Estimation challenges in planetary exploration rovers

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RML Robotic Mobility Lab

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RML Robotic Mobility Lab

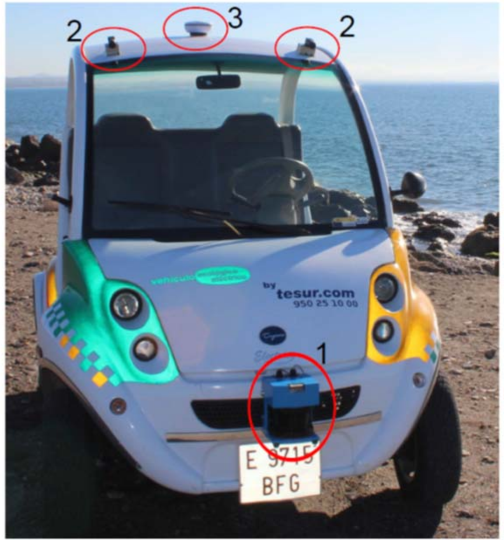
Research Interests:

- **Mobile robotics** for
  - Planetary exploration
  - Agriculture
- Vehicle dynamic modelling and estimation
- Advanced driving assistance systems (ADAS) towards self-driving vehicles
- New: Biomedical devices

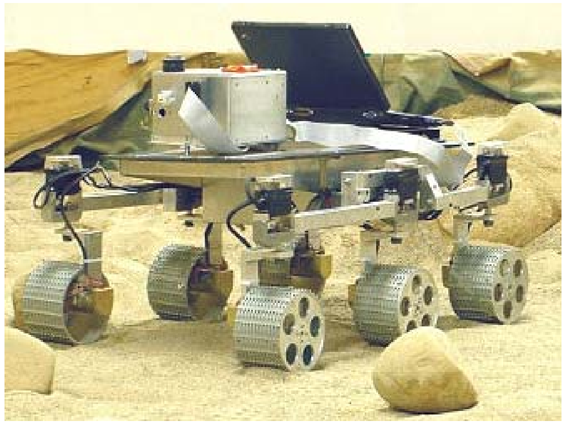
Advanced Mobile Robotics

- Navigation in challenging environments, including planetary surfaces and agricultural settings
- Mechanics of wheel/terrain interaction drawing from **Terramechanics** theory
- **State and parameter estimation**
  - Automated online estimation of motion states and key parameters of vehicle/terrain (e.g., **terrain awareness**)
- Identification of terrain regions that can be safely traversed

In-road → **Off-road**

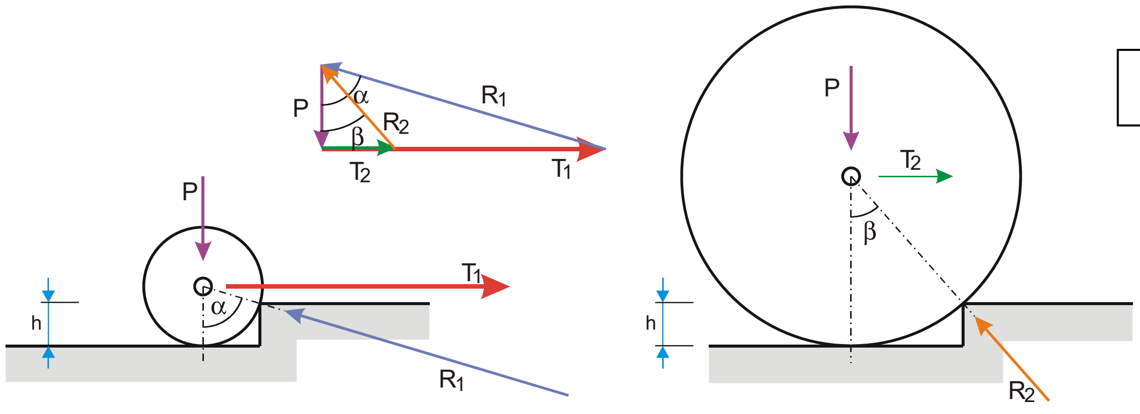


CLAAS AXION 840 4WD



Wheeled robots

- Limitations on irregular terrains



$\cos\alpha = 1 - h/r$

<u>Rule of thumb</u>: obstacles higher than wheel radius can not be climbed !!

Alternatives

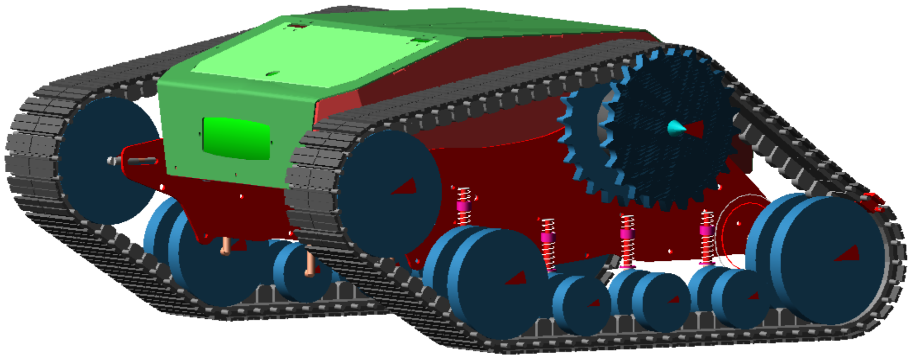
- Track-based locomotion

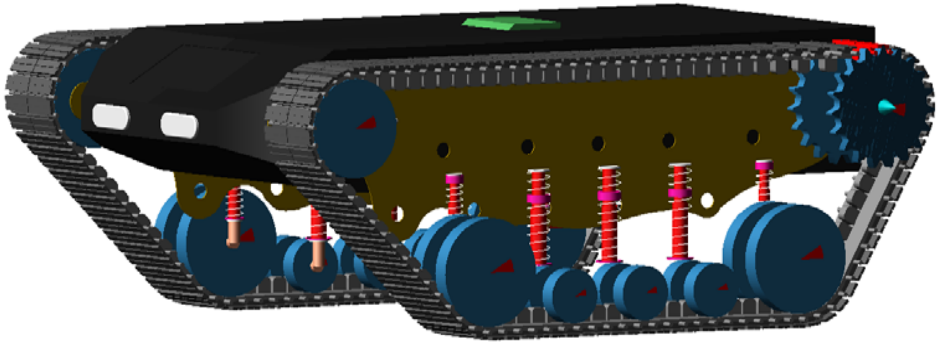
MAXX II – Fixed wheels

Alternatives cont'ed

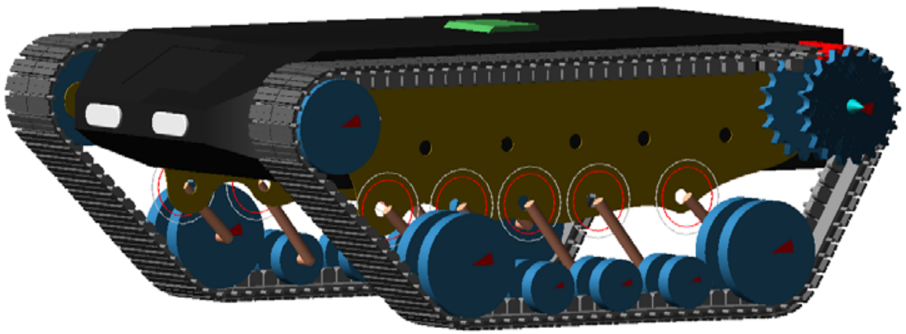
- Suspended wheels

a) Vertical spring and dampers





b) Torsion bars

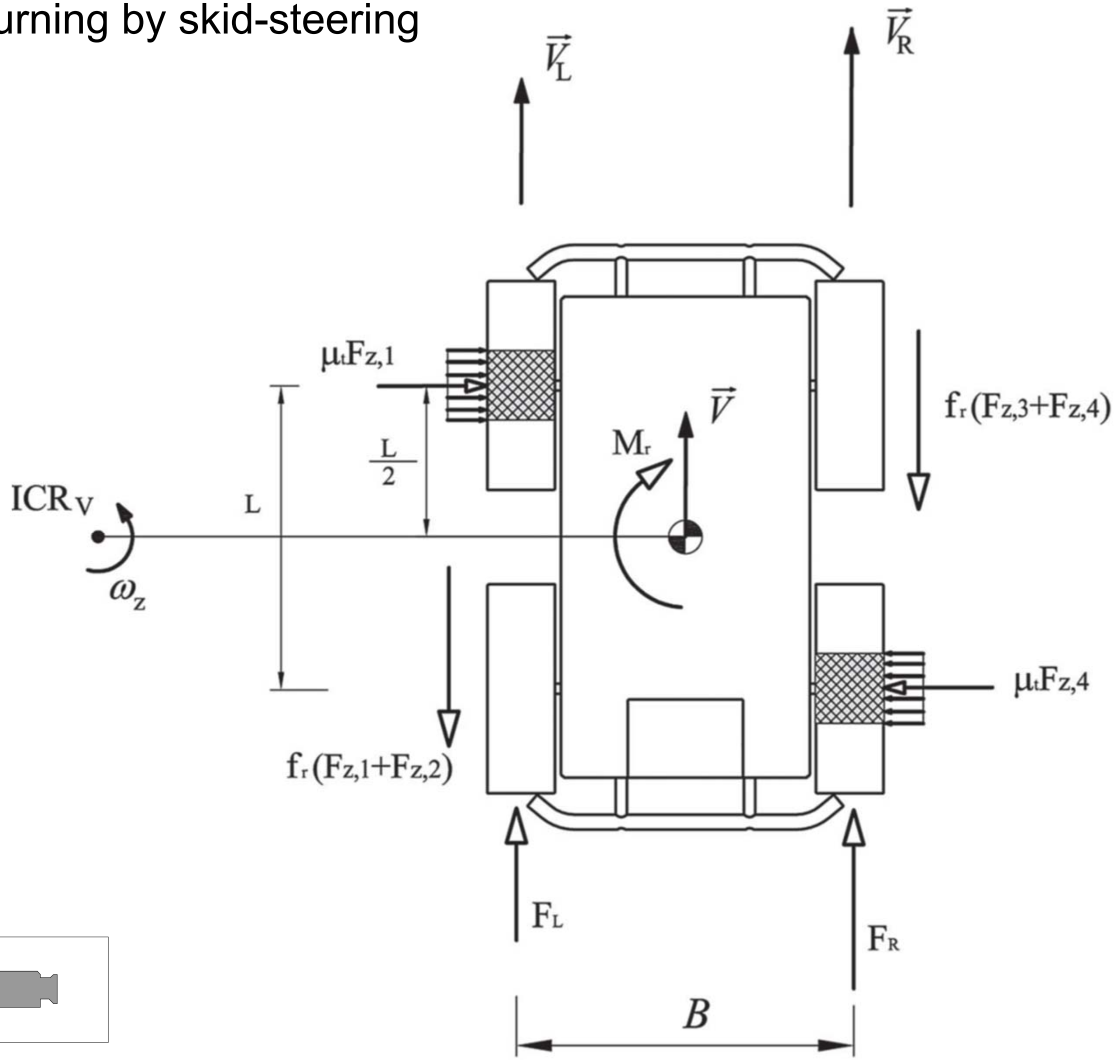


Alternatives cont'ed

https://www.youtube.com/watch?v=JoJ-8MdYjyc

Alternatives cont'ed

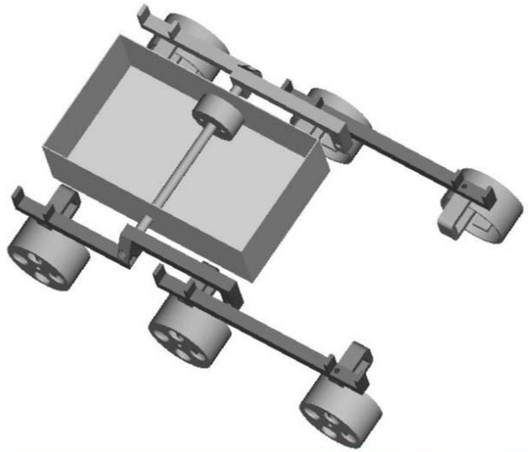
Issue: Turning by skid-steering

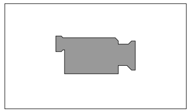


NASA/JPL's rovers

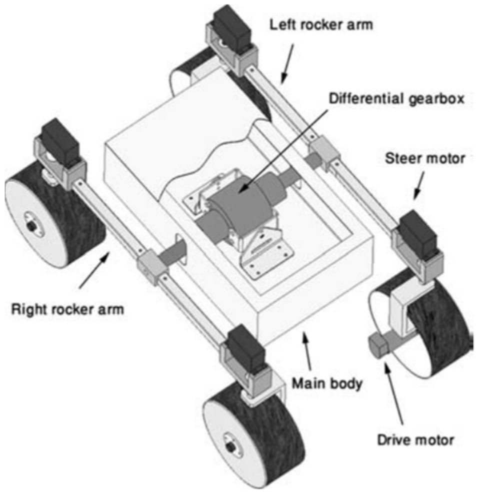
Rocky 8:

