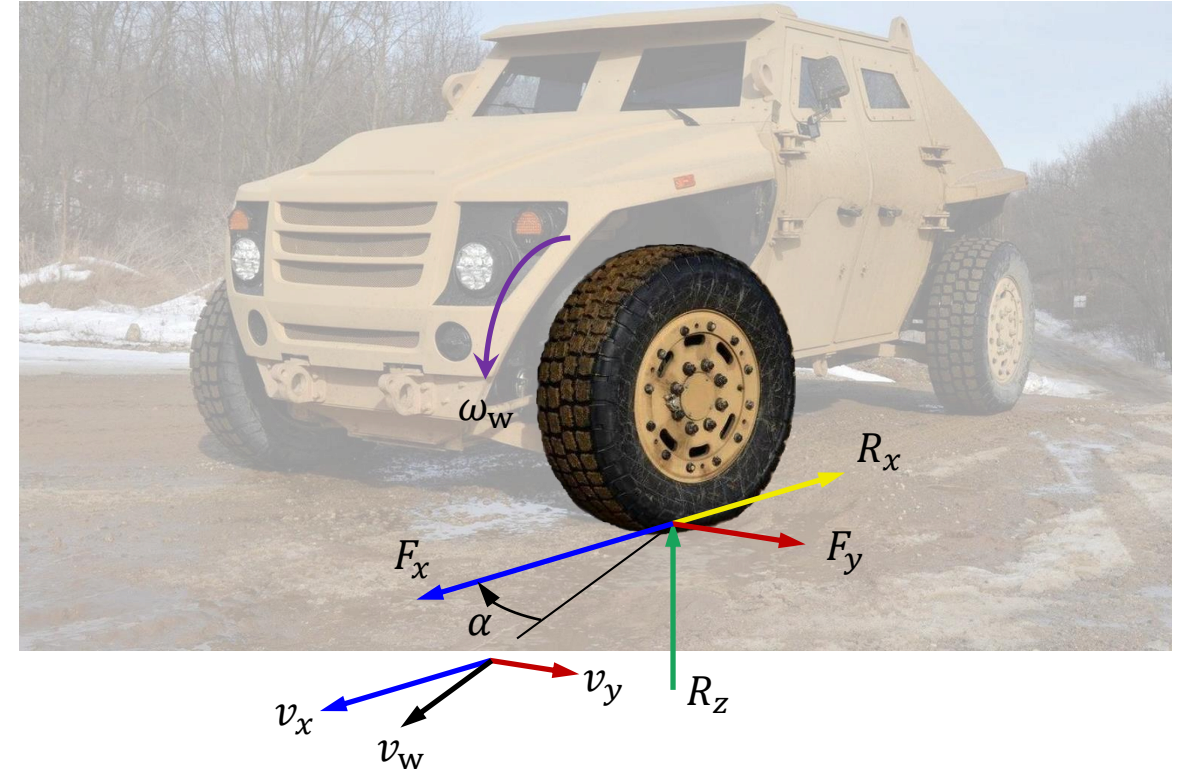
- ❑ The estimation utilizes the inverse dynamics model
 - ❑ The models used in the literature for the vehicle include **two-track model**, **bicycle model**, **quarter car model**, etc.
 - ❑ The models used for tire in the literature include **Pacejka**, **Dugoff**, **Brush**, **pure side-slip**, **pure longitudinal slip**, **combined slip**, **LuGre**, etc.
 - ❑ Some estimations are based on friction models.

Estimation	Type	Accuracy	Repeatability
Model-based	Vehicle dynamics	High	High
	Tire model	High	Medium
	Friction model	Medium	Low

- **Artificial Intelligence-based Estimation**

- ⇒ ARC Project 1 Year 2

Khaleghian, Seyedmeysam, Anahita Emami, and Saied Taheri. "A technical survey on tire-road friction estimation." Friction 5, no. 2 (2017): 123-146.



Force/Torque Field Estimation

- **Model-based Approach**

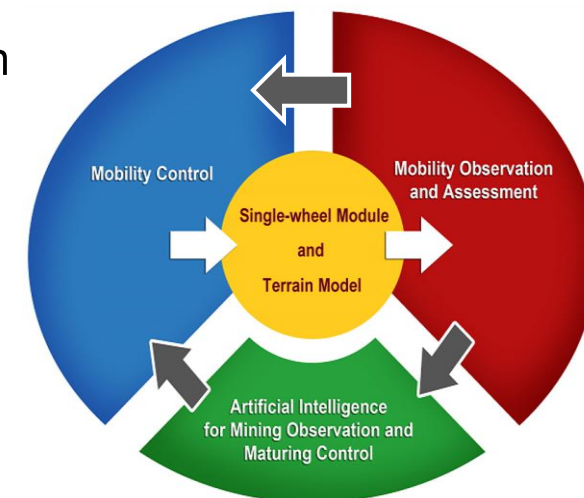
- ❑ The terrain data are not available. Thus, it needs time and effort to experimentally create a **data bank** describing the models associated with each **terrain type**.
- ❑ The model is highly **nonlinear**, which adversely affects model **complexity** and **computation cost** of the estimator.
- ❑ The subsystem dynamics are **coupled**.

- **Model-Free Approach**

- ❑ **No prior knowledge** of the terrain is needed.
- ❑ The design is simpler and **computationally efficient**.
- ❑ The subsystem dynamics can be **decoupled**, which simplifies control design and reduces computation cost.

- **Artificial Intelligence-based Approach**

- ❑ Needs a **training data set**
- ❑ **Computationally efficient**
- ❑ Provides an **adaptive** estimation and is able to **mature** over time



Force/Torque Field Estimation

- **Requirements of the Observer Design**

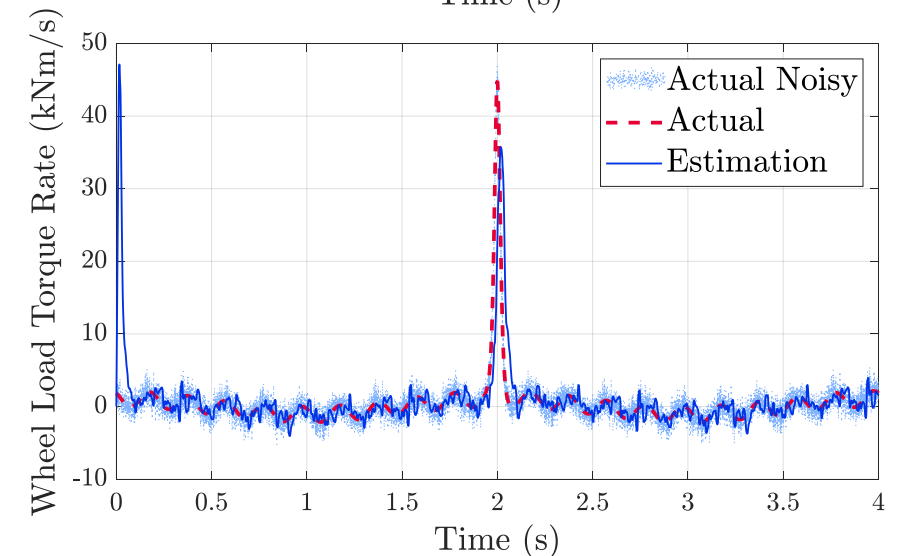
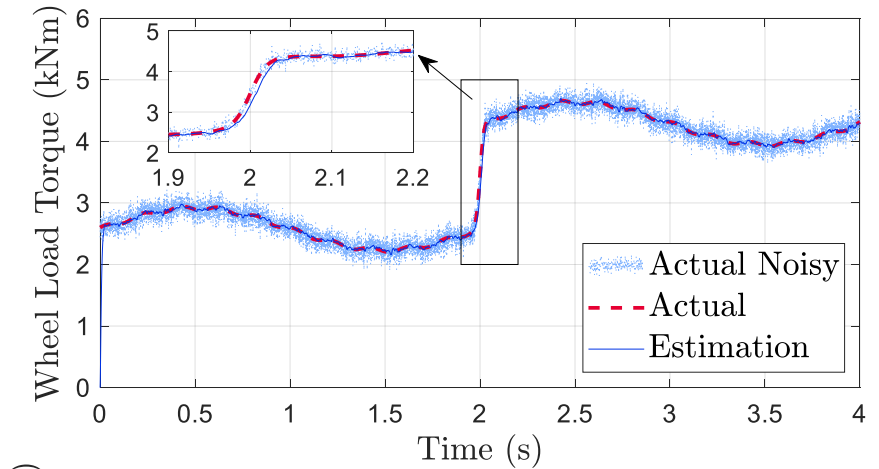
- ❑ Differentiate the states of the system
- ❑ Address **matched** and **mismatched** disturbances/uncertainties
- ❑ **Robustness** to external noises/disturbances
- ❑ **Simplicity** in design

- **Comparison with Common Observer Types**

- ❑ Do not estimate the time derivative of the states (LO, KF, EKF, UKF, PF)
- ❑ Requires a **fully-known model** of the system (LO, KF, EKF, UKF, SMO)
- ❑ Computationally **not efficient** (PF, UKF)
- ❑ Applicable only to **linear** systems (LO, KF)
- ❑ Address **specific types** of noises/disturbances (KF, EKF)

- **Higher Order Sliding Modes Differentiator**

- ❑ Stronger **insensitivity** to external disturbances
- ❑ Better **disturbance rejection** performance
- ❑ Higher **convergence accuracy**
- ❑ **Finite-time** and **fixed-time** convergence



Control System Design Approach

- **Single Wheel Module System (Plant Model)**

- ❑ The simulation model of a **quarter** of a 4x4 vehicle equipped with **IWMs**
 - ❑ Includes single wheel-tire system, propulsion system (**DC electric motor and driveline**), brake, suspension, and steering

- **Propulsion System Dynamics**

$$\frac{d}{dt} i_m(t) = -\frac{R_a}{L_a} i_m(t) - \frac{k_{emf}}{k_{rg} L_a} \omega_w(t) + \frac{k_{bat}}{L_a u_{max}} u(t) + h_1(t)$$

