Mobile robot control

Generic algorithm fo high accurate trajectory control in different conditions

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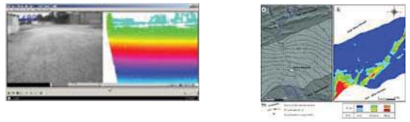
Introduction

Growing interest for autonomous vehicles for various application

- Transportation system
- Exploration
- Military application
- Work in different kind of environment
  - Civil engineering
  - Forestry
  - Agriculture

Different contexts requiring different behaviors and configurations

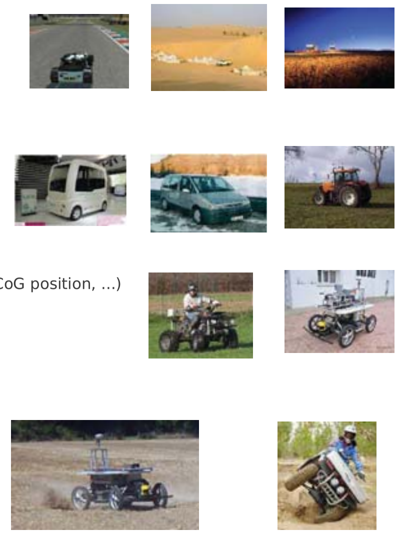
- Sensor – perception system
- Navigation strategy
- ***Control law***



Introduction

A variety of environment impacting robot dynamics

- Environments and terrain properties
  - Structured/unstructured environment
  - Nature of soil – grip conditions
  - Terrain geometry (regularity, slope, …)
- Robot design and capabilities
  - Velocity
  - General robot design (0/2/4WS, 2/4WD, …)
  - Design parameters (length, mass, inertia, CoG position, …)
  - Actuator properties and capabilities
- Phenomena to be accounted?
  - Sliding influence
  - Inertial effects
  - Dynamic stability
  - Robot controllability
  - Traversability and obstacles



Introduction

Robot dynamics to be accounted with respect to the context

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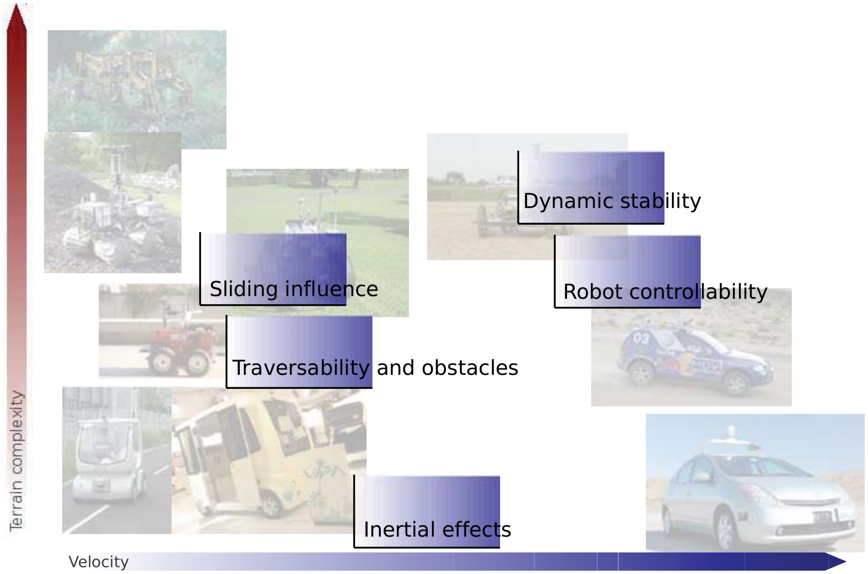
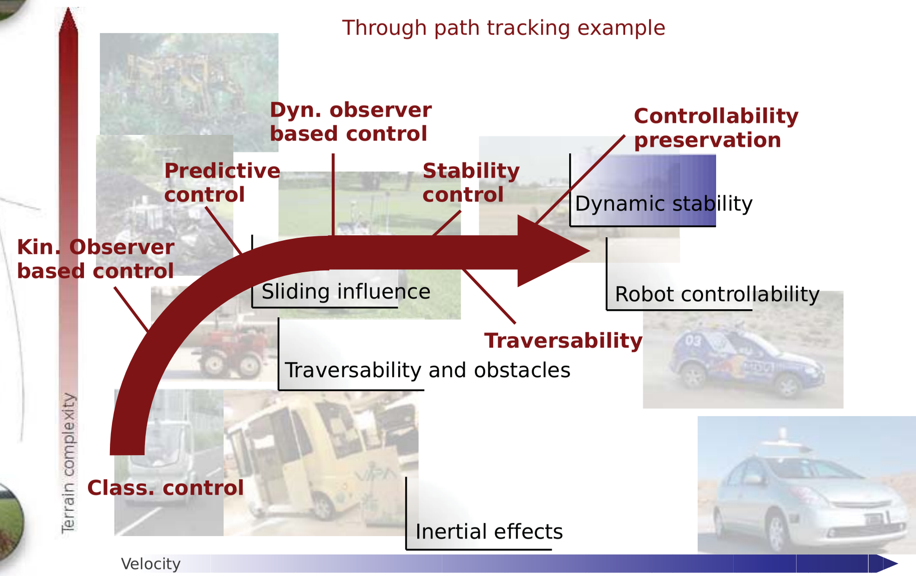