- 6 wheel/6-steer, rocker-bogie design
- Vehicle mass: 400 kg
- Manipulator: 1 m, Mini corer for 5 cm deep drilling
- Instrument deployment arm
- Communications: 40 Mbits/day = 20 Mbits/hr
- Energy availability: 2000-5000 W-hours
- Actual maximum speed envisaged: 6 cm/sec
- Dimensions: 2.9 m long, 3.6 m wide, Wheel: diameter=0.5 m, width=20-30 cm.
- Travel: 13 days dedicated to "*traverse days,*" 3 km/13 sols = 230 m/sol on average (rover will move only for about 4 hours/sol). Note: Sol = Mars day, about 23.5 hours.



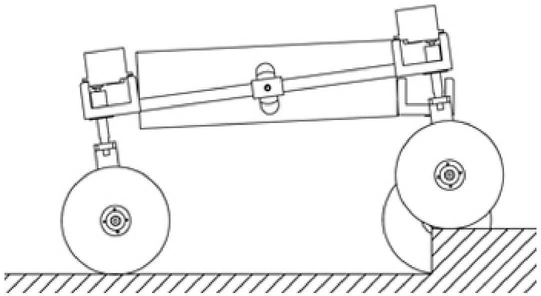


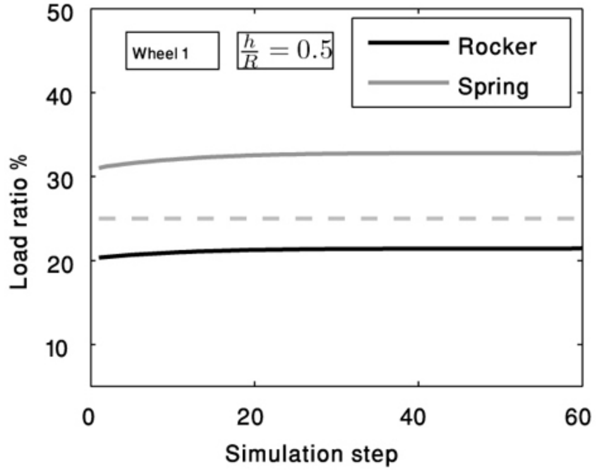
DUNE: 4-wheel drive 4-wheel steer rover employing a rocker-type suspension

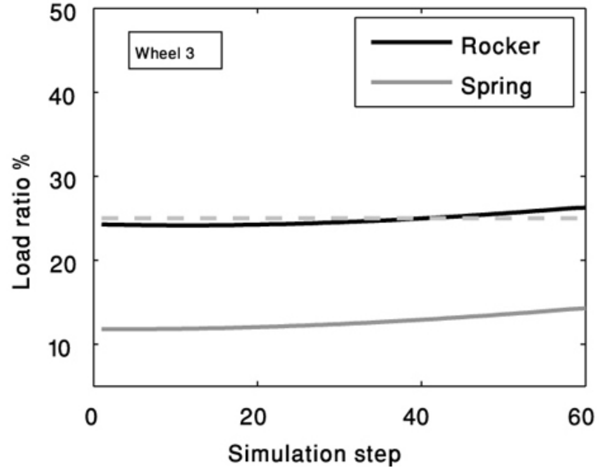


Rocker vs elastic suspension system

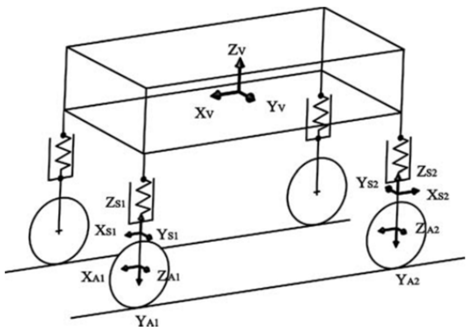
Rocker

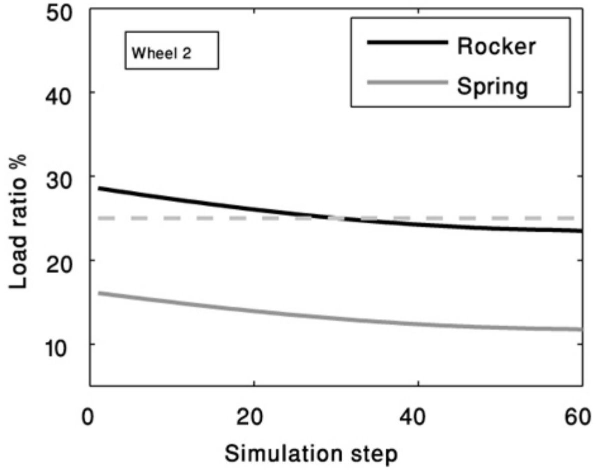


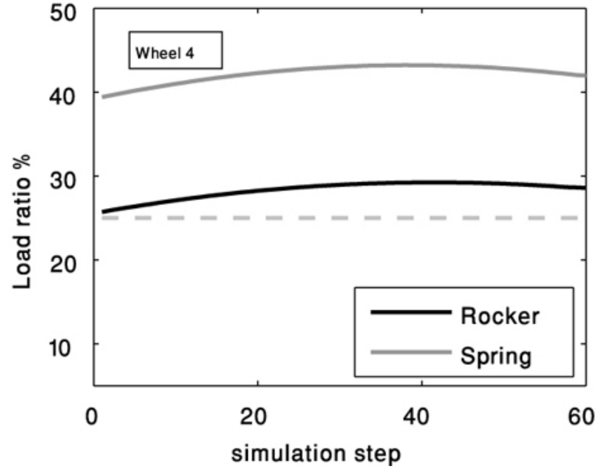




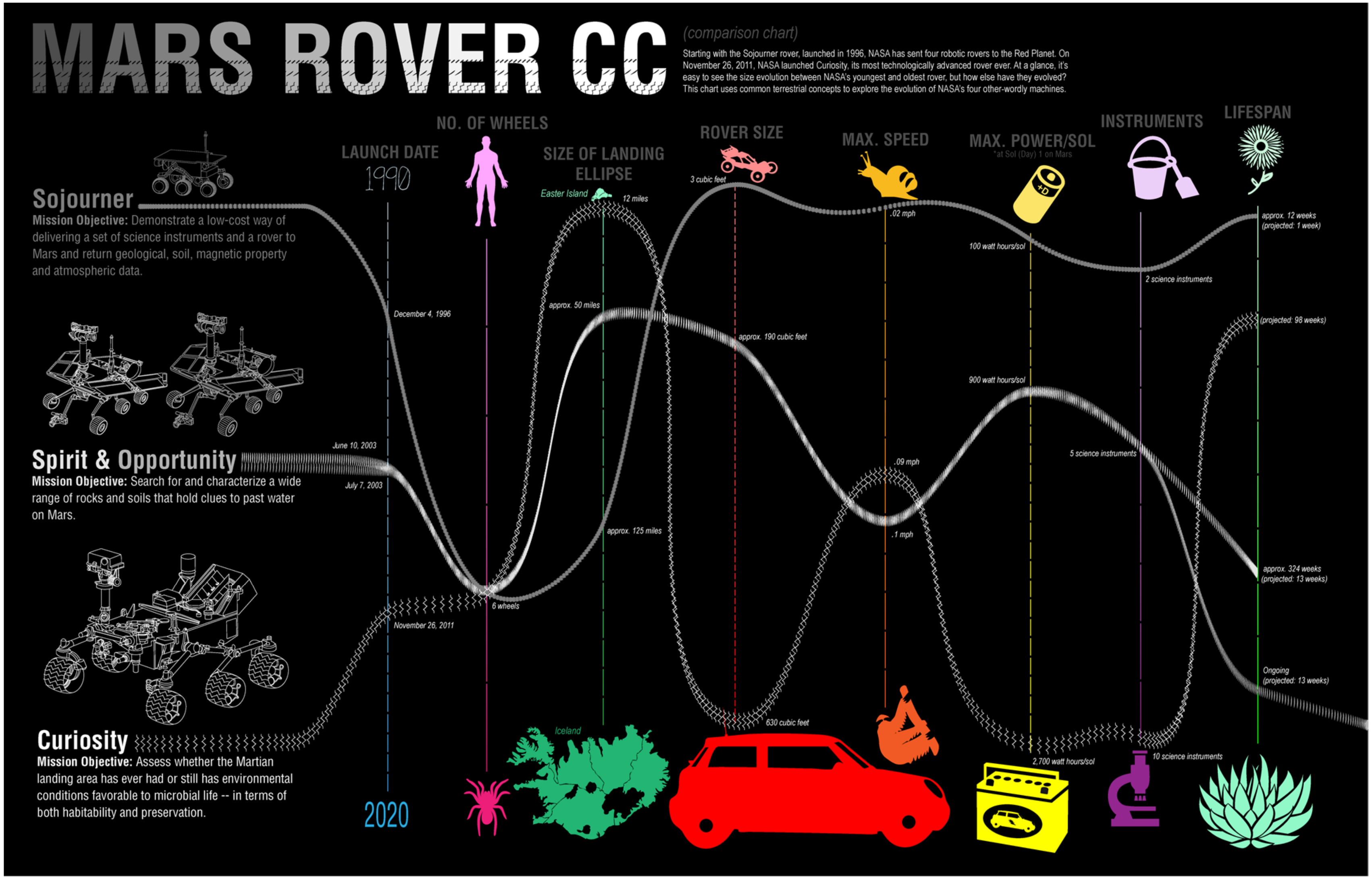
Elastic







Comparison chart



Sherpa rover

AUTONOMOUS DECISION MAKING IN VERY LONG TRAVERSES

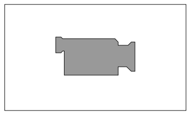
An H2020 project funded within Strategic Research Cluster on Space Robotics Technologies

German Research Center for Artificial Intelligence

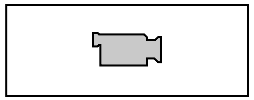
Estimation challenges

- **Mobile Robots** are increasingly being used in high-risk, **rough terrain situations**, such as reconnaissance, patrol, search and rescue applications, and planetary exploration.
- Conventional control and localization algorithms are not well suited to **uneven terrain**, since they generally do not consider the physical characteristics of the vehicle and its environment.
- Little attention has been devoted to the study of the **dynamic ill-effects** occurring at the wheel-terrain interface, including **slippage**.