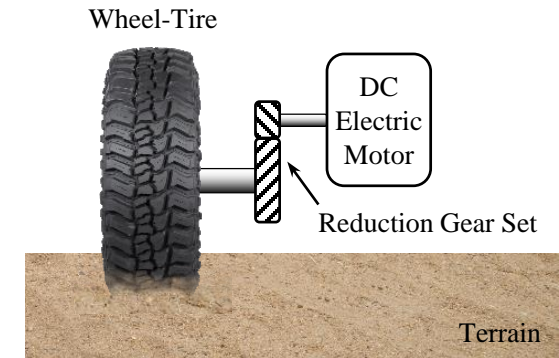
← Voltage control input
← Matched disturbance

$$\frac{d}{dt} \omega_w(t) = \frac{k_t}{k_{rg} J_{eq}} i_m(t) - \frac{1}{J_{eq}} T_{wl}(t) + h_2(t)$$

← Mismatched disturbance

$$\frac{d}{dt} v_x(t) = \frac{1}{m_s + m_u} (F_x(t) - R_x(t)) - g \sin \theta(t)$$

← Wheel load torque



- **Force/Torque Field Estimation**

- ❑ Using a **HOSM differentiator**, which **decouples** propulsion and suspension dynamics

- **Angular Speed Tracking**

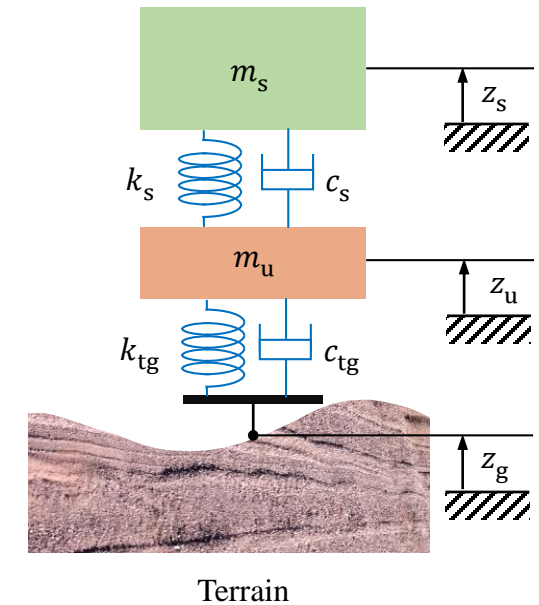
- ❑ Using a Sliding Mode Control method

- **Linear Speed Tracking**

- ❑ Tracking an **adjusted** reference angular speed

- **Slippage Suppression**

- ❑ Tracking an **corrected** reference angular speed (**Fuzzy logic corrector**)



Propulsion Dynamics Control

- **Control Objective**

- To track a reference angular speed

- **Error State**

$$e_\omega(t) \triangleq \omega_w(t) - \omega_{wr}(t), \quad t \geq 0$$

- **Sliding Surface**

$$\mathcal{S} \triangleq \{(X, t) \in \mathbb{R}^3 \times \mathbb{R} : \sigma(X, t) = 0\}$$

$$\sigma(X, t) \triangleq i_m(t) + \frac{u_g J_{eq}}{k_t} \xi_3(t) + \frac{u_g J_{eq} K_1}{k_t} \omega_w(t) - \frac{u_g J_{eq}}{k_t} \dot{\omega}_{wr}(t) - \frac{u_g J_{eq} K_1}{k_t} \omega_{wr}(t)$$

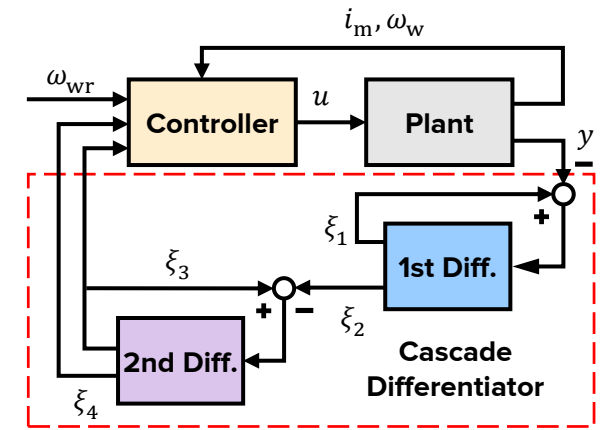
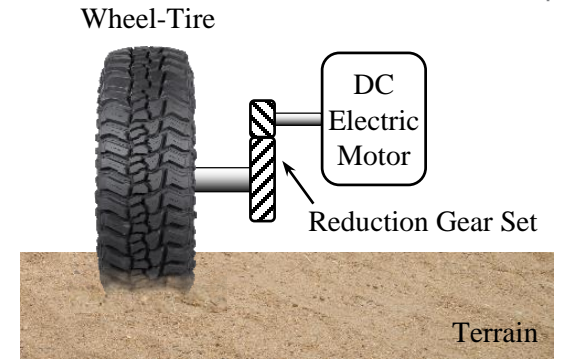
- $X(t) \triangleq [i_m(t), \omega_w(t), \xi_3(t)]^T, K_1 > 0$

- **Sliding Mode Controller**

$$u(t) = -\frac{L_a u_{max}}{k_{bat}} \left(K_1 - \frac{R_a}{L_a} \right) i_m(t) + \frac{u_{max} k_{emf}}{k_{rg} k_{bat}} \omega_w(t) - \varsigma \left(\xi_4(t) - \ddot{\omega}_{wr}(t) + K_1 (\xi_3(t) - \dot{\omega}_{wr}(t)) \right) - \frac{L_a u_{max}}{k_{bat}} (K_2 |\sigma(X, t)|^{\alpha_{c1}} + K_3 |\sigma(X, t)|^{\alpha_{c2}}) \text{sign}(\sigma(X, t))$$

- $K_3 > 0, \alpha_{c1} \in [0, 1), \alpha_{c2} > 0, \varsigma \triangleq k_{rg} J_{eq} L_a u_{max} / (k_t k_b)$

- $K_2 = \lambda + \|h_1(t)\|_\infty + \frac{k_{rg} J_{eq} K_1}{k_t} \|h_2(t)\|_\infty, \lambda > 0$



$$y(t) \triangleq \omega_w(t) - \frac{k_t}{k_{rg} J_{eq}} q_m(t)$$

$$\begin{cases} \xi_2(t), \xi_3(t) \rightarrow -\frac{1}{J_{eq}} T_{wl}(t) \\ \xi_4(t) \rightarrow -\frac{1}{J_{eq}} \dot{T}_{wl}(t) \end{cases}$$

Linear Speed Tracking

- **Reference Tire Slippage**

$$s_{\delta r}(t) \triangleq \frac{r_w^0 \omega_{wr}(t) - v_x(t)}{\max(r_w^0 \omega_{wr}(t), v_x(t))}$$

- $s_{\delta r}$ is a nondimensional measure of the linear speed tracking error

- **Adjusted Reference Angular Speed**

$$\hat{\omega}_{wr}(t) \triangleq \omega_{wr}(t)(1 + K_4 s_{\delta r}(t))$$

- K_4 is a proportional control gain

- **Corrected Reference Angular Speed**

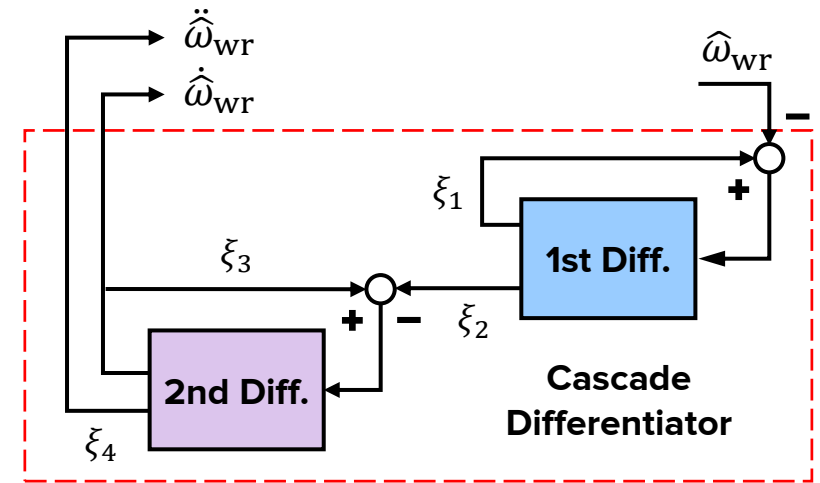
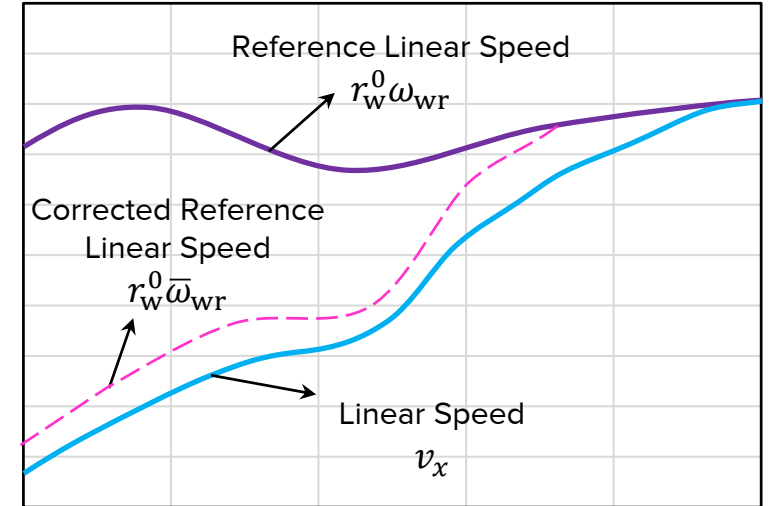
$$\bar{s}_{\delta} = \frac{|r_w^0 \bar{\omega}_{wr}(t) - v_x(t)|}{\max(r_w^0 \bar{\omega}_{wr}(t), v_x(t))} > 0$$

$$\Rightarrow \bar{\omega}_{wr}(t) = \frac{v_x(t)}{r_w^0} (1 - \bar{s}_{\delta}) \text{sign}(-s_{\delta}(t))$$