Introduction

Robot dynamics to be accounted with respect to the context

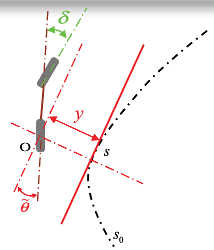
Through path tracking example



Classical path tracking control

Classical kinematic model

- Based on rolling without sliding assumption
- Can be turned into linear form



$$\begin{cases}\dot{s} = v\,\frac{\cos(\tilde{\theta}+\delta_R)}{1-c(s)\,y}\\ \dot{y} = v\,\sin(\tilde{\theta}+\delta_R)\\ \dot{\tilde{\theta}} = v\left[\cos(\delta_R)\frac{\tan(\delta_F)-\tan(\delta_R)}{L} - \frac{c(s)\cos(\tilde{\theta}+\delta_R)}{1-c(s)\,y}\right]\end{cases}$$

Control law design

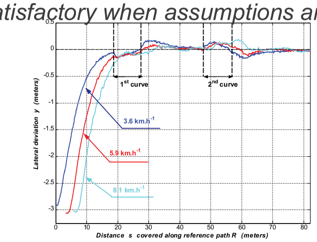
- Built in linear state space
- Objective is to ensure convergence of lateral and angular error to 0
- Reverse transformation leads to non linear control expression

$$\delta_{RSG}(y,\tilde{\theta}) = \arctan\Big(L\Big[\frac{\cos^3\tilde{\theta}}{(1-c(s)y)^2}\Big(\frac{dc(s)}{ds}y\tan\tilde{\theta} - K_d(1-c(s)y)\tan\tilde{\theta} - K_p y + c(s)(1-c(s)y)\tan^2\tilde{\theta}\Big) + \frac{c(s)\cos\tilde{\theta}}{1-c(s)y}\Big]\Big)$$

- Under the assumption that velocity is a known variable
- Result theoretically independent from velocity
- Control gains tune a settling distance

Classical path tracking control

Satisfactory when assumptions are valid



Classical path tracking control

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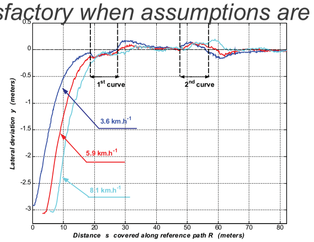
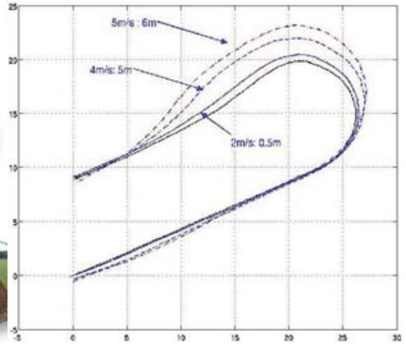
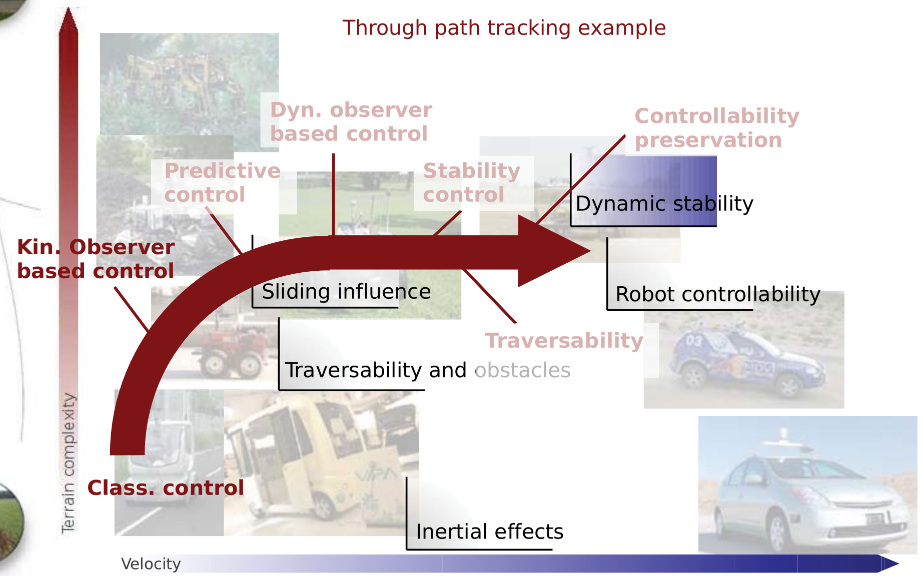


Unsuitable when running on natural ground [depends on speed!]



Sliding integration at low speed

Robot dynamics to be accounted with respect to the context

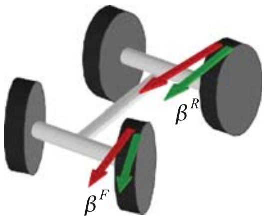


Sliding integration at low speed

Extended kinematical approach

- Introduction of sideslip angles in kinematics [Iros04]
  - β^F Front sideslip angles
  - β^R Rear sideslip angles

➡ **Tire-Based Kinematic Model (TBKM)**



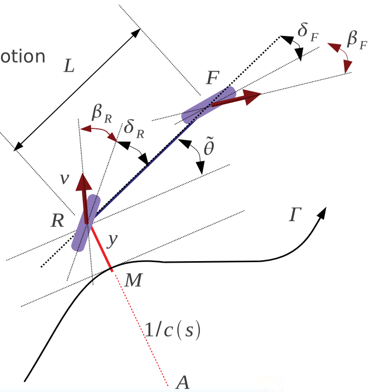
- ➞ Grip conditions viewed as part of model
- ➞ Representative of sliding effect on vehicle motion
- ➞ Preserve the "non-holonomic" notion

$$\begin{cases} \dot{s} = V_r \frac{\cos(\tilde{\theta}+\delta_R-\beta_R)}{1-c(s)\,y} \\ \dot{y} = V_r \sin(\tilde{\theta}+\delta_R-\beta_R) \\ \dot{\tilde{\theta}} = V_r\left[\cos(\delta_R-\beta_R)\lambda_1-\lambda_2\right] \end{cases}$$