These effects compromise the vehicle performance in terms of **odometry accuracy, traction ability, power consumption** leading to potential danger of entrapment with consequent mission failure



Sherpa

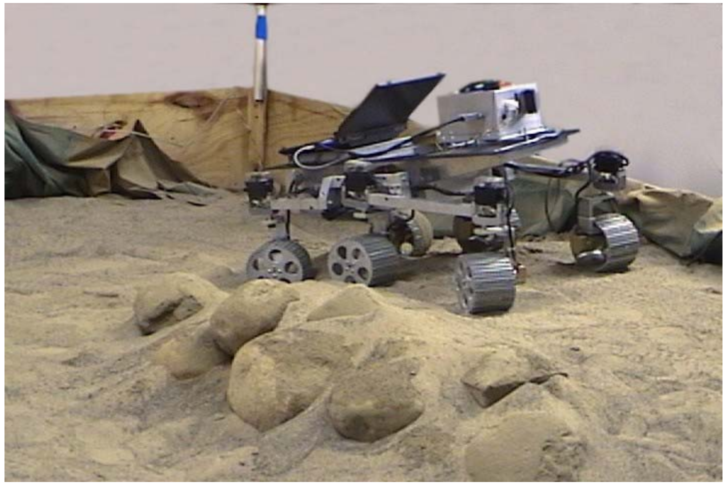


NASA

Solution: provide a planetary rover with **<u>terrain awareness</u>** ability

Slippage estimation

Improve odometry-based localization



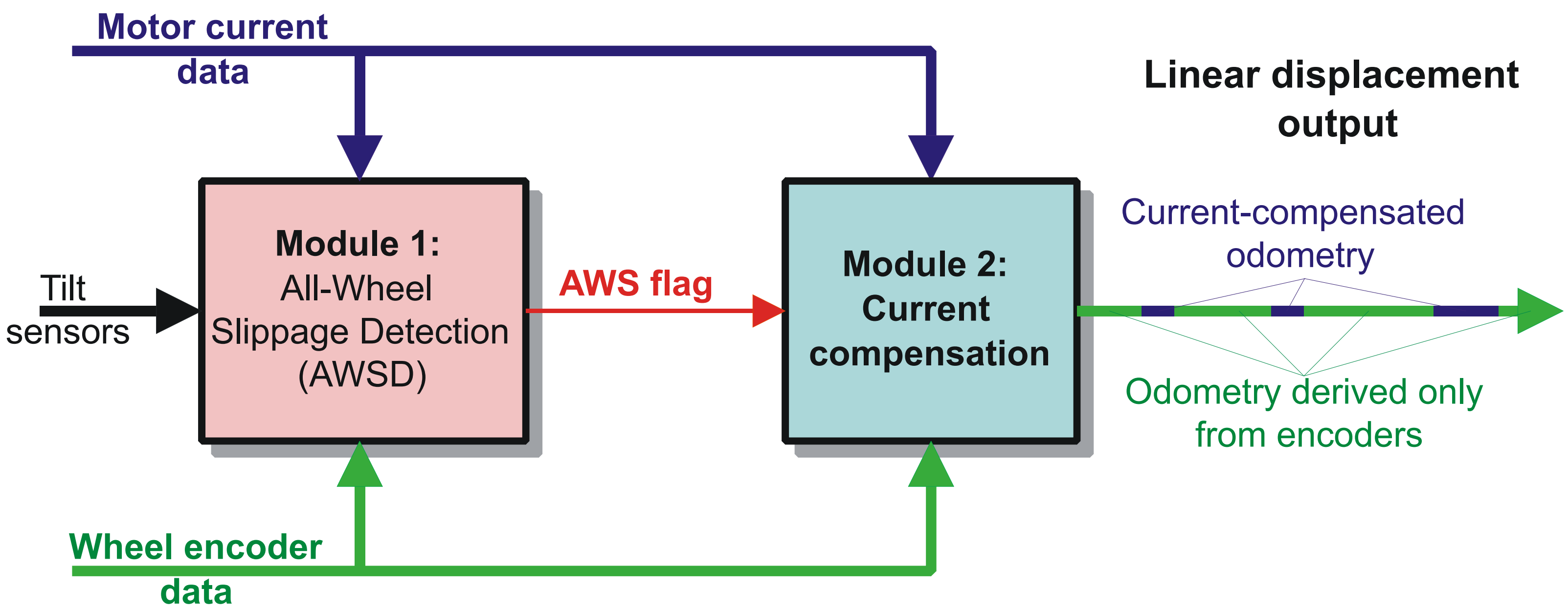
Six-wheeled Mars rover analogue
University of Michigan (NASA/JPL contract)

Four-wheeled Moon rover analogue
Tohoku University, Japan (JSPS Fellow)

Improve odometry-based localization

- **Wheel slip detection** based on observing different sensor modalities implemented onboard and defining deterministic conditions for **vehicle slippage** (AWSD)

- **Odometry correction** based on motor current measurements (iComp)
  - wheel slippage estimation from electrical current and correction of corrupted encoders readings accordingly

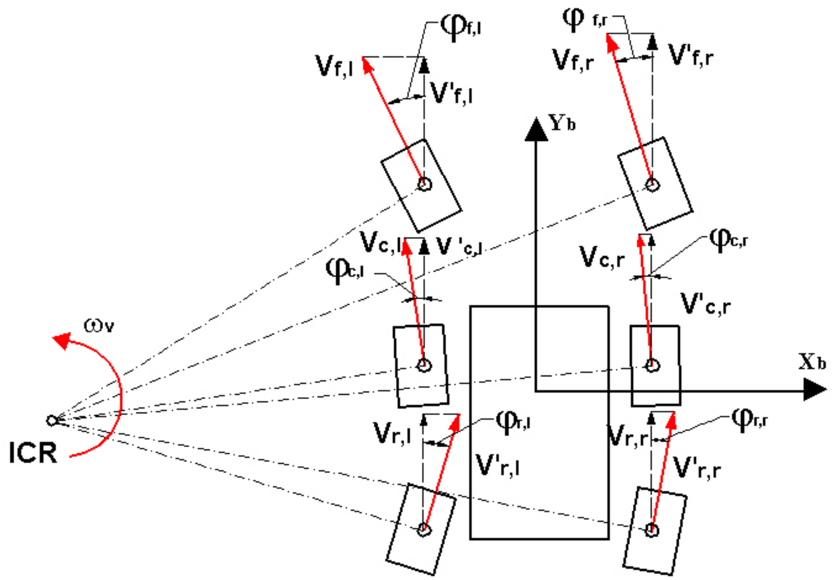


All Wheel Slippage Detection

- Encoder Indicator (EI) – compares encoder readings with each other
- Gyro Indicator (GI) – compares encoder readings with those of the gyro that measures rate-of-turn around the *z*-axis
- Current Indicator (CI) – monitors motor electrical currents, which are roughly proportional to the torque applied to each wheel

Encoder Indicator

- While the linear velocities of the wheels differ from each other according to their distance from the Instantaneous Center of Rotation (ICR) of the vehicle, their longitudinal components must be equal on either side of the vehicle
- Our hypothesis is that unequal speeds in the three wheels of a side suggest wheel slippage



No-slip maneuver

Left Side:

$$V'_{f,l} = V'_{c,l} = V'_{r,l}$$

Right Side:

$$V'_{f,r} = V'_{c,r} = V'_{r,r}$$

Encoder Indicator, cont'd

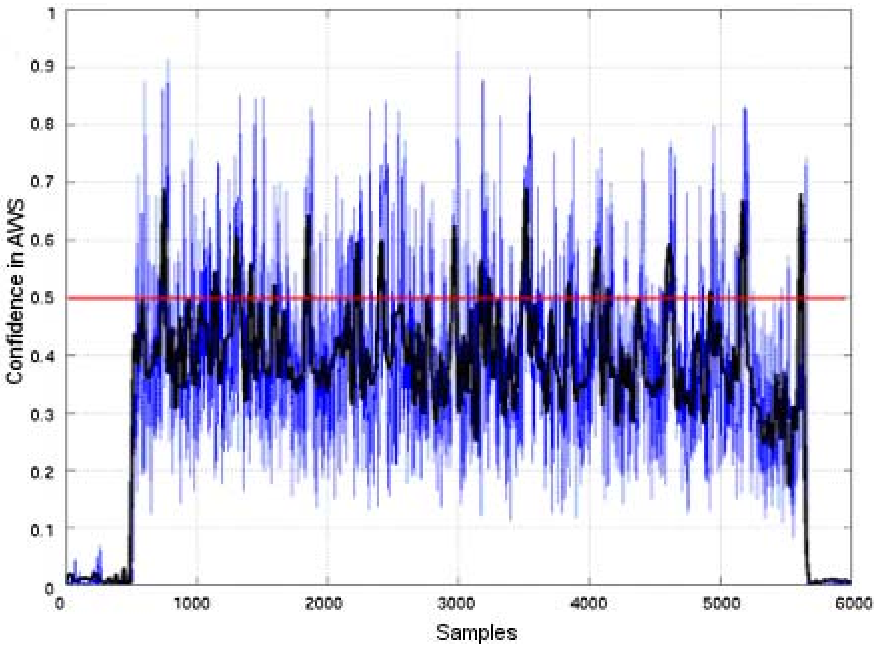
- In order to express this hypothesis mathematically, we adopted fuzzy logic that uses rules to map from inputs to outputs
- The Fuzzy inference system fuses the sensory information based on the rule set shown in Table 1, which implement our in-depth physical understanding of the behavior of the encoders

Table 1. Fuzzy Logic rules for the Encoder Indicator.

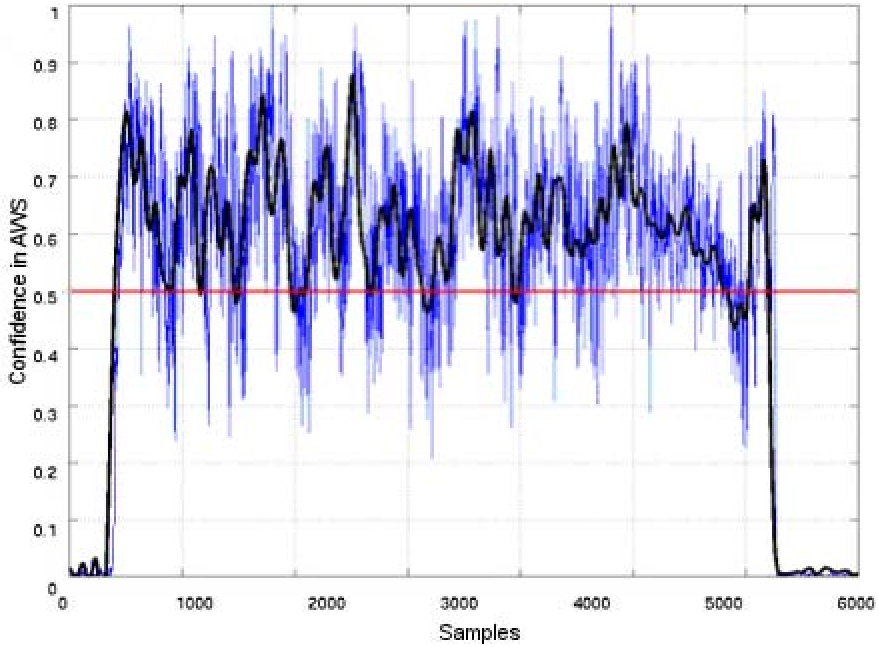
Rule	**Input:** Difference in longitudinal speeds between			**Output:** Confidence in AWS (low = vehicle gripping; high = vehicle slipping)
#	**Front-Center**	**Front-Rear**	**Center-Rear**	
1	Small	Small	Small	Low
2	Small	Small	Large	High
3	Small	Large	Small	Med.
4	Small	Large	Large	High
5	Large	Small	Small	Low
6	Large	Small	Large	Med.
7	Large	Large	Small	Med.
8	Large	Large	Large	High