- \bar{s}_{δ} : Maximum permitted slippage

- **Activation Condition**

$$|v_x(t) - r_w^0 \bar{\omega}_{wr}(t)| < |v_x(t) - r_w^0 \hat{\omega}_{wr}(t)|$$



Fuzzy Logic Inputs & Output

- **Fuzzy Logic Corrector**

- Adjusts the power transmitted to the wheel by correcting the error signal

$$|\omega_w - \bar{\omega}_{wr}| \leq |\omega_w - \omega_{wr}|$$

- **Slippage (Input)**

- **Characteristic slippage** determines the region where the wheel starts spinning

- **Rate of Changes of Wheel Torque (Input)**

- Determines if the traction is improving over time

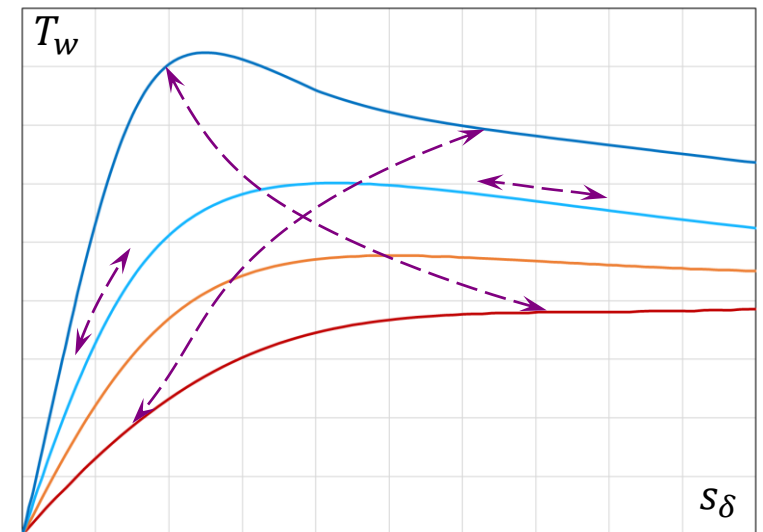
- **Rate of Changes of Slippage (Input)**

- Determines if the slippage is improving over time

$$\frac{dT_w}{ds_\delta} = \frac{\dot{T}_w}{\dot{s}_\delta}$$

- **Corrected Reference Angular Speed (Output)**

- A reference signal to the feedback controller
- With this reference the slippage is maintained within the acceptable range



Fuzzy Logic Corrector

- **Corrected Reference Angular Speed Bounds**

$$\omega_{wr1}(t) \triangleq \frac{v_x(t)}{r_w^0} (1 - \max\{s_{\delta c}\}) \text{sign}(-s_{\delta}(t))$$

$$\omega_{wr2}(t) \triangleq \omega_{wr}(t) (1 - \min\{s_{\delta c}\}) \text{sign}(-s_{\delta}(t))$$

- **Error Ratio**

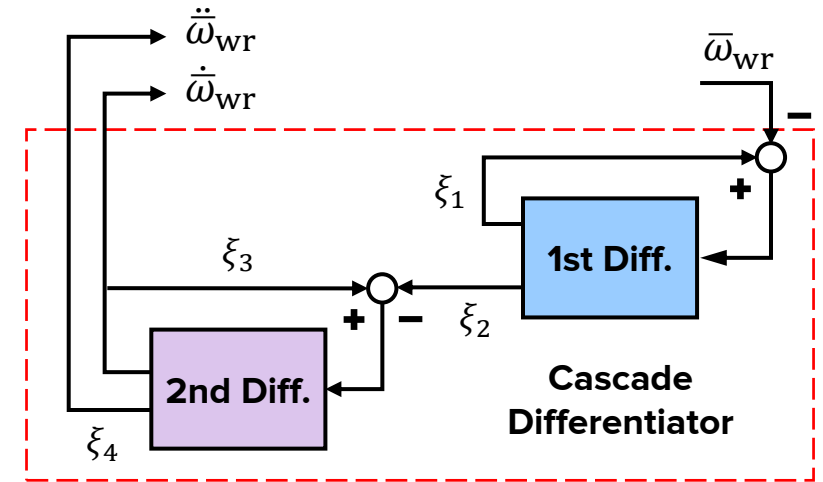
$$e_{\delta}(t) \triangleq \frac{\bar{\omega}_{wr}(t)r_w^0 - v_x(t)}{\omega_{wrb}(t)r_w^0 - v_x(t)}$$

- ❑ $e_{\delta}(t)$ (Fuzzy logic corrector output): Nondimensional linear speed tracking error

- **Upper Bound**

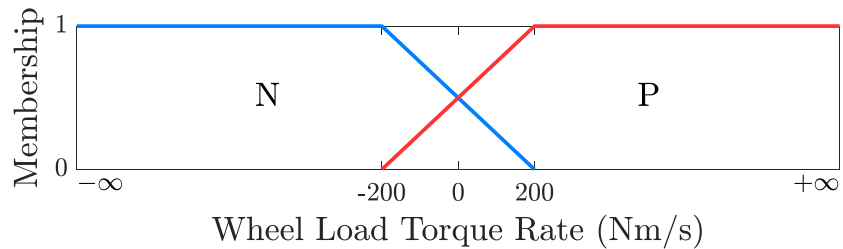
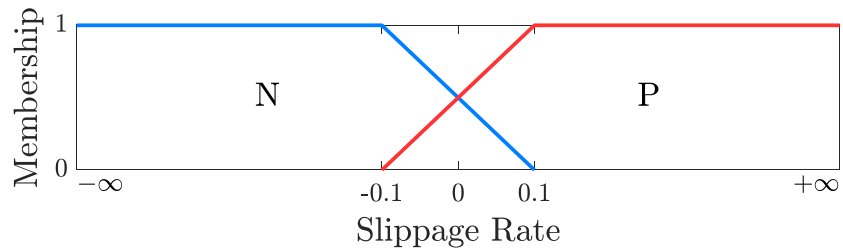
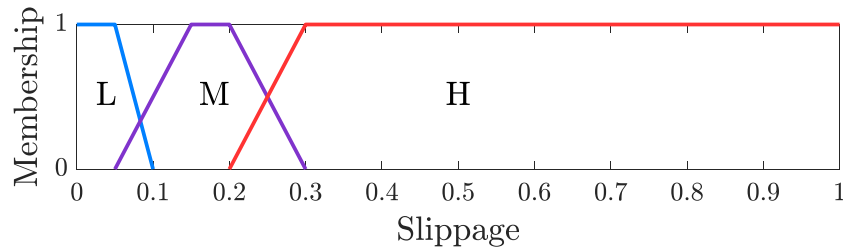
- ❑ $\omega_{wrb}(t) = \omega_{wr1}(t)$ if

$$|\omega_{wr1}(t)r_w^0 - v_x(t)| < |\omega_{wr2}(t)r_w^0 - v_x(t)|$$
 Otherwise, $\omega_{wrb}(t) = \omega_{wr2}(t)$
 - ❑ The stricter bound is selected



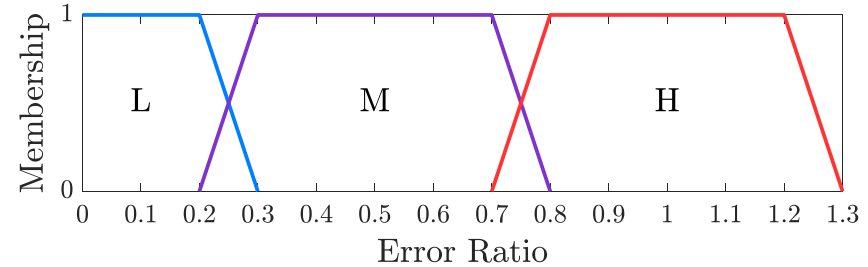
Fuzzy Logic Corrector

Input Membership Functions



L: Low, **M:** Medium, **H:** High
N: Negative, **P:** Positive

Output Membership Function



Linguistic Rules

Rules	Inputs			Output
#	$ s_\delta $	$\text{sign}(s_\delta)\dot{s}_\delta$	$\text{sign}(s_\delta)\dot{T}_w$	e_δ
1	L	—	—	H
2	M	P	P	M
3	M	N	N	M
4	M	P	N	L
5	M	N	P	L
6	H	—	—	L

Simulation

- **Stochastic terrain**

- ❑ The stochastic terrain is based on Bekker-Wong model
- ❑ A transition occurs from **meadow** to **snow** terrain at $t = 2$ s within 50 ms