- ➞ Provided sideslip angles control is similar

$$\delta_F = \arctan\left\{\tan(\delta_R-\beta_R)+\frac{L}{\cos(\delta_R-\beta_R)}\left(\frac{c\cos\tilde{\theta}_2}{\alpha}+\frac{A\cos^3\tilde{\theta}_2}{\alpha^2}\right)\right\}+\beta_F$$

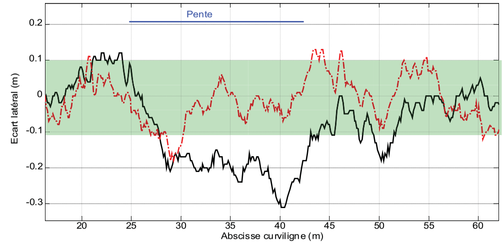
$$\begin{cases} \tilde{\theta}_2 = \tilde{\theta}+\delta_R-\beta_R \\ \alpha = 1-cy \\ A = -\frac{K_p^2 y}{4}-K_d\,\alpha\tan\tilde{\theta}_2+c\,\alpha\tan^2\tilde{\theta}_2 \end{cases}$$



Sliding integration at low speed

Validation on straight-line following on slope

- Validation on tractor (5km/H)



Sliding integration at low speed

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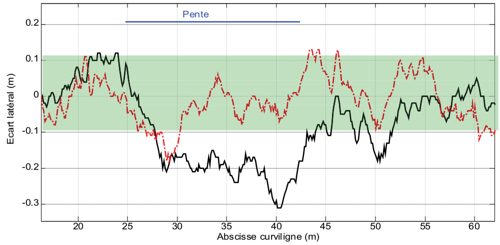
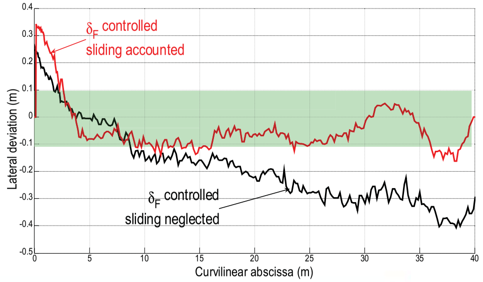
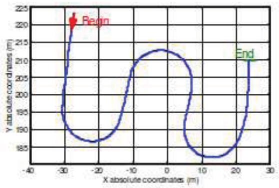


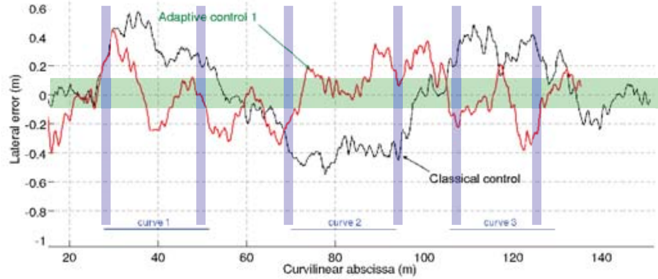
- Validation on Arroco (5km/H)



Sliding integration at low speed

- Tracking at 5km/H

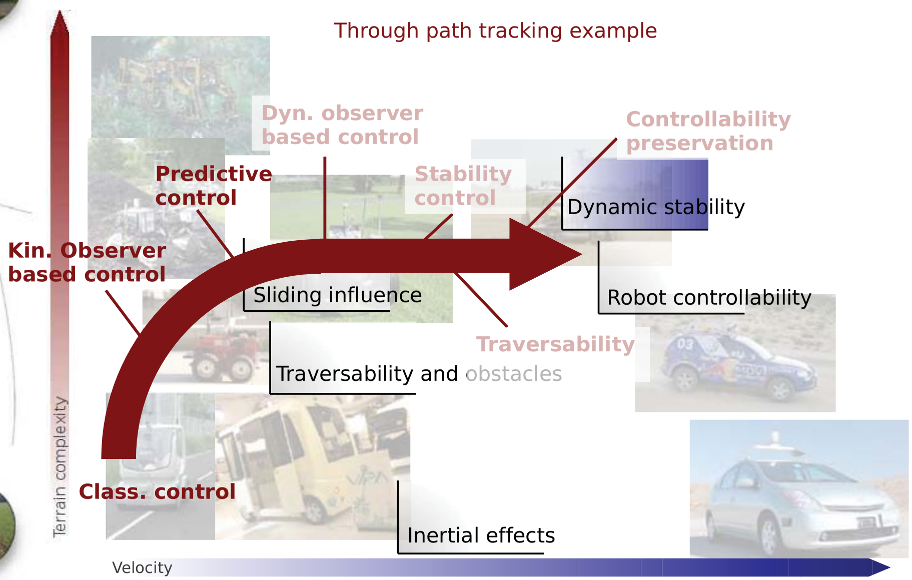




- Satisfactory in steady state (constant curve)
  - Constant slope
  - Constant curve
- Non negligieble overshoots during transition
  - Low level delay
  - Inertial effects

Anticipation of delays (actuator/inertial)

Robot dynamics to be accounted with respect to the context



Anticipation of delays (actuator/inertial)

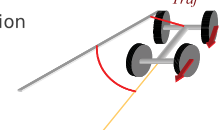
Anticipation of transition in ref path curvature [AutonRobots2006, Icra2008]