Encoder Indicator, cont'd

- Output of the fuzzy logic system of the Encoder Indicator (blue line, the bold line shows the smoothed output):
  - for a high-traction terrain (Figure a)
  - and a high-slippage terrain (Figure b)



a) High traction terrain (no slippage)



b) Sloped, sandy terrain with substantial slippage

Gyro Indicator

- This method aims at detecting wheel slippage by comparing encoder data with gyro data.
- We can compute the rate-of-turn ω of the vehicle from each one of the three encoder pairs, identified by index *i*: the front, the center, and the rear pair, according to:

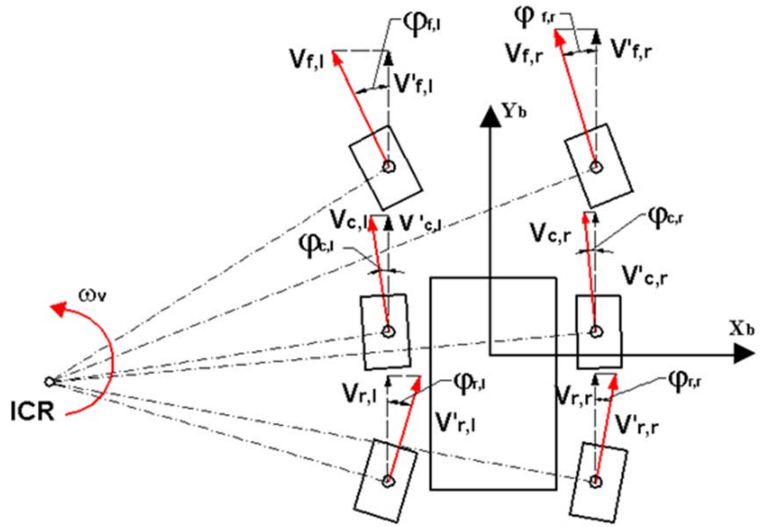
$$\omega_{Enc,\,i} = \frac{d_{i,r} \cdot \cos\varphi_{i,r} - d_{i,l} \cdot \cos\varphi_{i,l}}{b \cdot T}$$

$d_{i,\,r/l}$ - distance traveled by the right/left wheel of wheel pair *i*.

$\varphi_{i\,,r/l}$ - steering angle of the right/left wheel of wheel pair *i*.

b - vehicle width (distance between the left and right wheel).

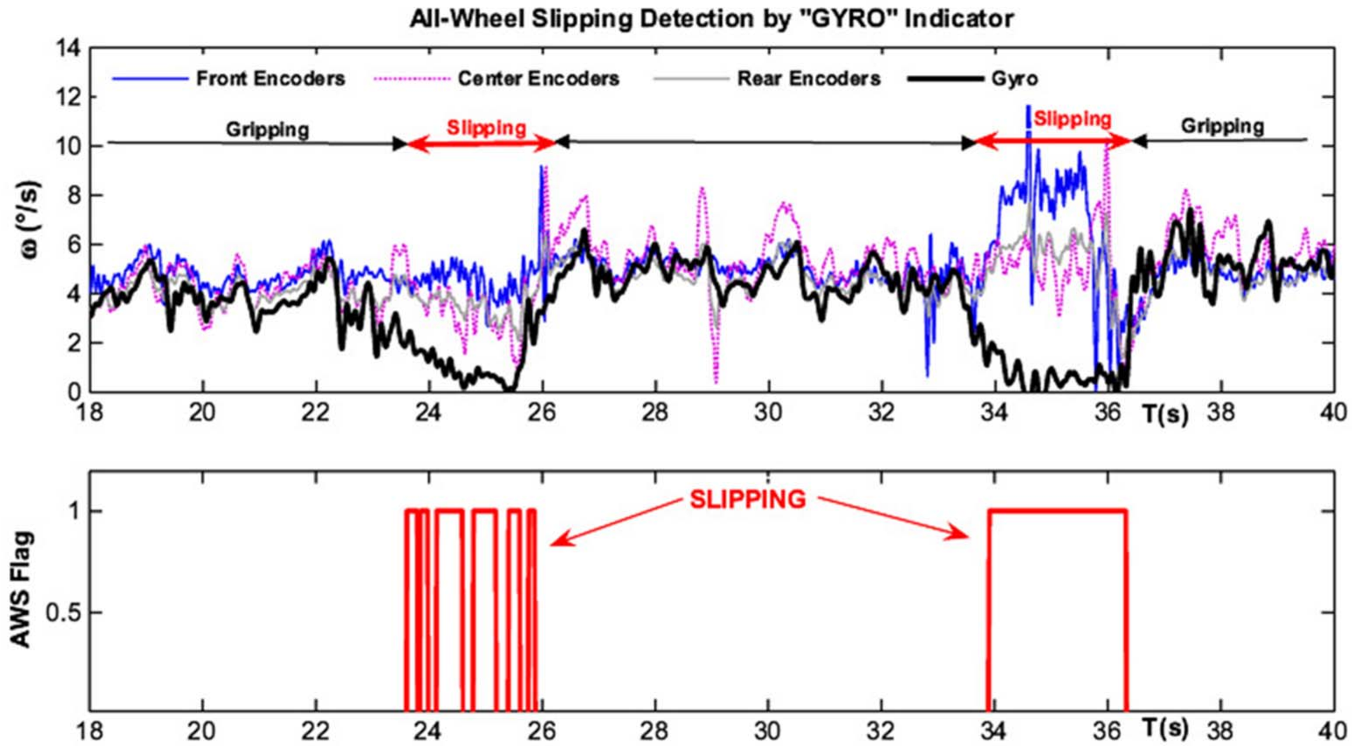
T - sampling interval.



- We can now compare each of the three $\omega_{Enc,i}$ with the rate-of-turn measured by the *z*-axis gyro ω_{Gyro}, which we consider the ground truth in this approach.
- If no slippage occurred in a wheel pair, then one can expect good correspondence between the rates-of-turn derived from the encoders of that wheel pair and the gyro. Poor correspondence suggests wheel slippage

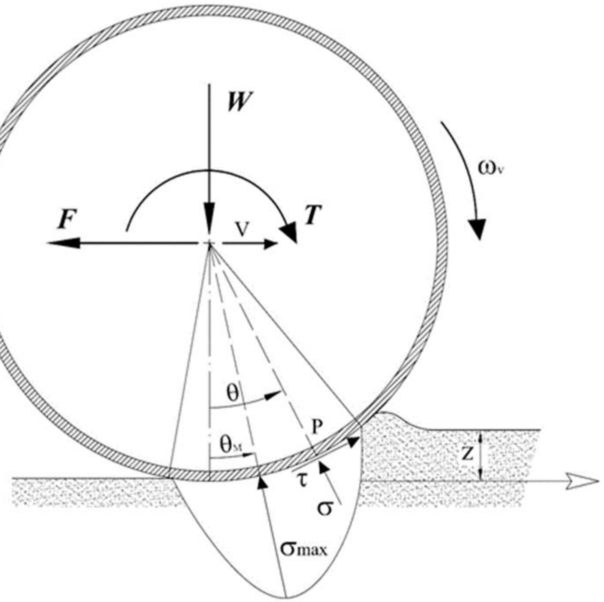
Gyro Indicator, cont'd

- Also for the Gyro Indicator, we developed a Fuzzy inference system to fuse sensory data.
- The fuzzified output of the GI is here expressed in terms of a binary, so-called "AWS flag," which is raised whenever the system's confidence in the existence of an AWS condition is greater than 0.5 (red bold line in the bottom graph).



Current Indicator

- The ***Current Indicator*** aims at detecting AWS by monitoring the electrical currents drawn by the drive motors of the vehicle.
- When a torque is applied to a wheel, shearing action is initiated on the terrain interface creating a tangential stress region τ, whose resultant gives the so called tractive effort ***F***
  - Using Terramechanics theory it is possible to find a relationship between *F* and the wheel slip *i*
  - Since torque is roughly proportional to the motor current *I*, it is also possible to link *I* to the wheel slip



Terramechanics theory (Bekker, Wong):

$$\tau(\theta) = [c + \sigma(\theta)\tan\varphi]\left(1 - e^{-\frac{j(\theta)}{K}}\right)$$

(1) $$T = r^2 b \int_{\theta_2}^{\theta_1} \tau(\theta)\, d\theta = F(i)$$

(2) $$T = k_I I$$

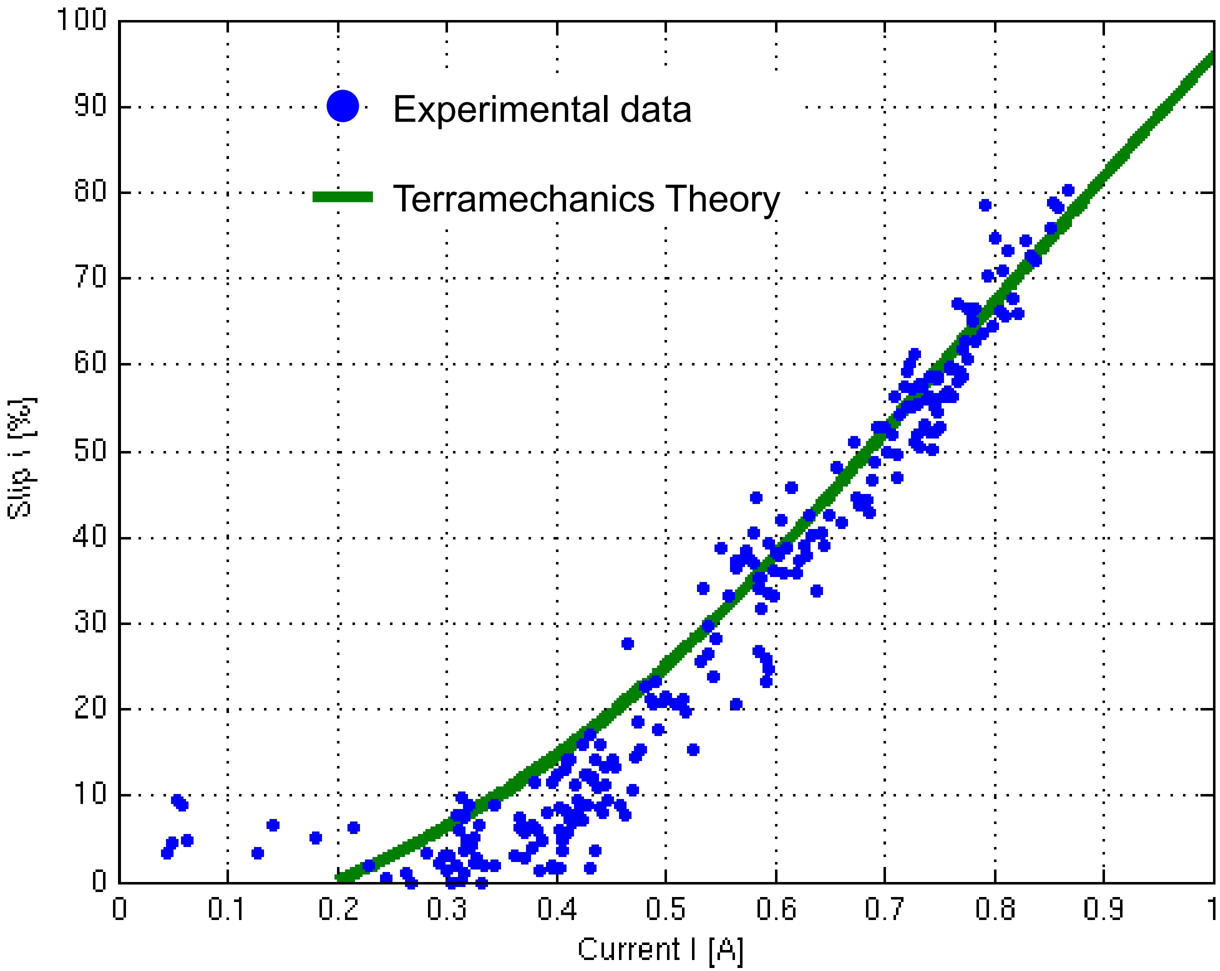
$$i = S(I)$$

c, φ	-	cohesion and internal friction angle, respectively
K	-	shear deformation modulus (i)
j	-	shear displacement.