- **Reference angular speed**

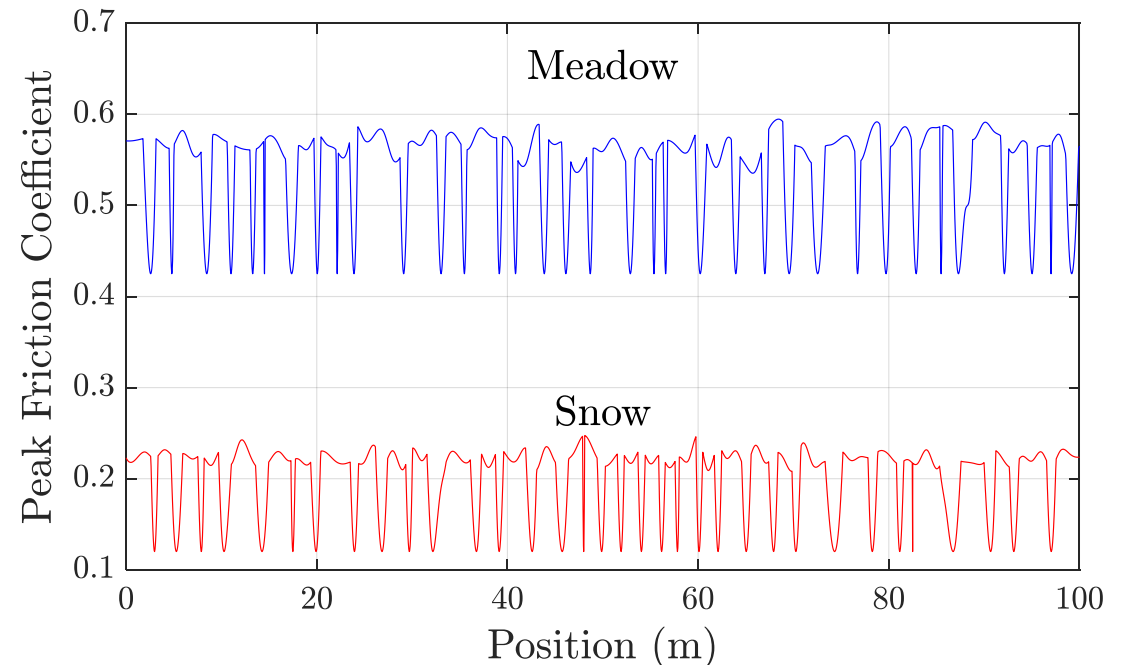
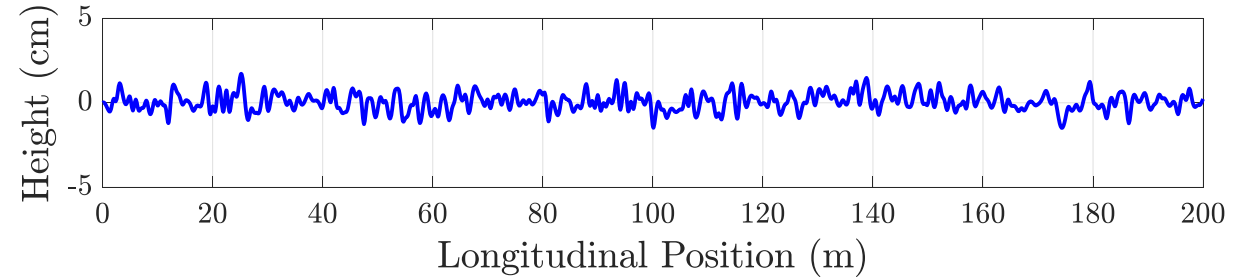
$$\omega_{wr} = \frac{1}{r_w^0} \left(\sin \left(t - \frac{\pi}{6} \right) + 10 \right)$$

- **Linear speed tracking**

- ❑ Utilizes adjusted reference speed

- **Tire slippage suppression**

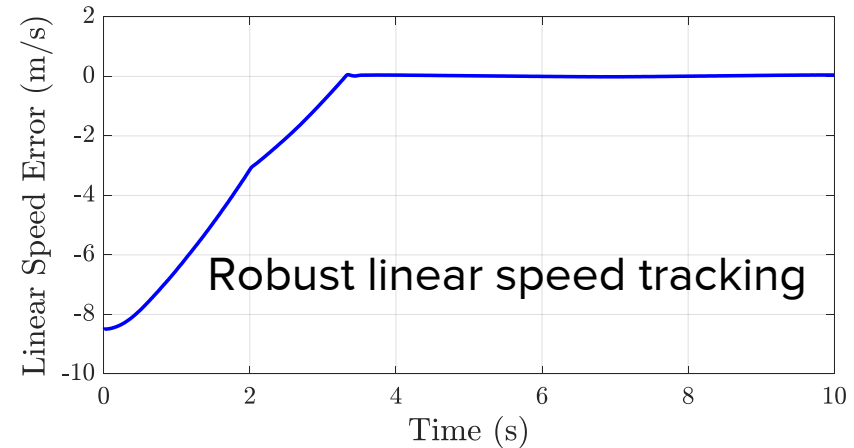
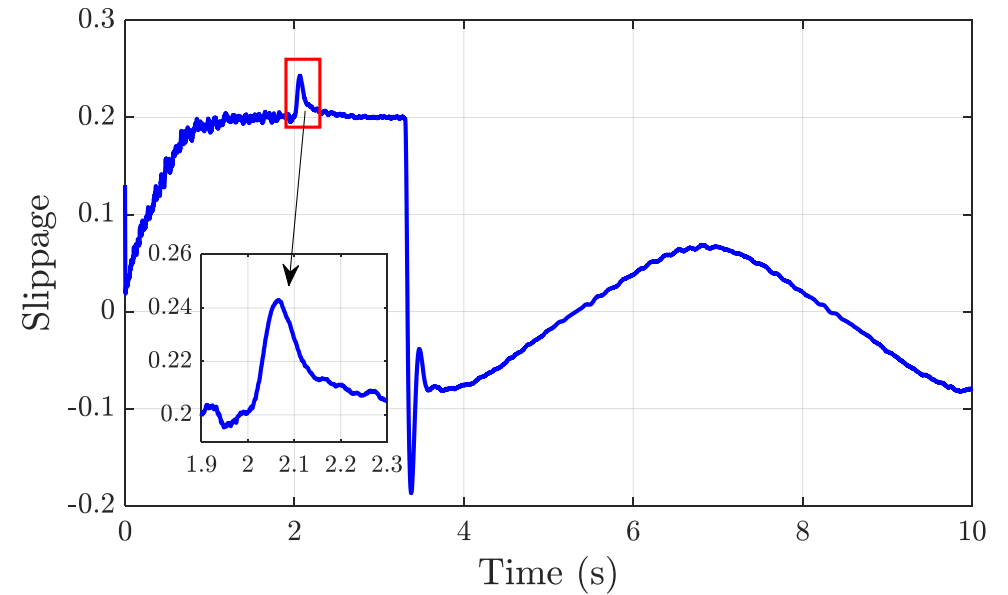
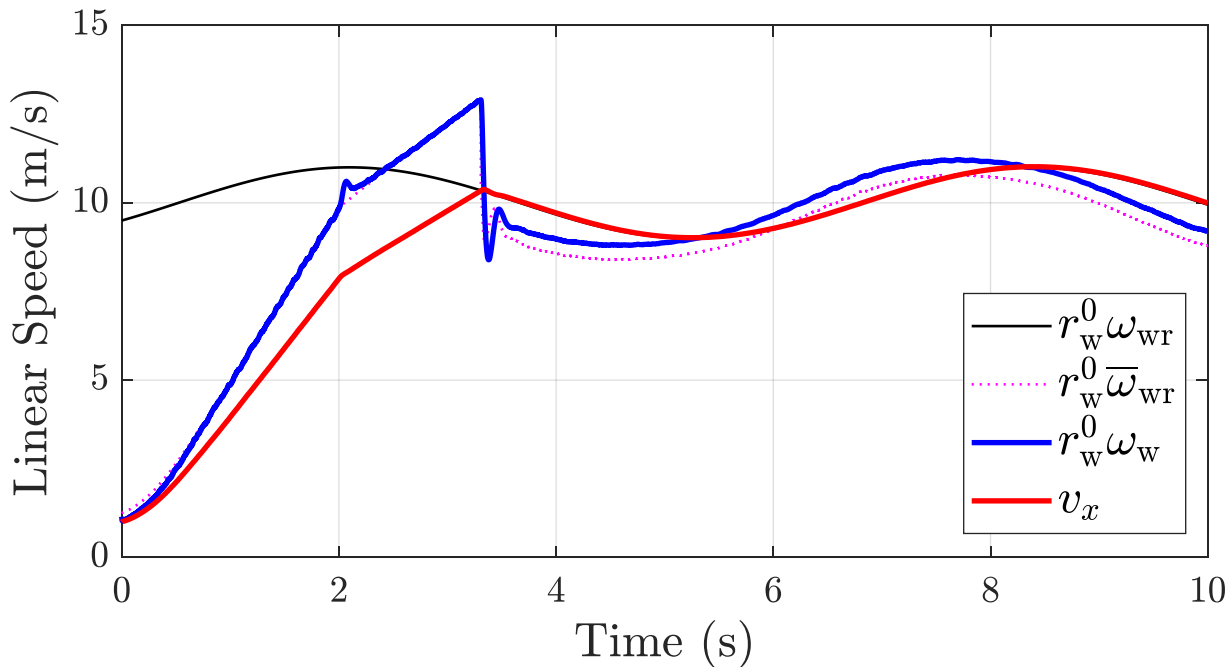
- ❑ Utilizes corrected reference speed