- Decomposition of control law expression

$$\delta = \delta_{Traj} + \delta_{Deviation}$$

- Terms attached to deviations sliding compensation

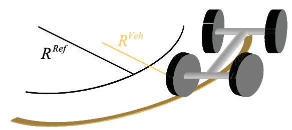
$$\delta_{Deviation} = \arctan\left(\frac{v}{1+uv+u^2}\right) \qquad v = \frac{L}{\cos\beta^R} A \frac{\cos^3\theta_2}{\alpha^2} + \tan\beta^R$$



➡ **Has to be reactive (no prediction available)**

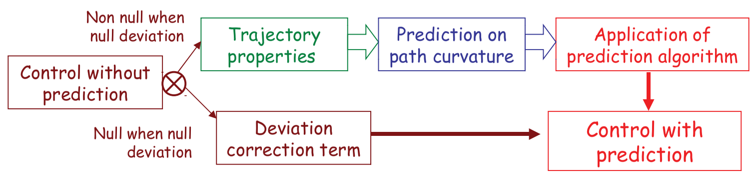
- Terms attached path curvature following

$$\delta_{Traj} = \arctan(u) \qquad u = \frac{L}{\cos\beta^R} c(s) \frac{\cos\theta_2}{\alpha}$$



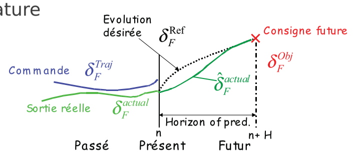
➡ **Can be predicted (knowledge of the reference path)**

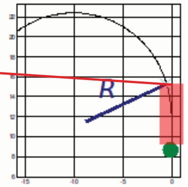
- Predictive and adaptive control algorithm



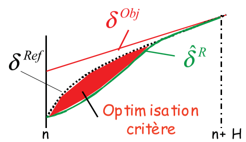
Anticipation of delays (actuator/inertial)

- Predictive term calculation:
  - Extraction of future set point attached to path curvature





  - Definition of desire shape to reached the set point
  - Computation of minimizing control sequence
  - Based on low level model

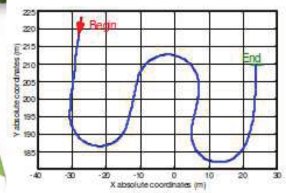


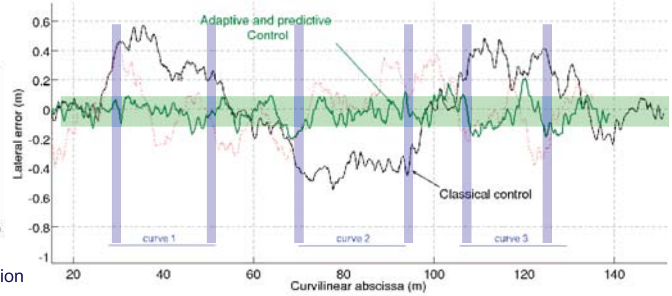
- Adaptive and predictive control law

$$\delta = \delta_{Traj}^{Pred} + \delta_{Deviation}$$

Anticipation of delays (actuator/inertial)

- Tracking at 5km/H



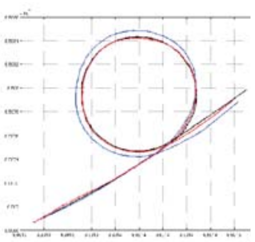


- Satisfactory whatever the variation

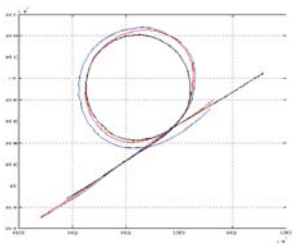
Anticipation of delays (actuator/inertial)