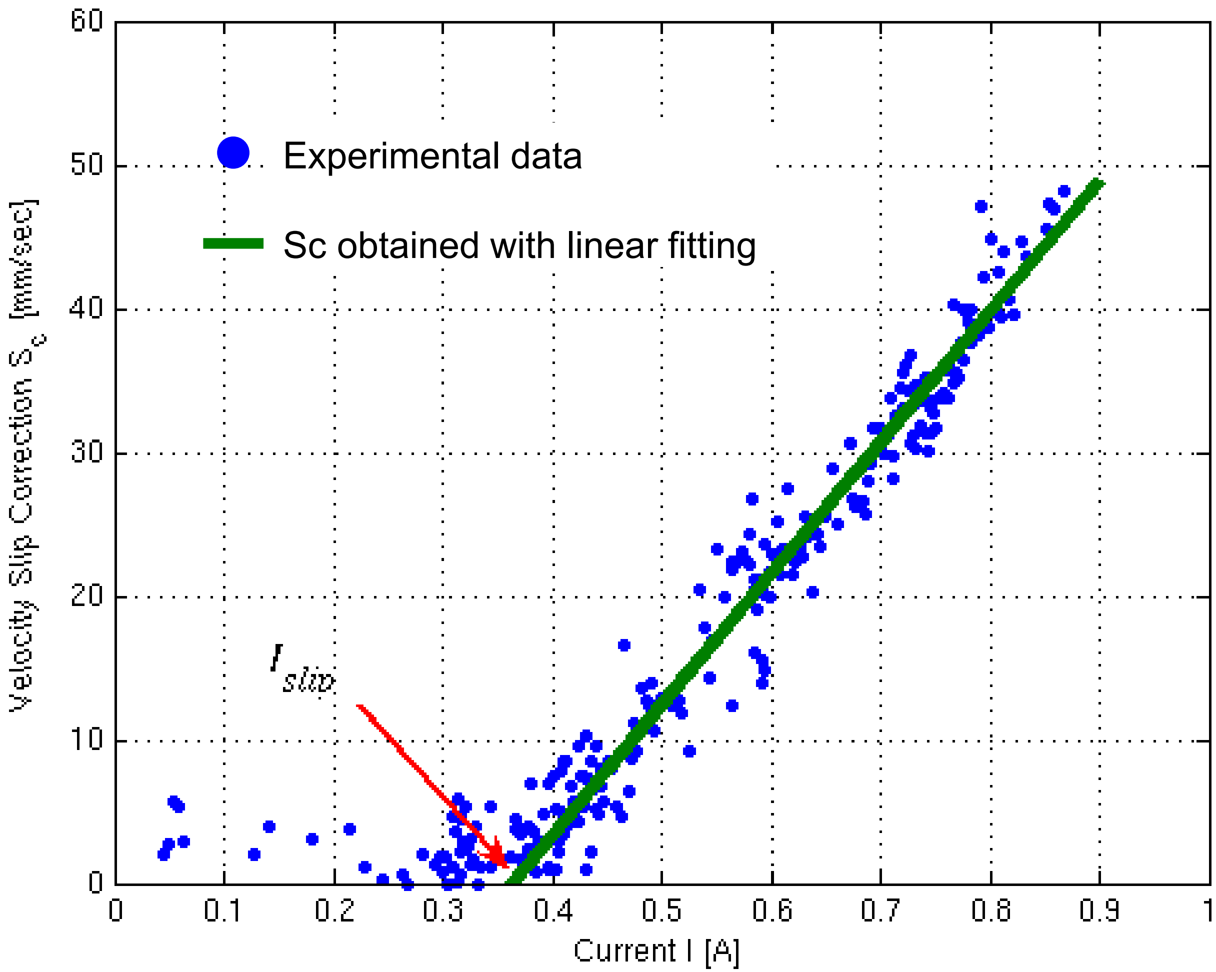
Politecnico di Bari

Relating wheel slip with motor current

DIPARTIMENTO DI MECCANICA MATEMATICA E MANAGEMENT



We defined the parameter velocity slippage correction ***Sc***, which represents the correction value to be used for slippage compensation



Velocity slip correction S_c

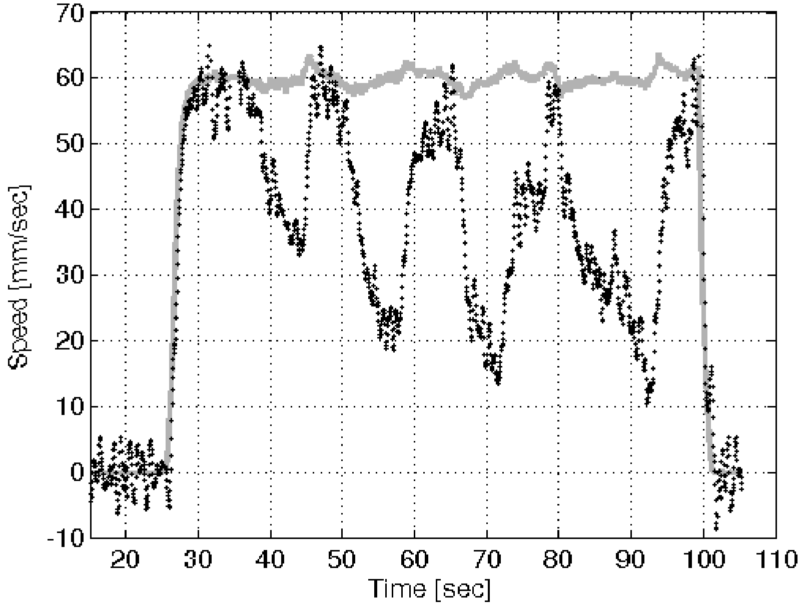
$$S_c = \begin{cases} \xi\left(I - I_{slip} - C_{pitch}\theta_r\right) & I > I_{slip} \\ 0 & otherwise \end{cases}$$