Simulation

- **Pre-defined desired slippage**

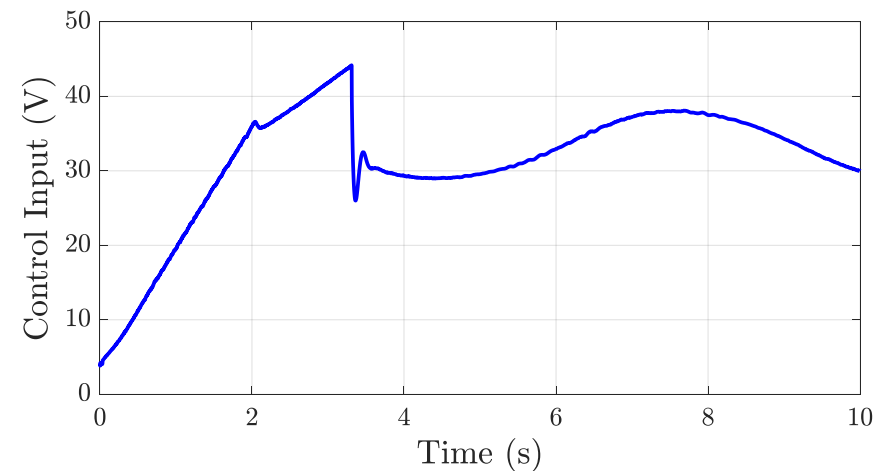
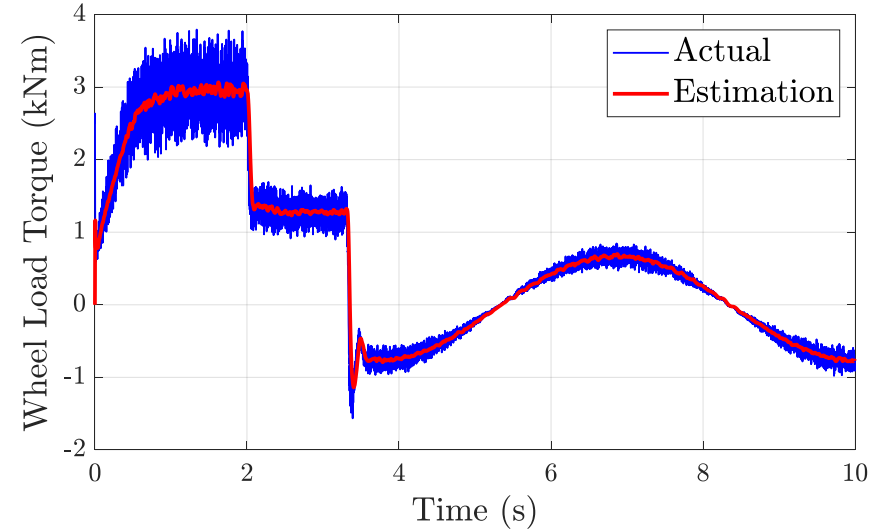
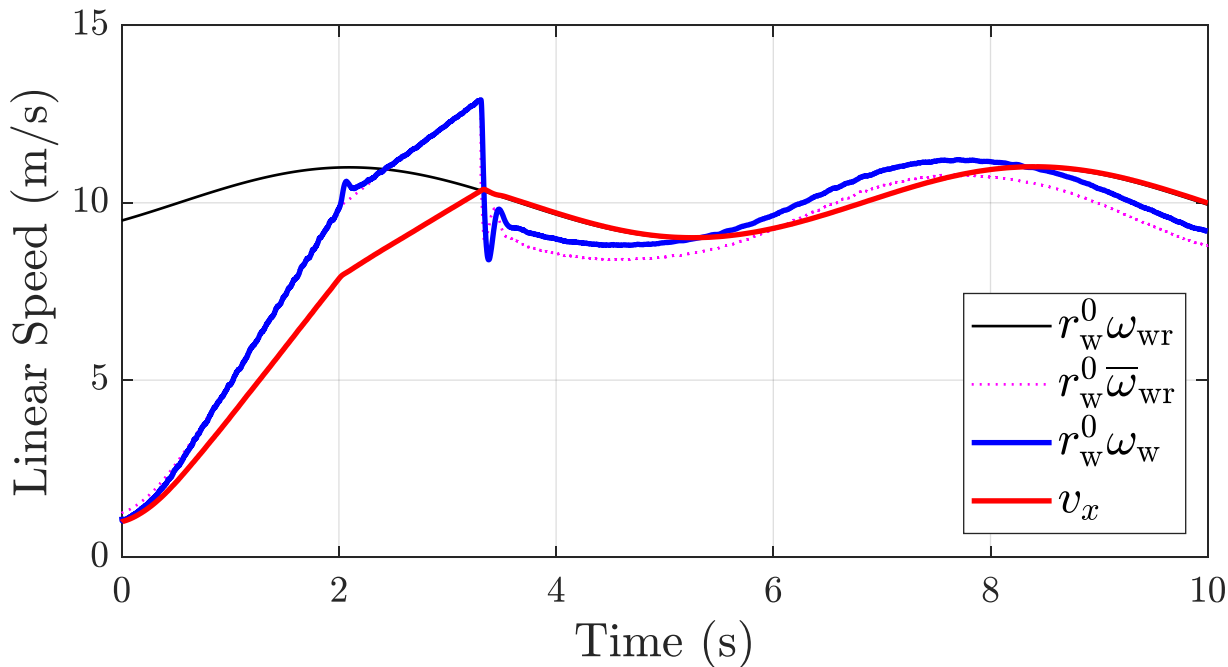
- ❑ Overshoot at the time of terrain transition
- ❑ Slippage is adapted to different terrain conditions (kept at 20% in this simulation)



Simulation

- **Pre-defined desired slippage**

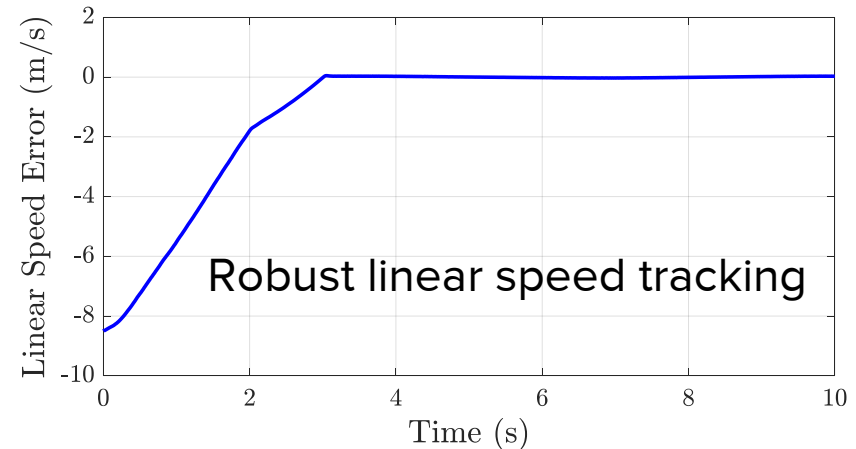
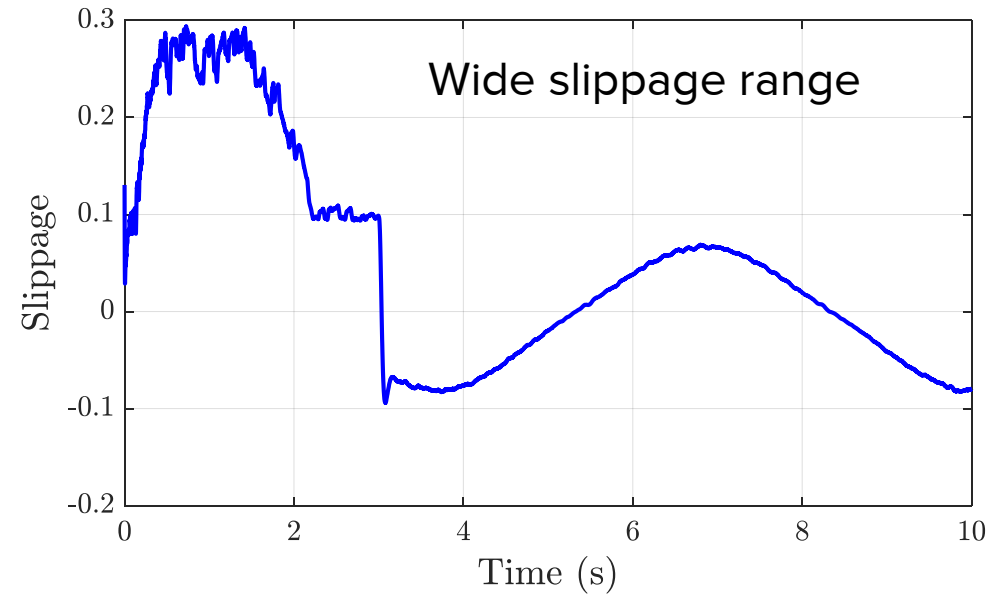
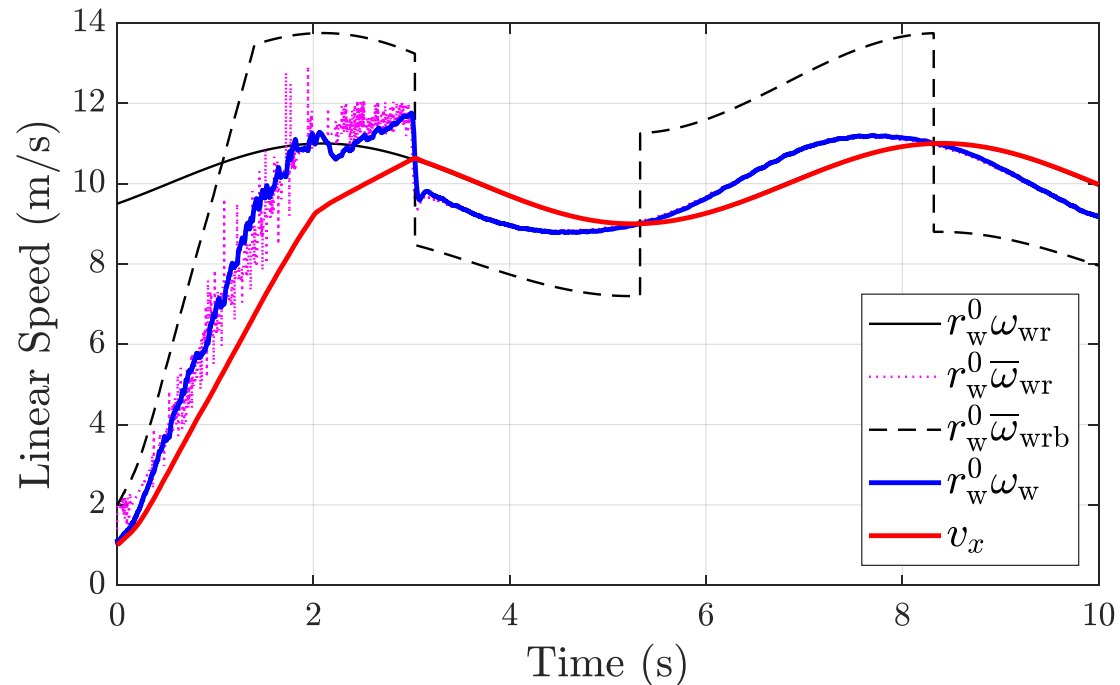
- Overshoot at the time of terrain transition
- Slippage is adapted to different terrain conditions (kept at 20% in this simulation)