Reactivity of sliding estimation based on extended kinematic is limited

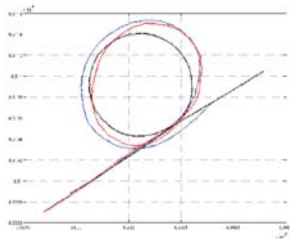
- 2m/s : 0.1m



- 3m/s: 0.5m



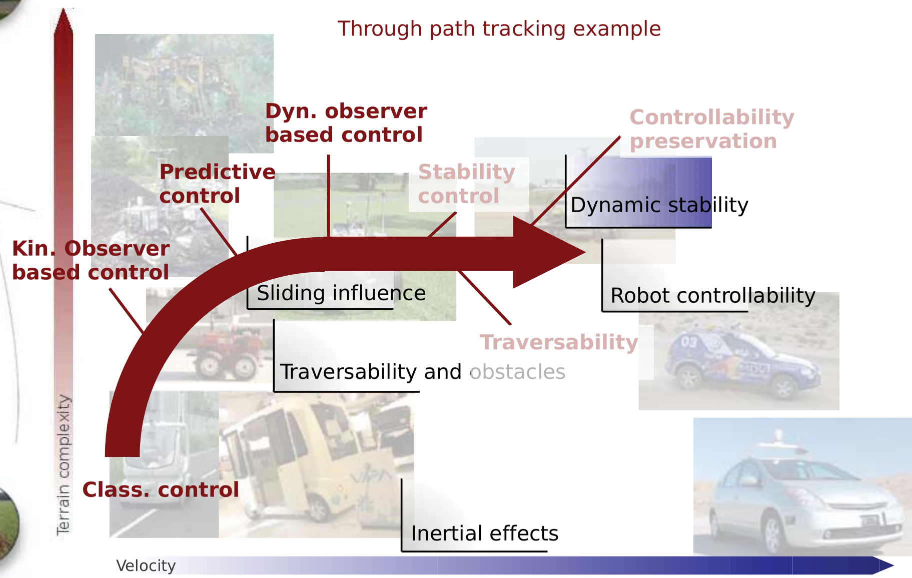
- 4m/s : 1m



Dynamic observer based motion control

Robot dynamics to be accounted with respect to the context

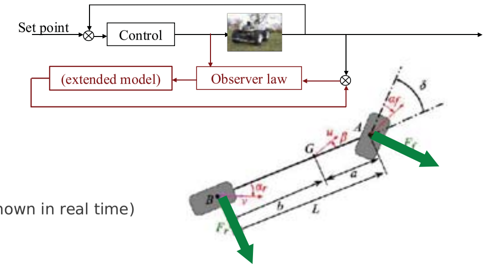
Through path tracking example

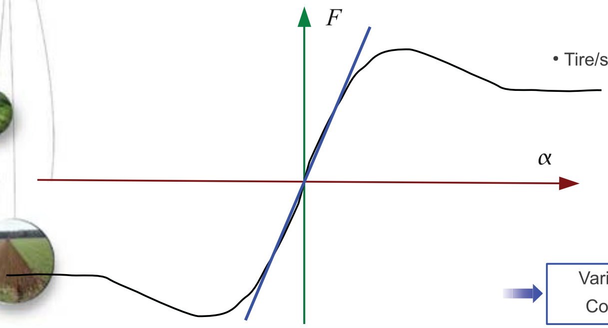


Dynamic observer based motion control

New observer design

- Extended kinematic observer
  - Accurate
  - Slow reactive (dynamic neglected)
- Dynamic model based observer
  - More reactive
  - Not accurate (grip conditions to be known in real time)





- Tire/soil model depends on 14 param.
  - Ground properties
  - Vertical load
  - Tire properties

Not Tractable for control purpose

Variable Linear Description
Cornering stiffnesses

Dynamic observer based motion control

Principle

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  - Accurate
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- Dynamic model based observer
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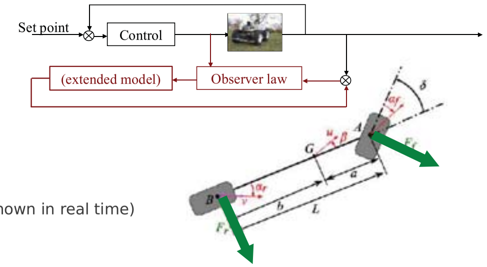

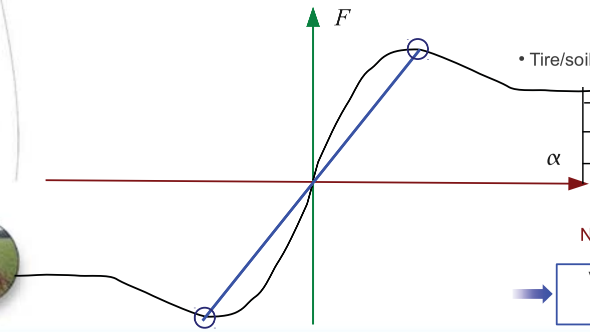

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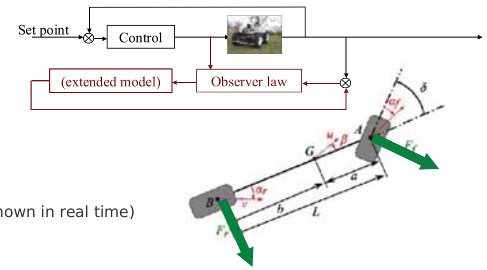
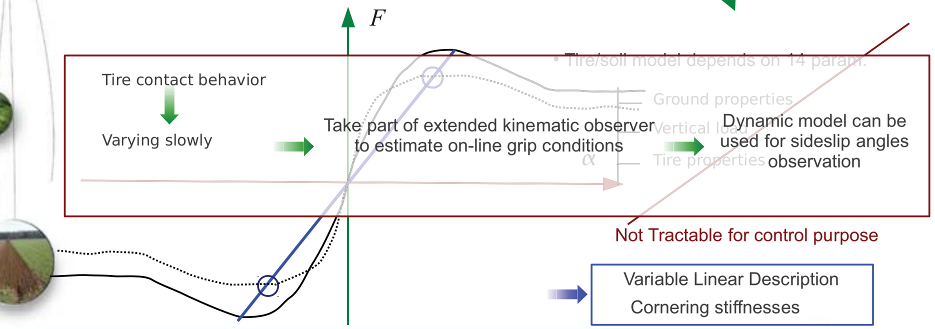




Tire contact behavior → Varying slowly → Take part of extended kinematic observer to estimate on-line grip conditions → Dynamic model can be used for sideslip angles observation