Odometry correction

$$v_c = v_{odo} - S_c$$

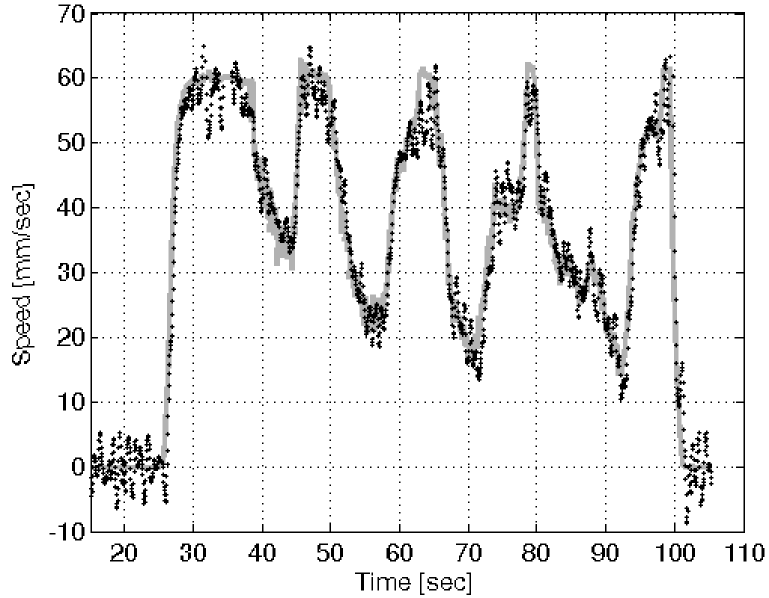
On-line calibration

iComp



● Encoder
● Ground truth

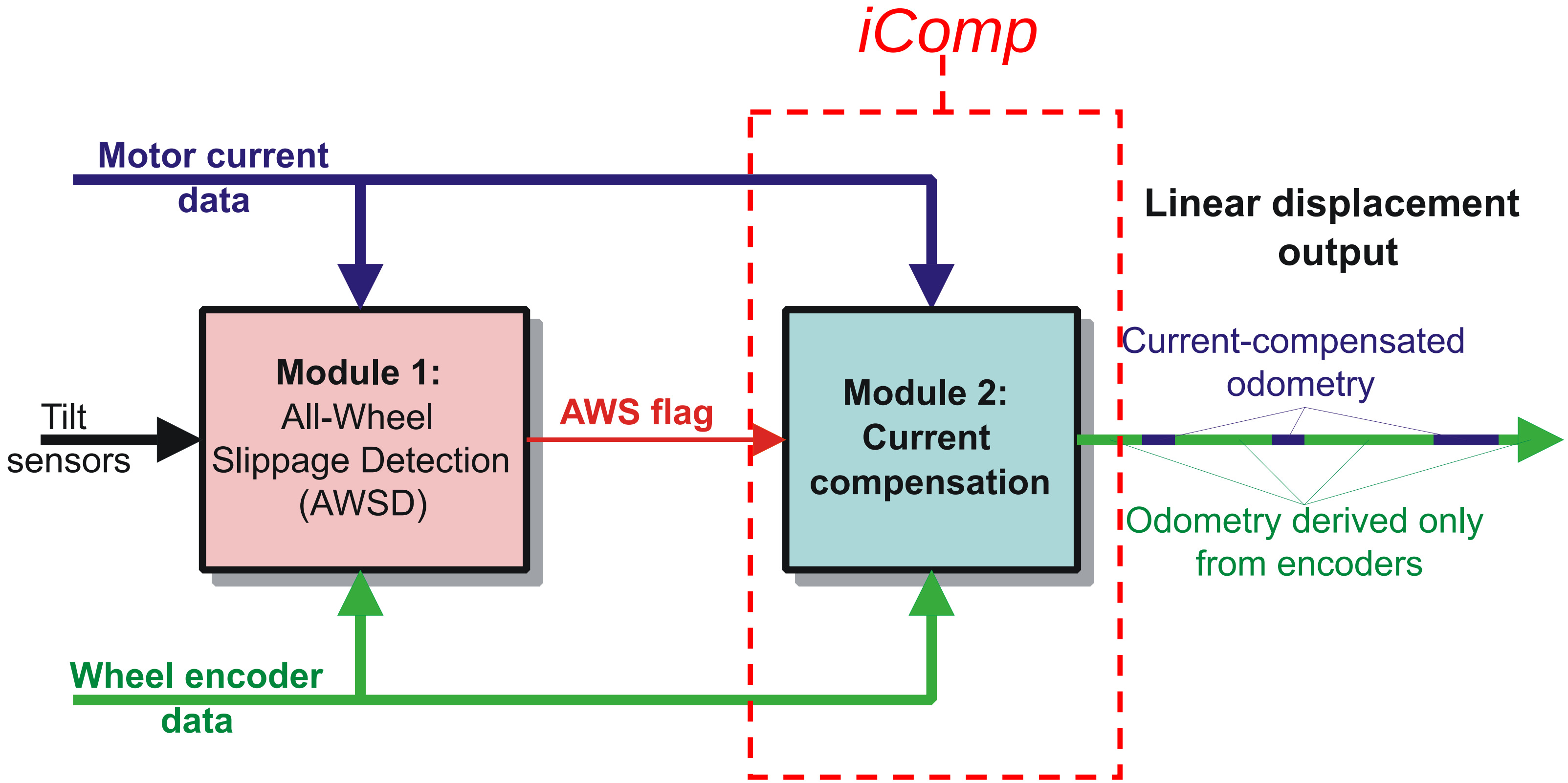
After compensation



● Encoder
● Ground truth

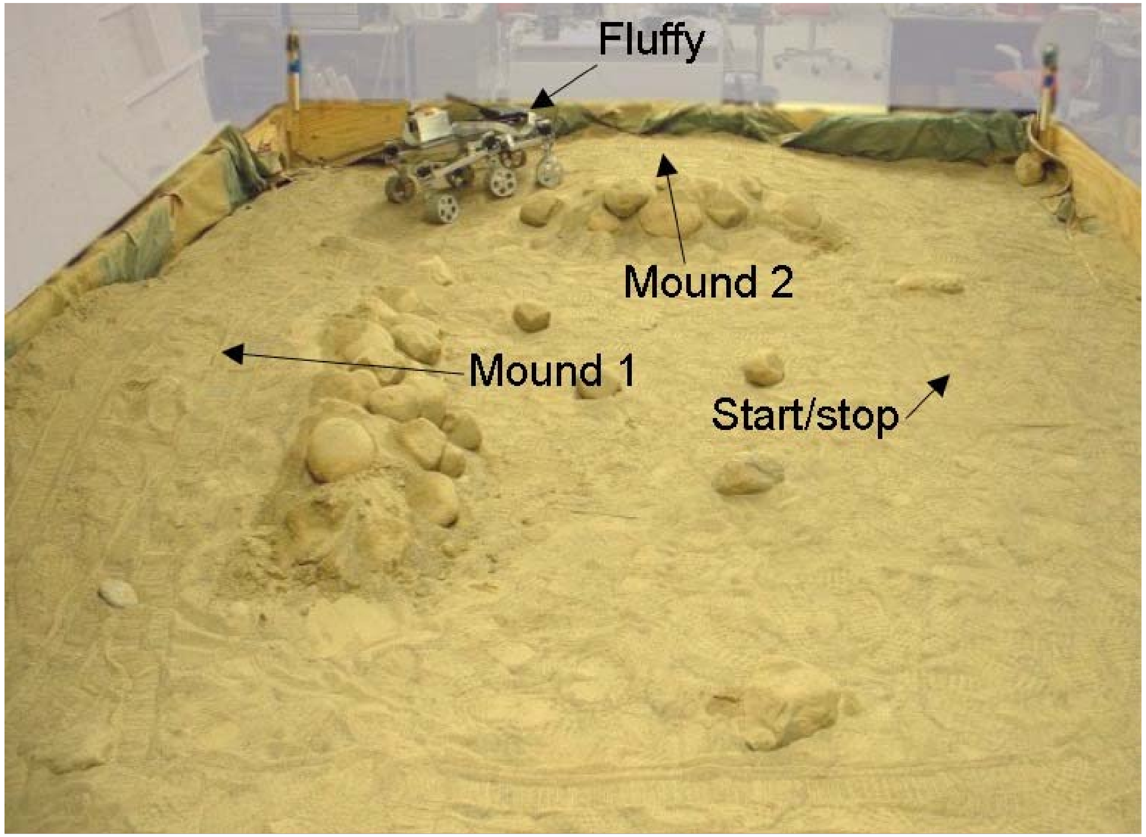
iComp

- It is generally beneficial to know that AWS has occurred or that some wheels are approaching a condition of impending slippage to compensate odometry errors and optimize traction control.
- The CI is useful not only to flag occurrences of AWS but indeed is also useful for correcting odometry errors incurred by AWS with values derived from momentary motor currents.

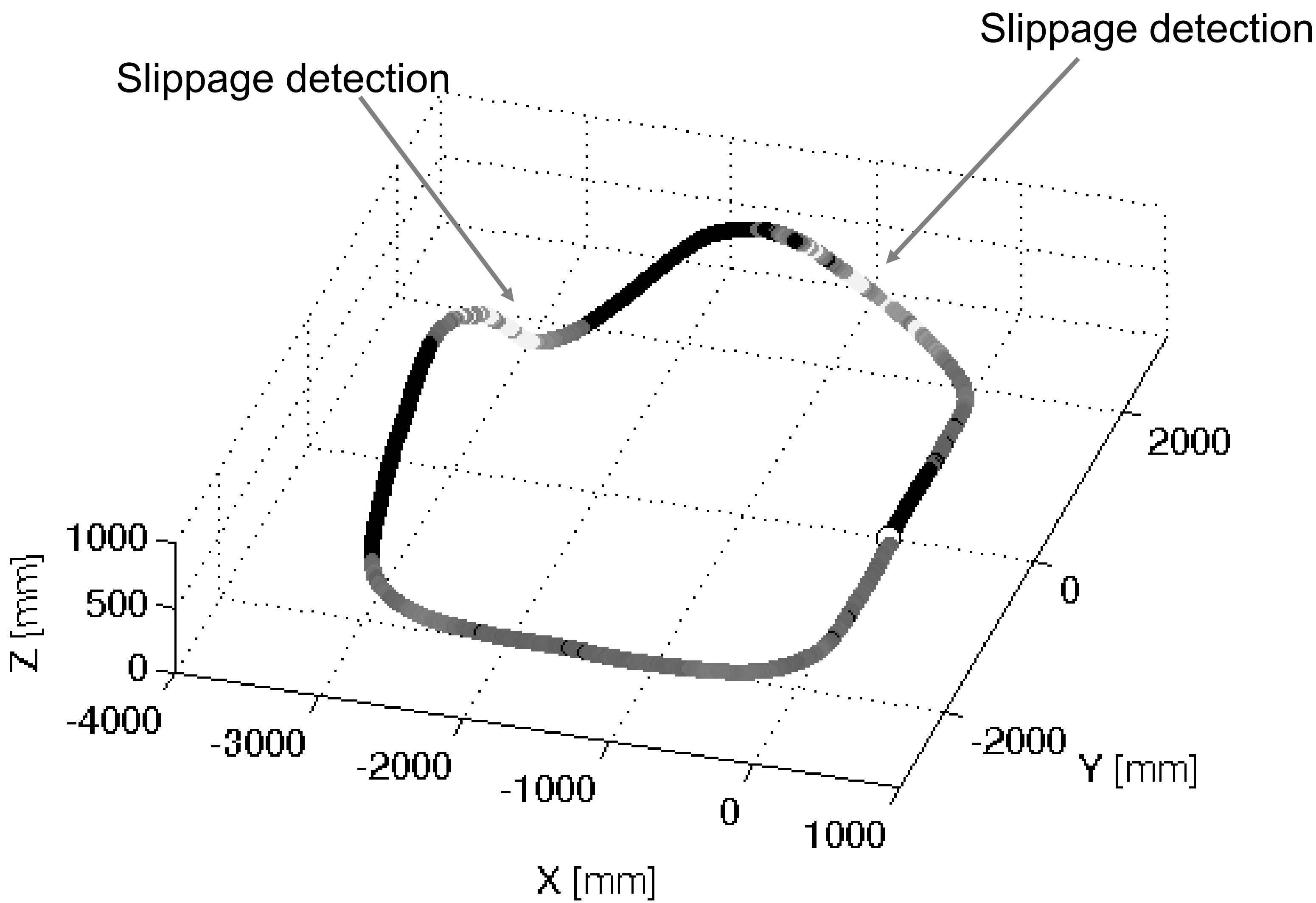


Experiments

- The rover traveled autonomously along a pre-programmed, near-rectangular path
- Each run consisted of three uninterrupted loops, resulting in a total travel distance of D = 43 m per run



Path of the rover



Results

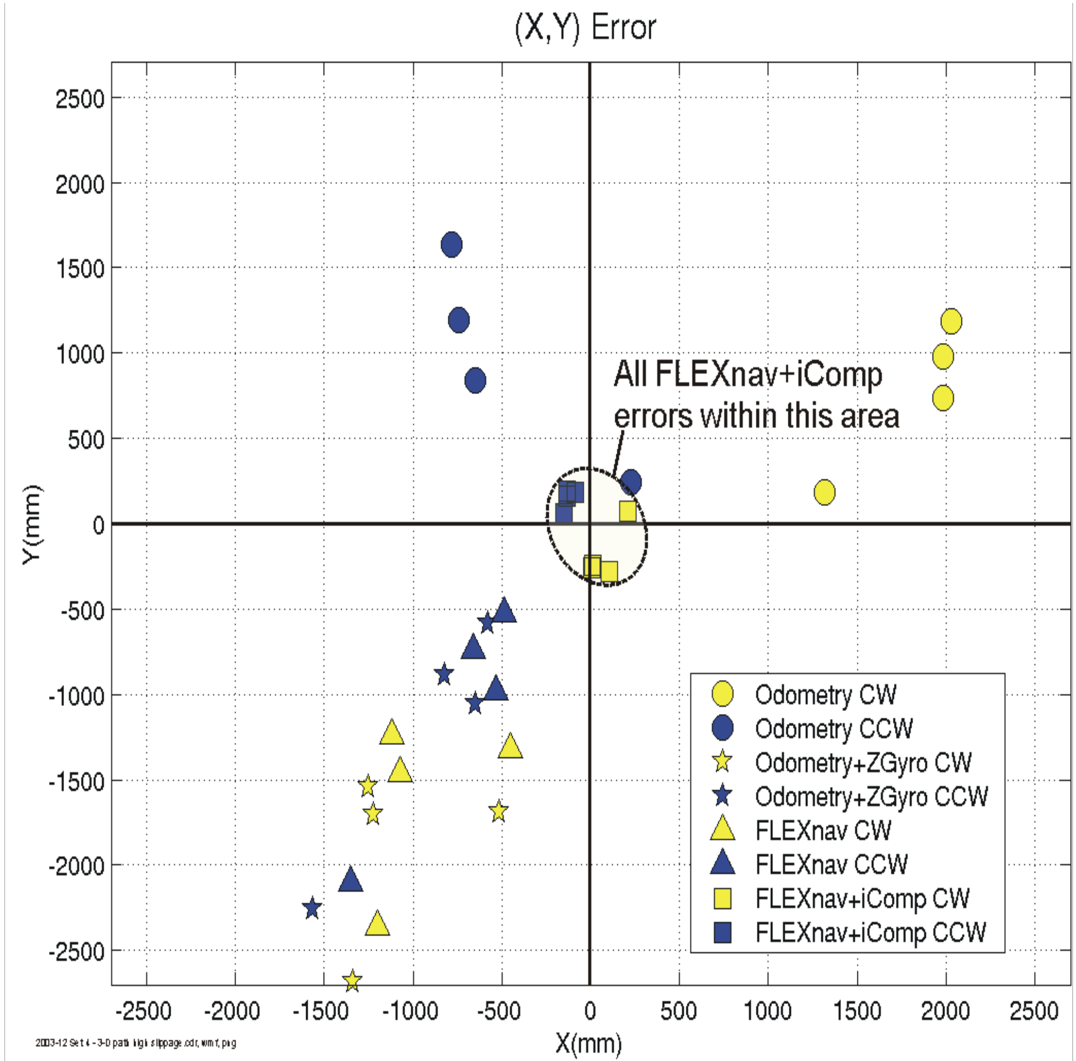
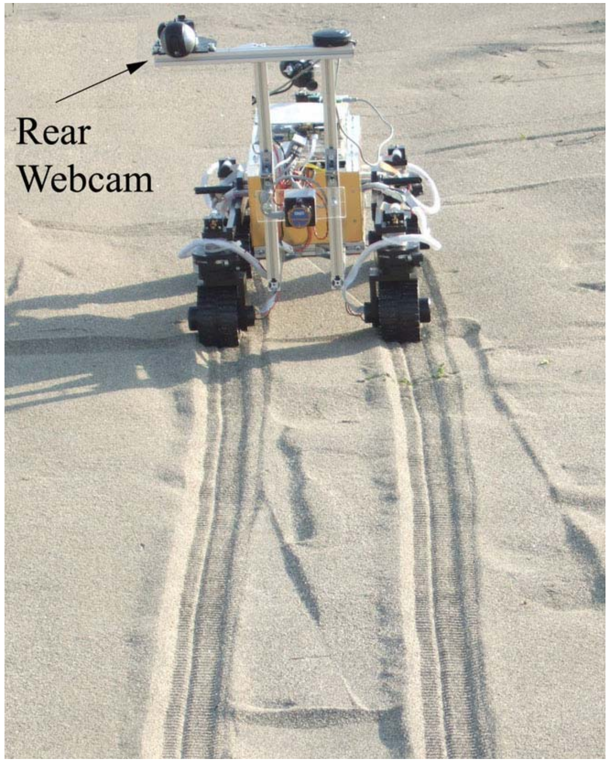