Simulation

- **Fuzzy Logic Corrector**

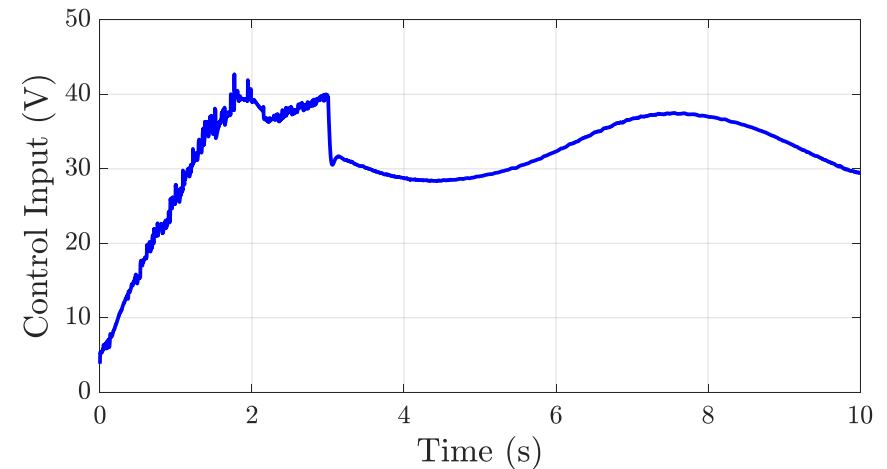
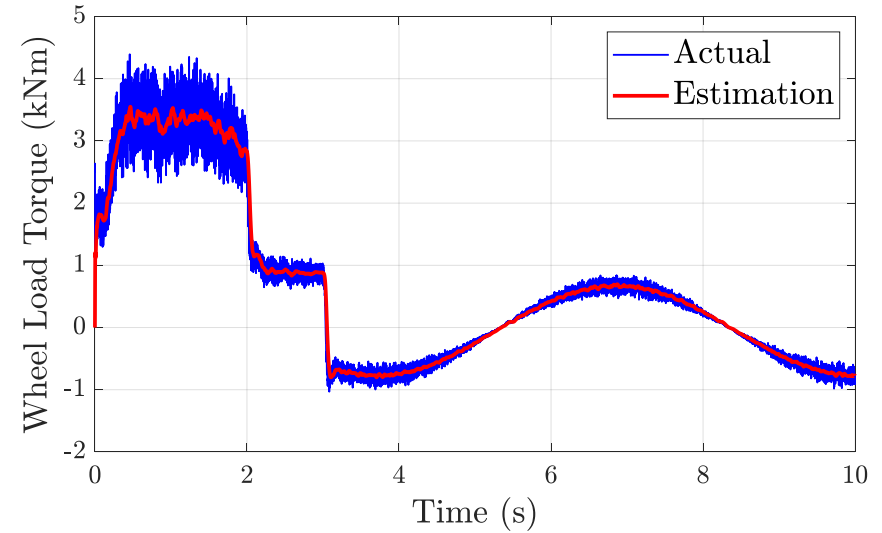
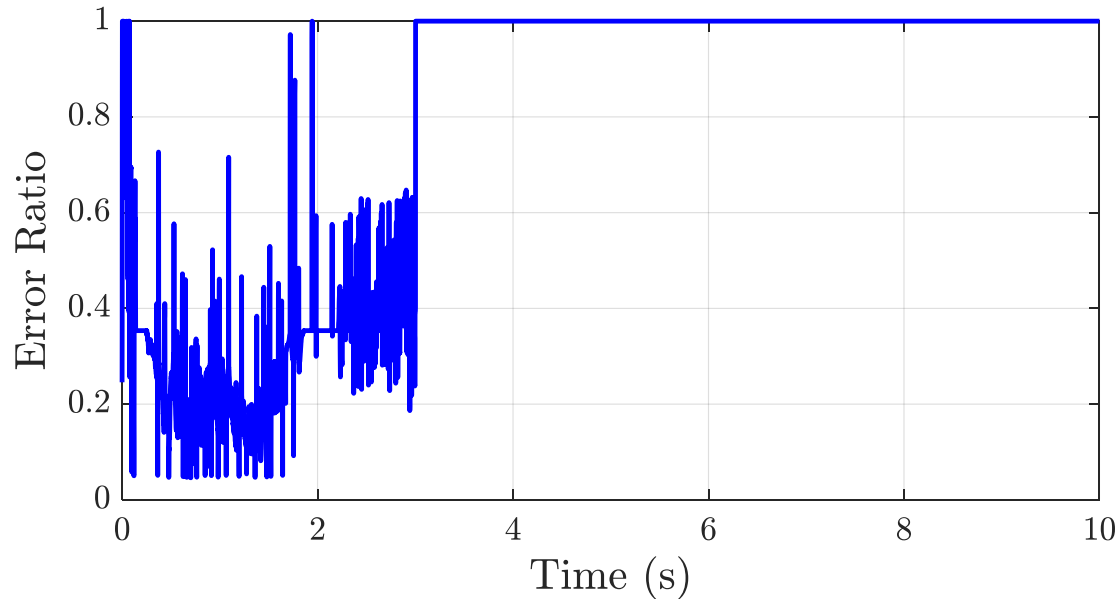
- No overshoot at the time of terrain transition
- Slippage is adapted to different terrain conditions (30% to 10% in this simulation)



Simulation

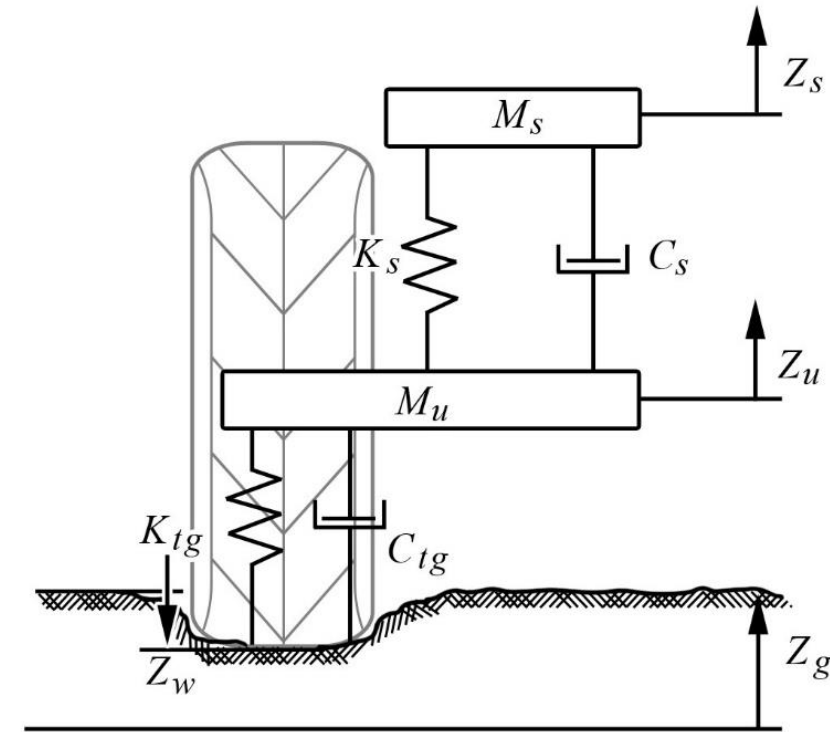
- **Fuzzy Logic Corrector**

- ❑ No overshoot at the time of terrain transition
- ❑ Slippage is adapted to different terrain conditions (30% to 10% in this simulation)



Impact of Wheel Normal Reaction on Terrain Mobility

- **Normal reaction force in the tire-soil patch is a continuously changing wheel parameter**
 - ❑ Motion in the vehicle's sprung and unsprung masses produce dynamic shifts in the magnitude of the load transmitted to the ground
 - ❑ Suspension damping force may be damping force controlled for better ride quality
 - ❑ Tight constraining of the sprung mass motion may lead to significant dynamic changes of the normal load
- **Implications for wheel mobility**
 - ❑ Excessively high or low values of the normal load may lead to soil damage or loss of traction
 - ❑ Extreme values of the normal reaction are researched to establish boundaries for mobility and bearing capacity
 - ❑ Need a method to model and estimate the normal reaction when limiting travel of the sprung mass
 - ❑ A virtual sensor that measures the suspension travel is used to determine the normal reaction in real time