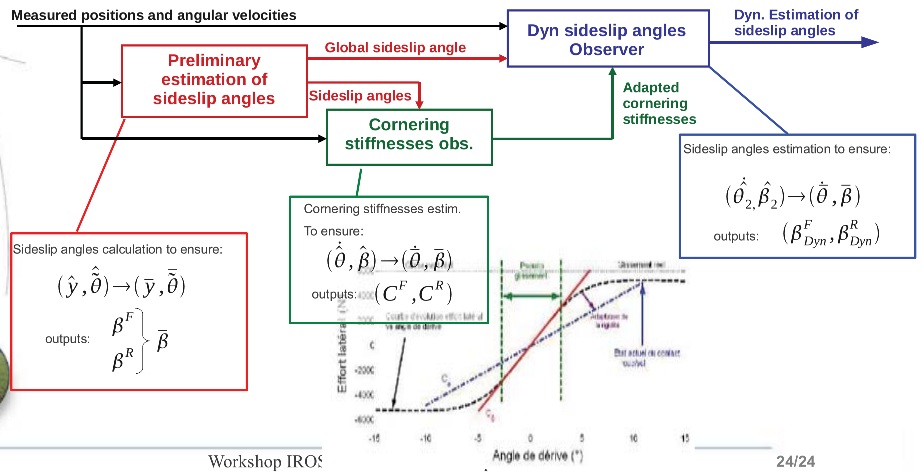
Not Tractable for control purpose

Variable Linear Description
Cornering stiffnesses

Dynamic observer based motion control

Proposed algorithm: Mixed-model observers

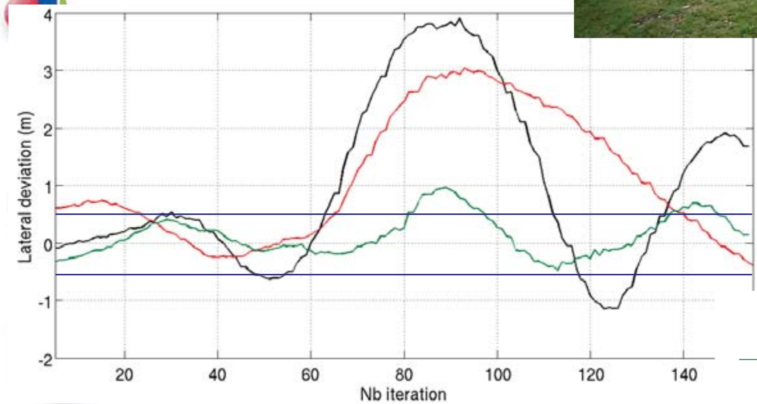
- Decomposed in several steps
  - S1: Preliminary sideslip angles observer.
  - S2: Cornering stiffnesses adaptation
  - S3: Sideslip angles observation based on dynamic model



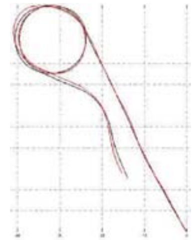
Dynamic observer based motion control

Path tracking results

- Experimental background
  - grass terrain
  - Velocity of 6m/s
  - Half-turn path tracking



Dynamic observer based motion control



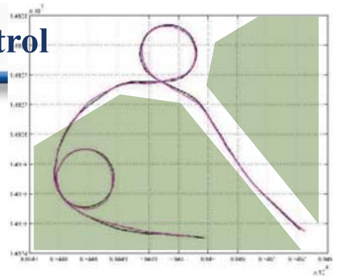
Velocity of 6m/s

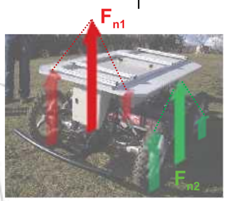
Max dev: 0.9m (max st angle)

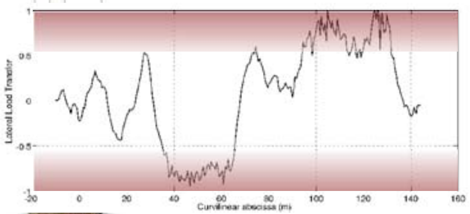
Dynamic observer based motion control

Good accuracy, but stability is at the limit

- Motion control without considering stability/achievability
  - Lateral load transfer considered and computed
  - Reaches high values (2 wheels lift-off)



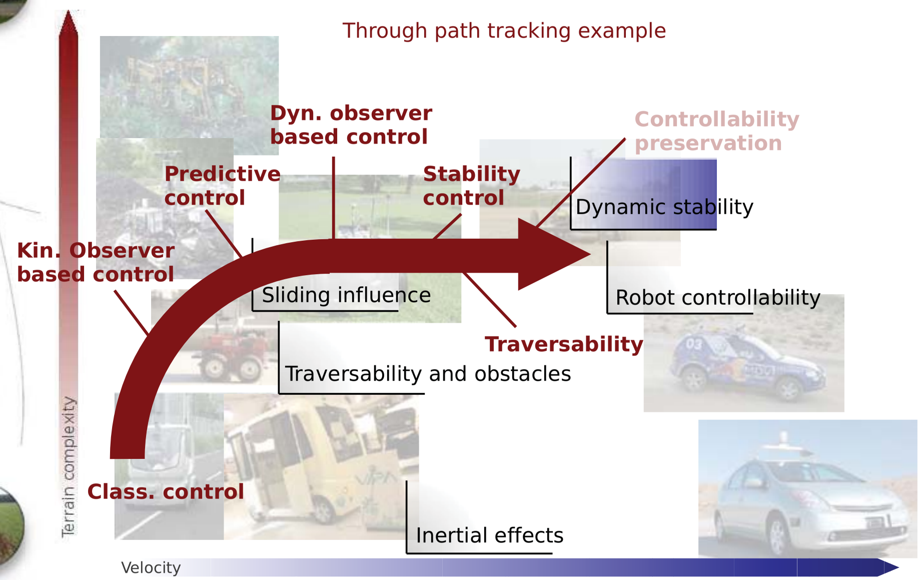




Dynamic observer based motion control

Robot dynamics to be accounted with respect to the context

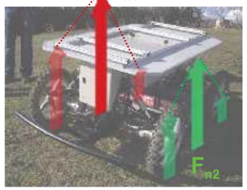
Through path tracking example

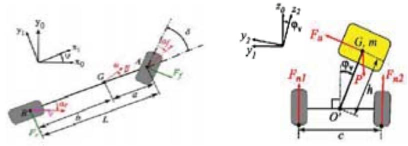


Dynamic stability preservation

Moderation of robot speed is investigated

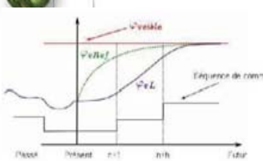
- Predictive control is applied to compute maximal velocity
  - An limit for Lateral Load Transfer is chosen
  - Velocity leading to this LLT threshold is computed