Table I: Return Position errors

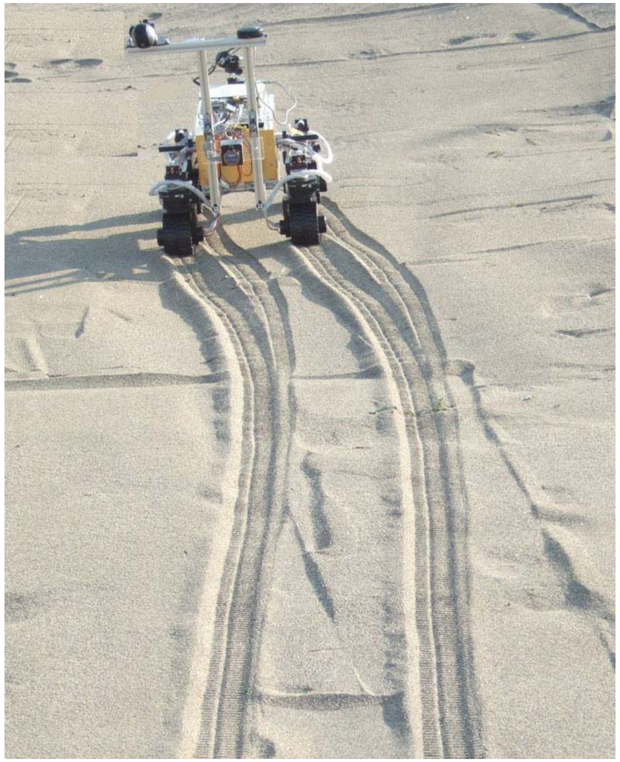
	Odometry	Odometry +Gyro	iComp
E % ***(CW)***	**3.7**	**3.0**	**0.45**
E % ***(CCW)***	**4.6**	**4.3**	**0.53**

Lateral drift

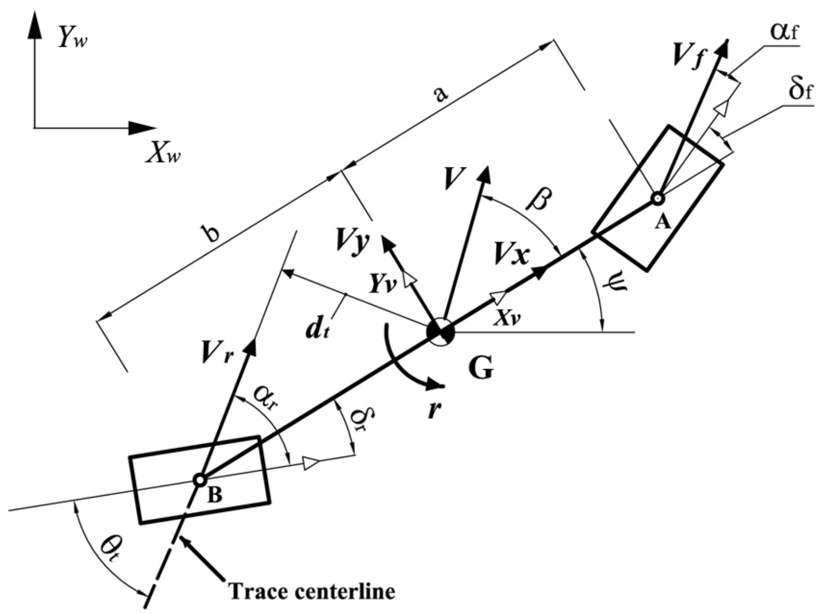
No Drift

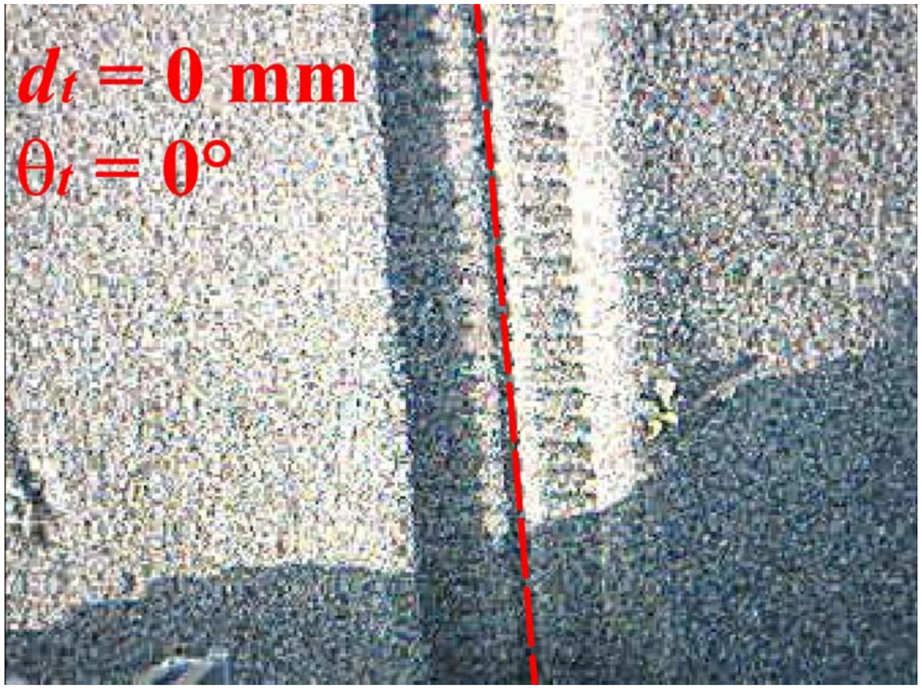


Lateral Drift



FTrace system

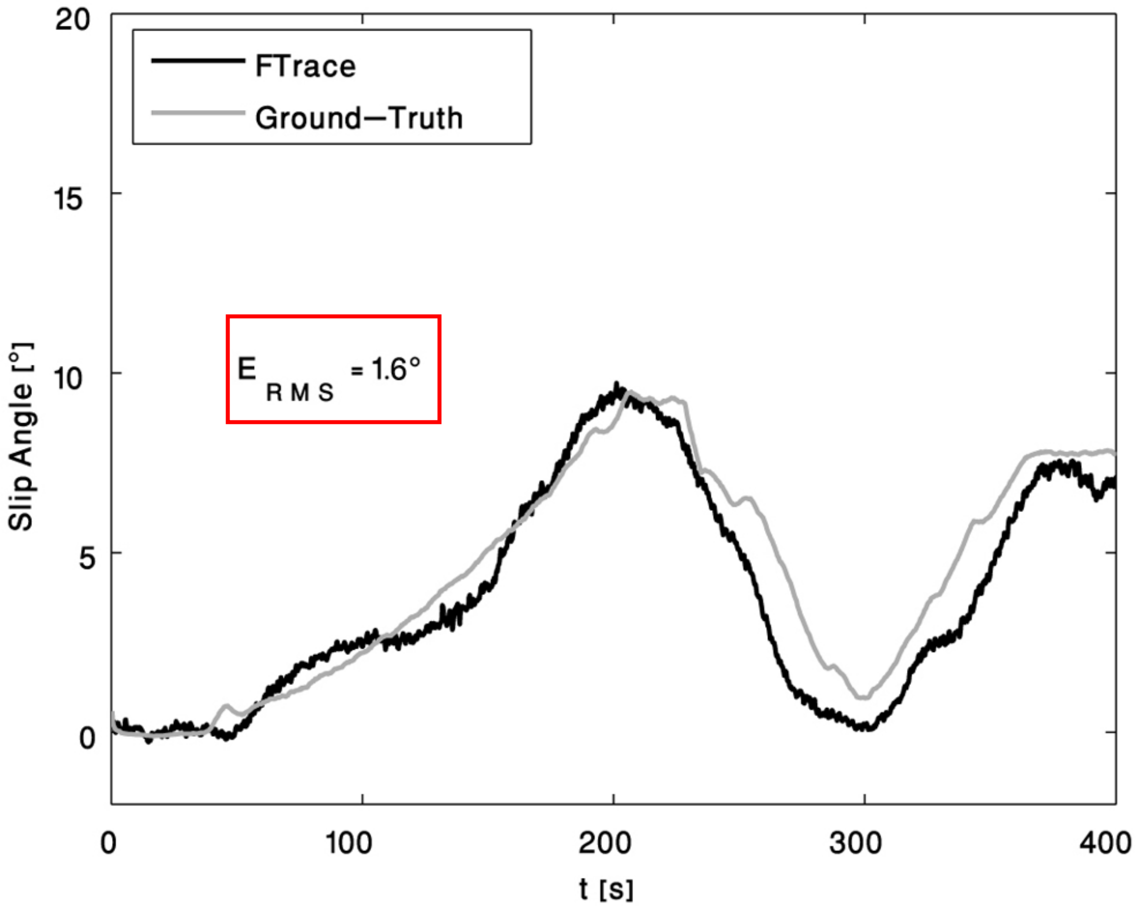




Experimental Validation

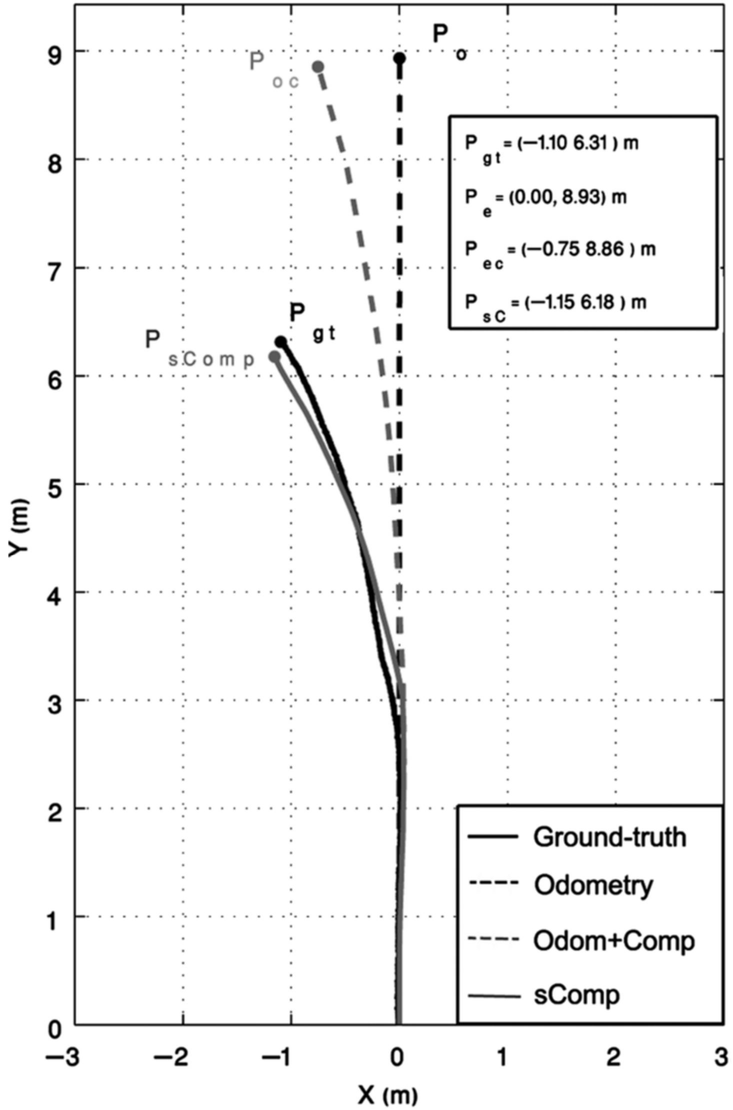
- The FTrace system was tested in the field using the rover El-Dorado, equipped with a cost-effective rear webcam, and a sampling rate of 5 Hz.
- The test field was located on the shorelines of a sandy beach, comprising large flat areas and sparse mounds of different extensions and heights.
- Ground-truth data was provided by a laser-based tracking system.