Impact of Wheel Normal Reaction on Terrain Mobility

- Single-wheel Module: Differential equations for the motion of sprung and unsprung masses:

$$m_s \ddot{z}_s = K_s(z_u - z_s) + C_s(\dot{z}_u - \dot{z}_s) + F_{sd}$$

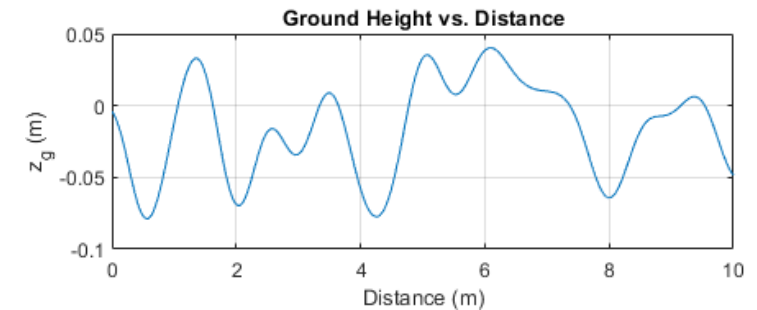
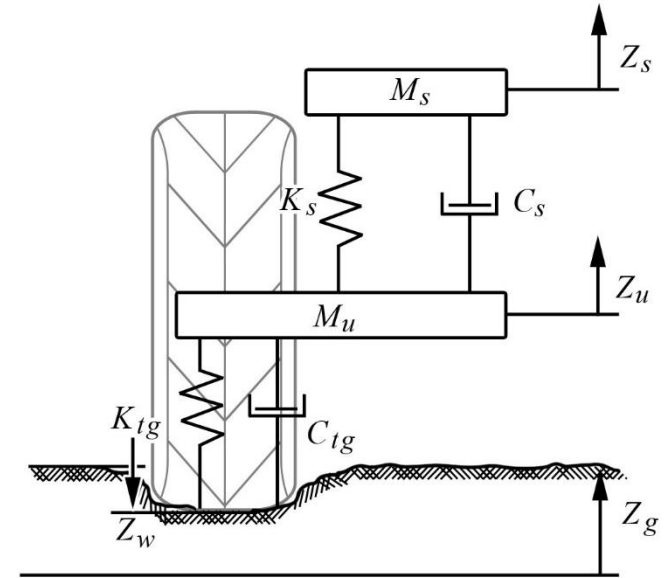
$$m_u \ddot{z}_u = -K_s(z_u - z_s) + K_{tg}(z_g - z_u) - C_s(\dot{z}_u - \dot{z}_s) - F_{sd} + C_{tg}(\dot{z}_g - \dot{z}_u)$$

- Dynamic effect on wheel normal reaction R_z :

$$R_z = R_{z_s} + K_{tg}(z_u - z_g) + C_{tg}(\dot{z}_u - \dot{z}_g)$$

- Static normal reaction R_{z_s} changes to dynamic R_z under influence of relative travel $z_u - z_g$ and velocity $\dot{z}_u - \dot{z}_g$

- Combined tire and soil stiffness $K_{tg} = \frac{K_t K_g}{K_t + K_g}$



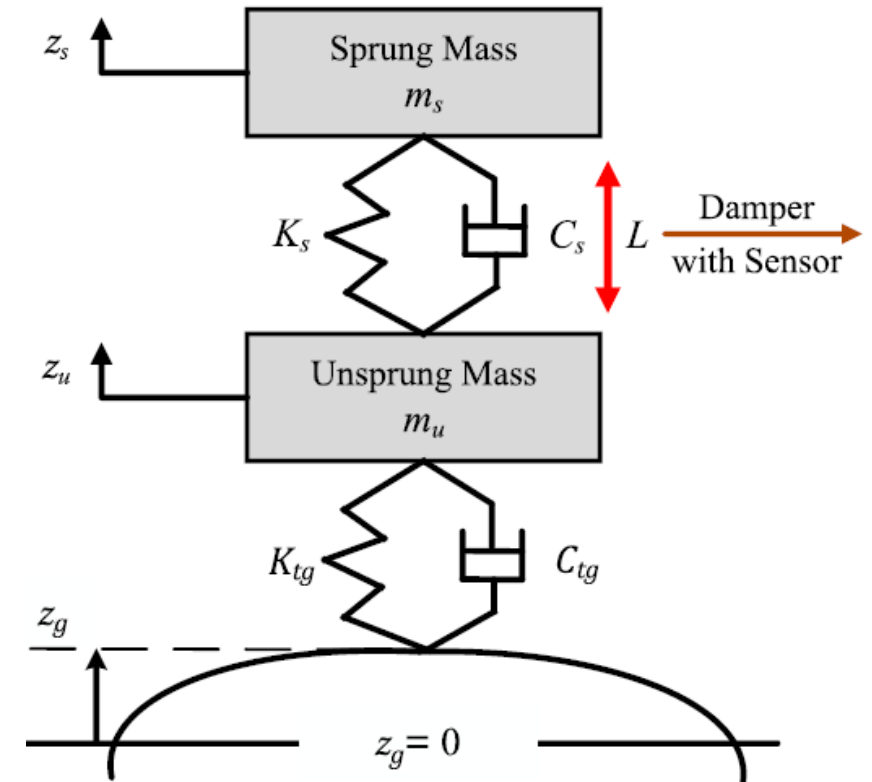
Varying ground height profile z_g produces disturbances in motion of wheel module masses, affecting dynamic normal reaction

Impact of Wheel Normal Reaction on Terrain Mobility

- Normal reaction in terms of the relative travel of the sprung and unsprung masses L :

$$R_Z = R_{z_s} + m_u \ddot{L} + \left(\frac{m_u}{m_s} + 1 \right) (C_s \dot{L} + K_s L - F_{sd})$$

- Obtaining R_Z from the suspension dynamics allows determining dynamic normal reaction without needing to know terrain properties
- Solve inverse dynamics problem to get actuator force F_{sd} from sprung mass acceleration \ddot{z}_s
- Find R_Z for passive damping, stabilized sprung mass



Impact of Wheel Normal Reaction on Terrain Mobility

Boundaries for the Normal Reaction:

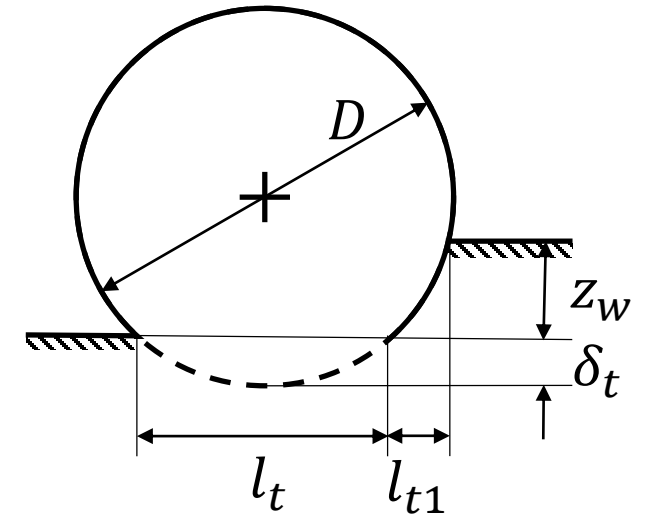
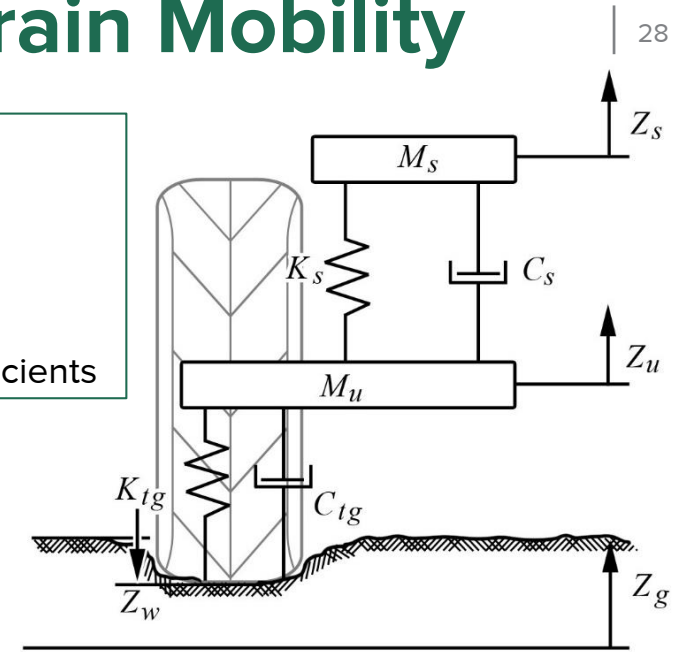
1) Safe weight based on bearing capacity

$$W_s = A(cN_c + \gamma z_w N_q + 0.5\gamma b N_\gamma)$$

Iterative process for deflection δ_t of deformable tire: balance normal load R_z with soil reaction:

- $R_z = p_{gr} l_t b + W_{cu}$
- $W_{cu} = l_t \left(\frac{k_c}{b} + k_\phi \right) \sqrt{D} (z_w + \delta_t)^{n-1} \times \frac{[(3-n)(z_w + \delta_t)^{3/2} - (3-n)\delta_t^{3/2} - 3z_w \sqrt{\delta_t}]}{3}$
 - (W_{cu} : component of soil reaction on curved portion of contact length l_{t1})
- Tire patch contact Length $l_t = 2\sqrt{D\delta_t - \delta_t^2}$
- Sinkage $z_w = \left(\frac{p_{gr}}{\frac{k_c}{b} + k_\phi} \right)^{\frac{1}{n}}$

A: contact area
b: contact width
c: soil cohesion
 γ : soil unit weight
 z_w : sinkage
 N_c, N_q, N_γ : bearing capacity coefficients



Impact of Wheel Normal Reaction on Terrain Mobility

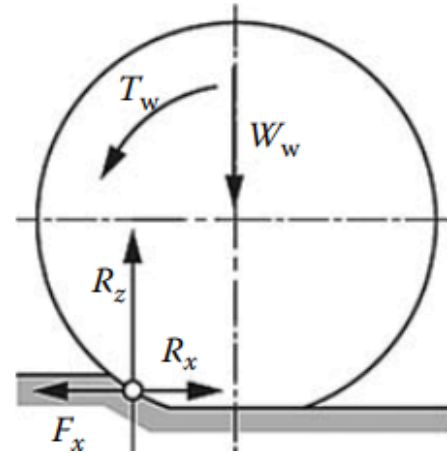
Boundaries for the Normal Reaction:

- 2) Boundary R_z^{min} limited by circumferential wheel force F_x , resistance to motion $R_{m\Sigma}$, and peak friction coefficient μ_{px} :