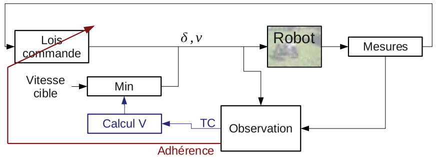


$$TC_l = f\,(EtatRobot)$$

Objective : $|TC_l| < TC^{max}$



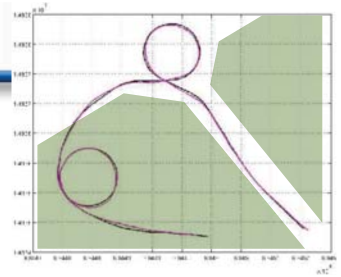
Applied control : $v = min(v_{max}, v_{consigne})$

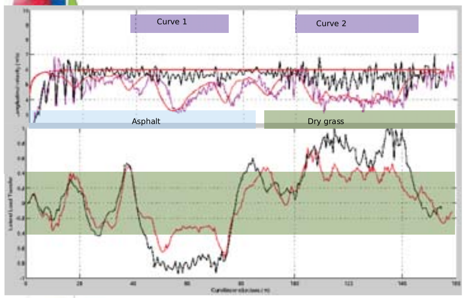


Dynamic stability preservation

Maximal velocity considered to limit LLT

- Robot slow down when a risk is anticipated
  - Velocity reaching to LLT limit computes
  - Minimum between maximal and desired is applied



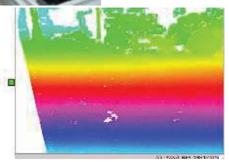


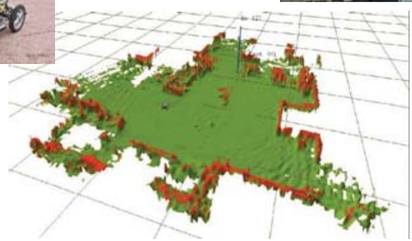
Extension to traversability – obstacle avoidance

Considering that a MNT reconstruction is available

Stereo-vision

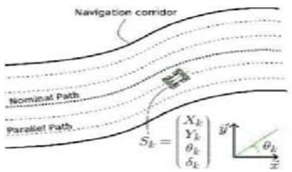
Velodyne



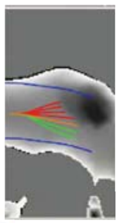


Stability is considering in front of the robot

- Generation of a fixed number of lateral off-set along trajectory



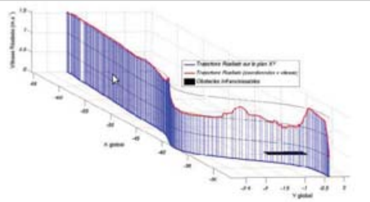
- Definition of trajectories to reach these offset



Extension to traversability – obstacle avoidance

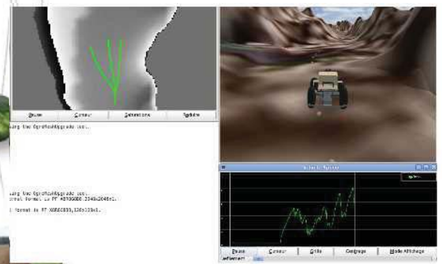
Stability is considering in front of the robot

- Evaluation of maximal speed along generated paths
- Selection of « optimal path »
  - Deviation with respect to the reference path
  - Deviation with respect to the desired speed



Results

- Simulation (MNT at high speed)

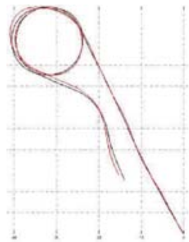


- Experimentation (limited speed)

Dynamic stability preservation

Rollover risk is not the unique sense of stability

- Motion control does not check
  - Reference path achievability (computed or manually recorded at low speed)
  - Robot controlability pending on environment (e.g grip conditions/speed)
  - Transient deviation possibly above desired max error
- Example of controlability loss



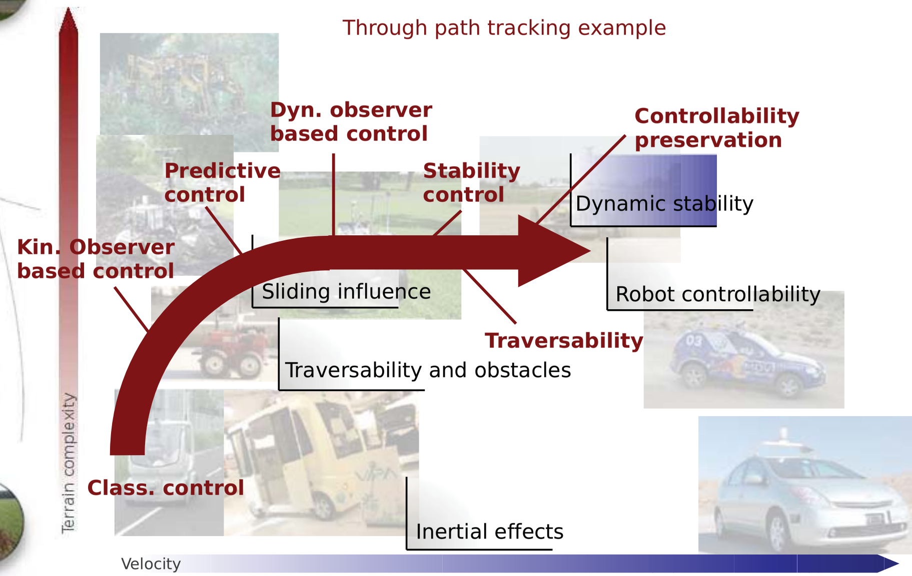
Achiveable at 6m/s [1m because St angle]

Stab loss at 7m/s

Controllability preservation...

Robot dynamics to be accounted with respect to the context

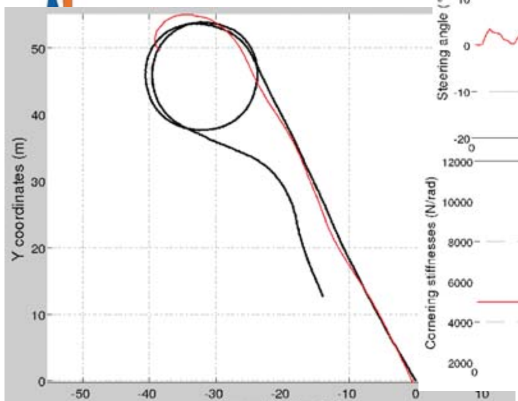
Through path tracking example

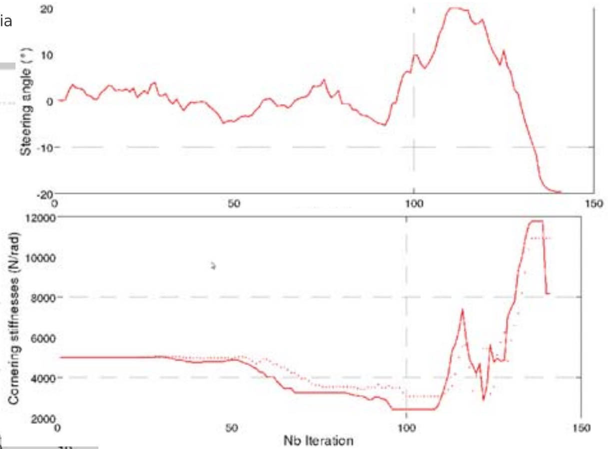


Controllability preservation...

Desired path even recorded is no more achievable at high speed

- Required high steering angle
  - The fastest, the lowest grip conditions
  - Mobile robot inertia





- Maximal achievable steering angle reached

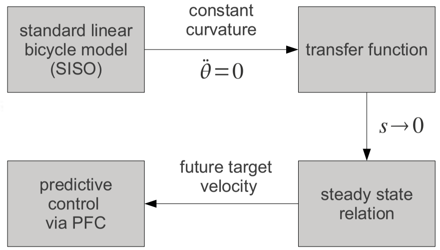
➡ ***Steering angle limit viewed as an achievability criterion***

Controllability preservation...

Objective of the controllability preservation

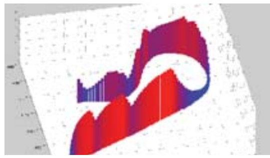
- Derive the maximal velocity
- Leading to a steering angle limit

Computation of the relationship between steering angle and velocity



$$v=-\left(c\,m(C_f L_f - C_r L_r)\right)^{-1} - \left(c\,m\,C_f C_r (L_f+L_r)(C_f L_f - C_r L_r)\left[c(L_f+L_r)-\delta_f\right]\right)^{1/2}$$

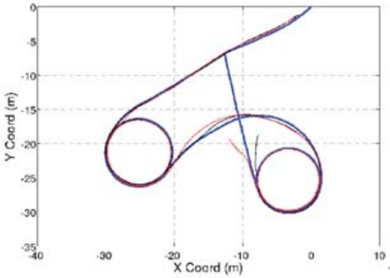
- Future desired path curvatures
- Current grip conditions

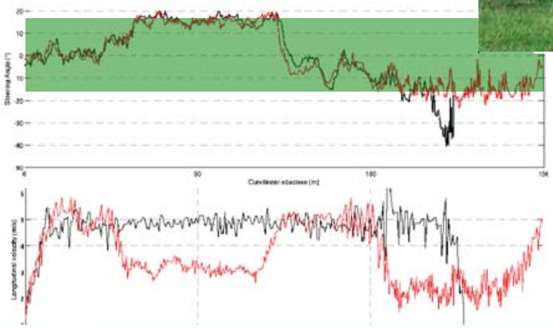


Computation of velocity profile

Controllability preservation...

Saturation set to 17°





- Without speed limitation
- Applying speed limitation

Summary

Off-road path tracking algorithm

- Generic approach to meet different kind of robots
- Preserving a high level of accuracy
  - Grip conditions
  - Terrain geometry
  - Delay and dynamical effects
  - Robot speed
- Preserving its integrity
  - Traversability
  - Dynamic stability

Terrain geometry reconstruction
Obstacle avoidance

Longitudinal and lateral Rollover
Spin around situations

Summary

Several control law for advanced path tracking

- *Adaptive and predictive control*
- *High accuracy despite grip conditions*
- *On several and widely different robot*

Limited number of measures

- *Only position and orientation is needed*
  - Adaptive and predictive control
  - 4WS and trailer control
- *Yaw rate may be required*
  - Half turn (has speed cross 0)
  - High speed (to feed dynamic equations)

Current developments

- *Perception system (avoid RTK-GPS)*
- *Account for robot limitations*
- *Ensure the robot performances*