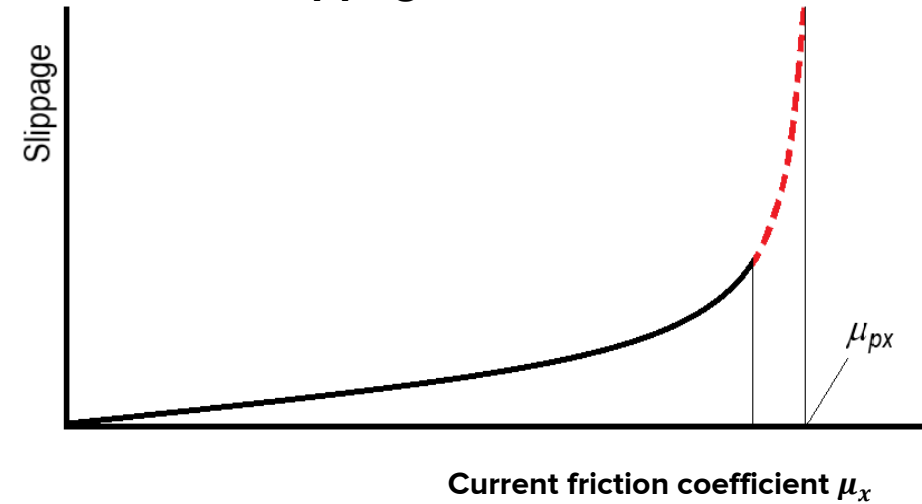
$$\mu_{px} R_z^{min} > R_{m\Sigma}$$

The wheel circumferential force F_x produced by the applied torque must overcome resistance to motion for the wheel to maintain mobility

- When condition (2) is not satisfied, the wheel is immobilized
 - Resistance to motion requires more traction than the wheel can provide due to reduced friction with the ground.
- When $R_z^{min} < 0.2R_{z_s}$, the wheel is hardly steerable.



Tire slippage curve:



- Current friction coefficient μ_x is the fraction of R_z used in generating the circumferential force F_x :

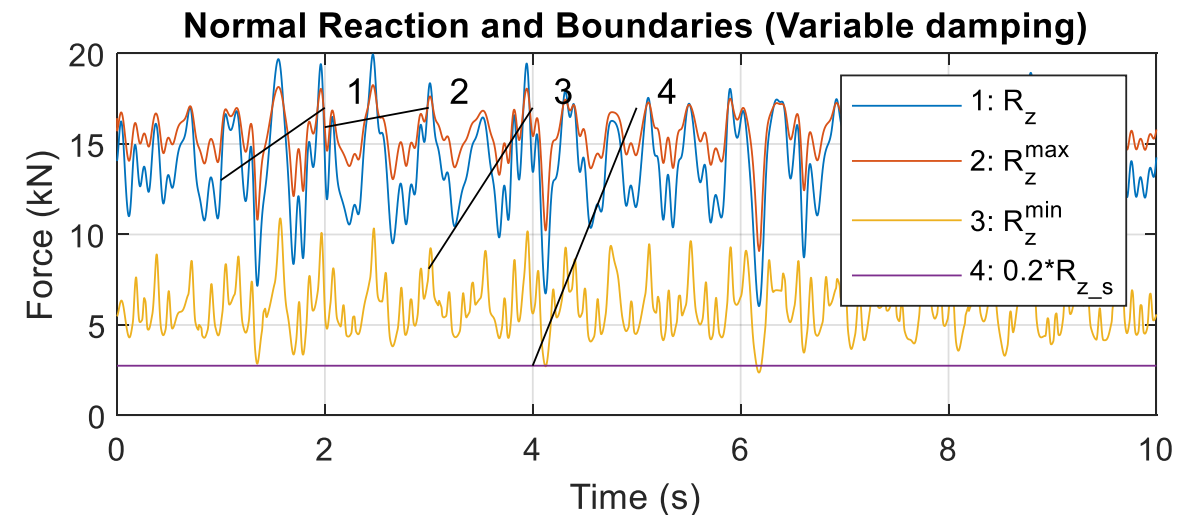
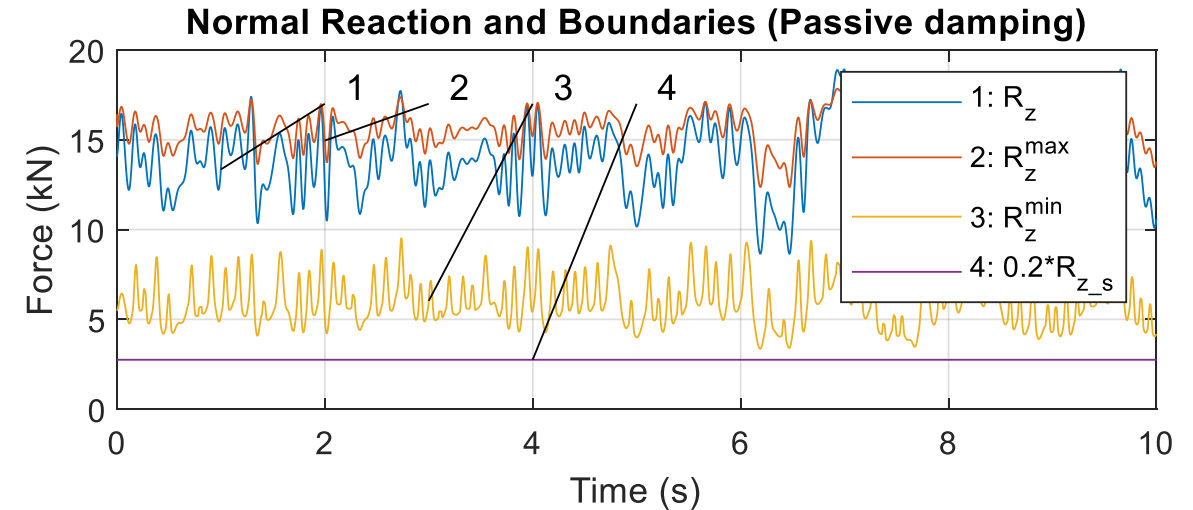
$$\mu_x = \frac{F_x}{R_z}$$

- As μ_x increases, the tire slippage increases exponentially.
- μ_{px} defines the upper boundary on F_x and μ_x

Impact of Wheel Normal Reaction on Terrain Mobility

Simulation example: wheel module dynamic normal reaction and boundaries for passive damping (upper) and stabilized sprung mass (lower):

1. Dynamic R_z
2. Upper limit R_z^{max} based on bearing capacity:
 $R_z^{max} < W_s$
3. Lower limit based on minimum for required circumferential force: $\mu_{px} R_z^{min} > R_{m\Sigma}$
4. Lower limit based on steerability: $R_z^{min} > 0.2R_{z_s}$



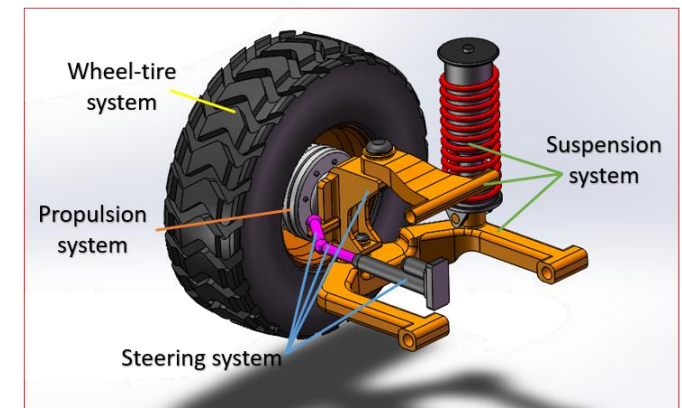
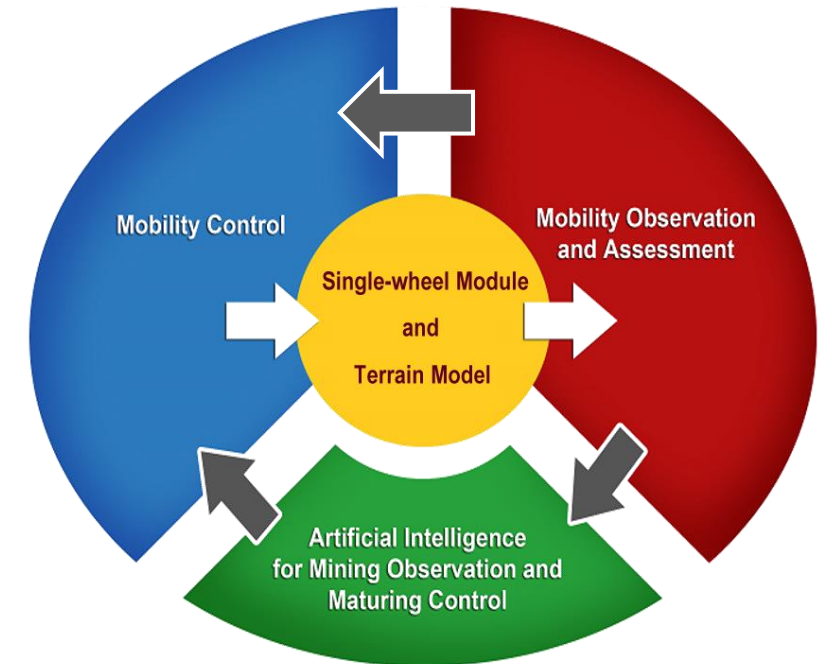
Conclusion and Future Work

- **Agile Control System Solution**

- ❑ Designed a superimposed mobility control algorithm combining robust feedback controller and fuzzy logic corrector
- ❑ Provided a robust force/torque filed estimation
- ❑ The coupled mobility control algorithm and force/torque filed estimation provided an agile solution able to respond faster than the tire relaxation time to terrain stochastic behavior and temporal transitions
- ❑ Using an inverse dynamics approach, linked the wheel normal reaction to trafficability prediction and provided the boundaries for normal reaction force

- **Future Work**

- ❑ Develop an AI to solve an on-line optimization problem to determine current reference velocity magnitudes at each time moment
- ❑ Define a performance metric of the controller and establish a feedback to the RL-algorithm for self-learning and maturing the controller and corrector's parameters



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Discussion Section