Slip Angle Estimation



VIDEO

Odometry-based localization



Soil modelling

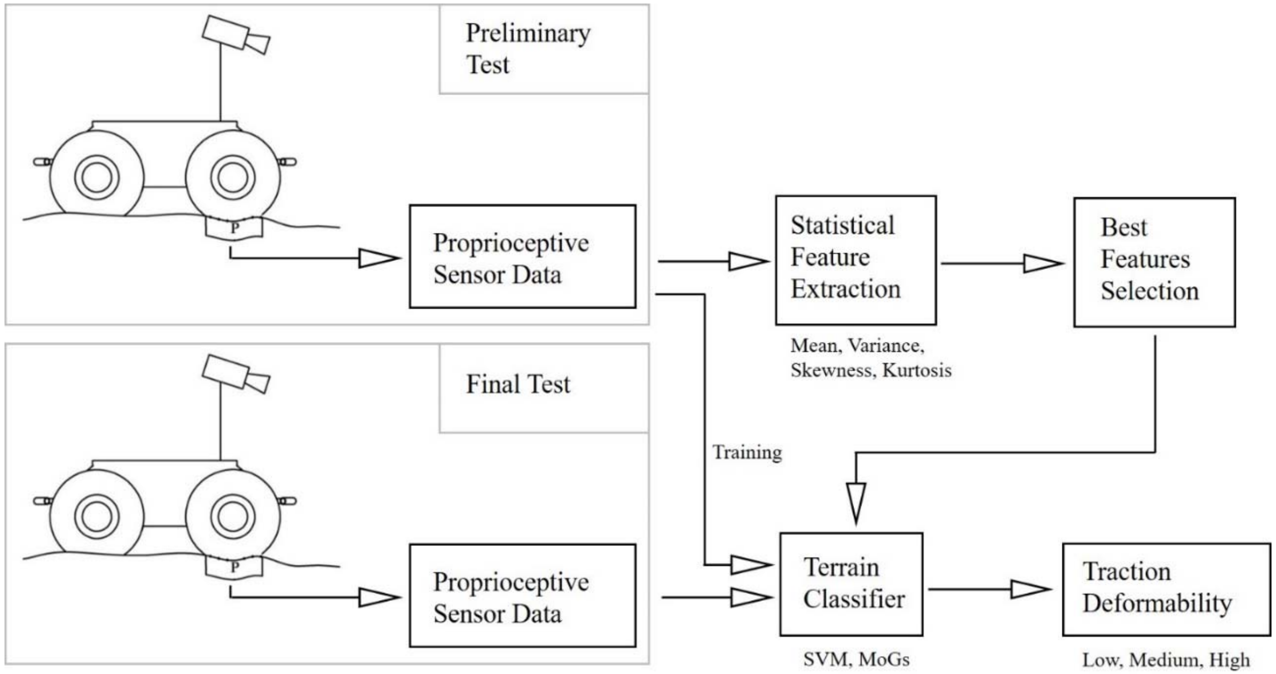
- *Experimental data*: results here presented are obtained from two previous SherpaTT test campaign
  - Utah: rocky terrain; sensors unavailable: stereo camera,
  - Morocco: sandy terrain; sensors unavailable: stereo camera , IMU, GPS

Utah

Morocco

Soil modelling

Main goal: build a terrain model based on a set of selected proprioceptive features

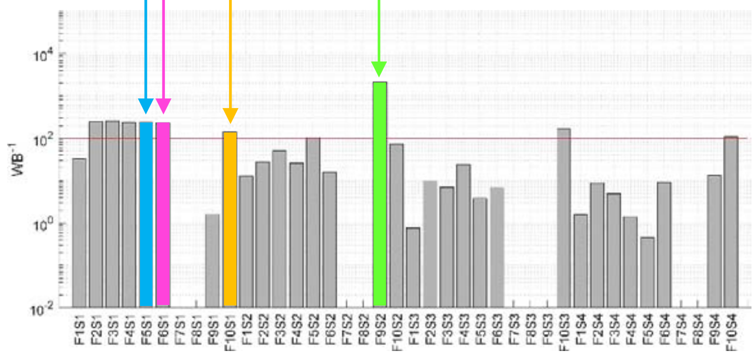


Soil modelling

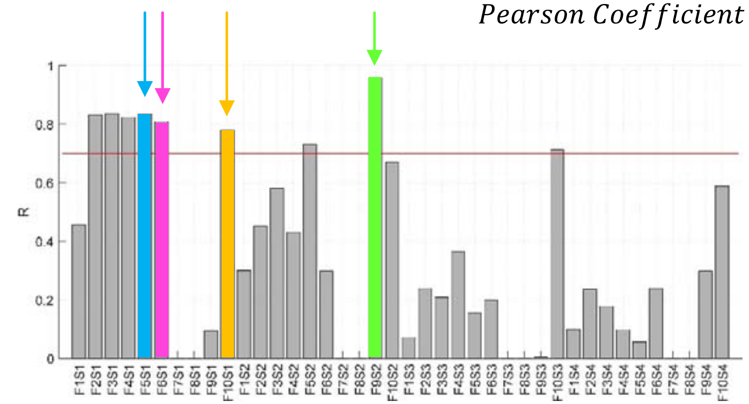
FEATURE SET	
F1	Longitudinal Force
F2	Torque
F3	Current
F4	Mechanical Power
F5	Electrical Power
F6	Friction Coefficient
F7	Acceleration X
F8	Acceleration Z
F9	Speed Deviation
F10	Sinkage
F11	Slippage

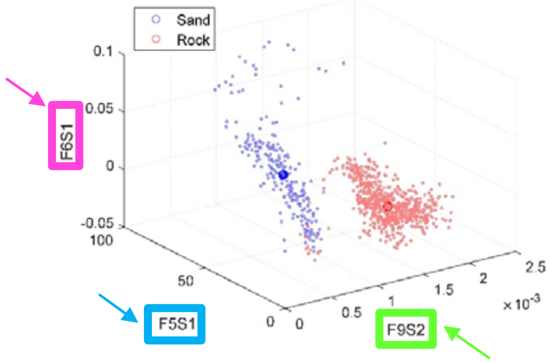
STATISTIC MOMENTS	
S1	Mean
S2	Variance
S3	Skewness
S4	Kurtosis

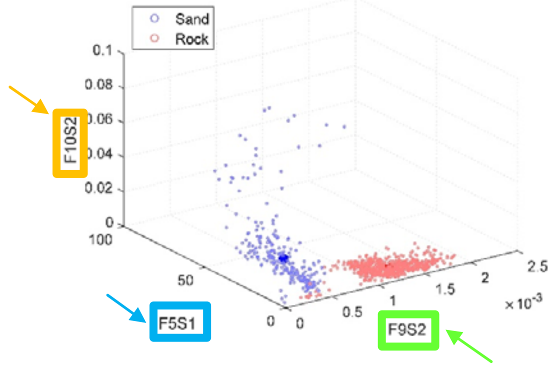
$$WB = m \cdot \frac{SSW}{SSB}$$



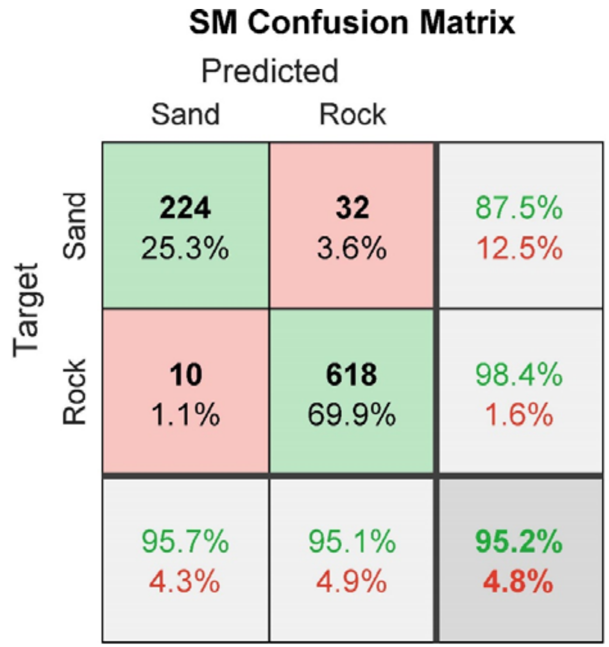
Pearson Coefficient







Statistical Terrain classifier

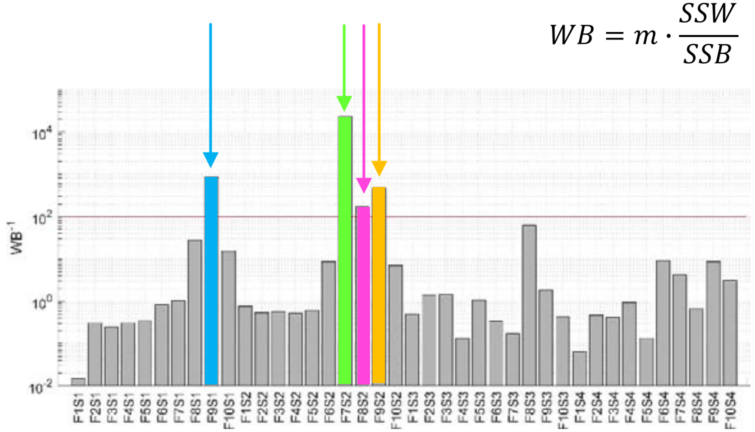


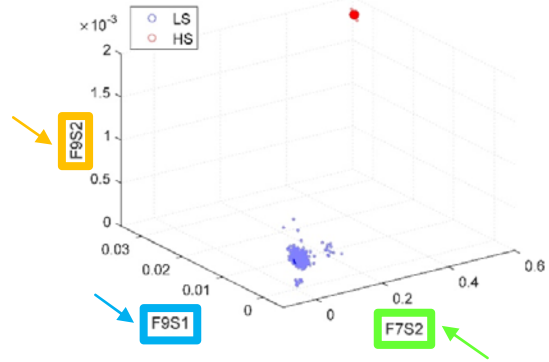
Excessive wheel slippage estimation

FEATURE SET	
F1	Longitudinal Force
F2	Torque
F3	Current
F4	Mechanical Power
F5	Electrical Power
F6	Friction Coefficient
F7	Acceleration X
F8	Acceleration Z
F9	Speed Deviation
F10	Sinkage

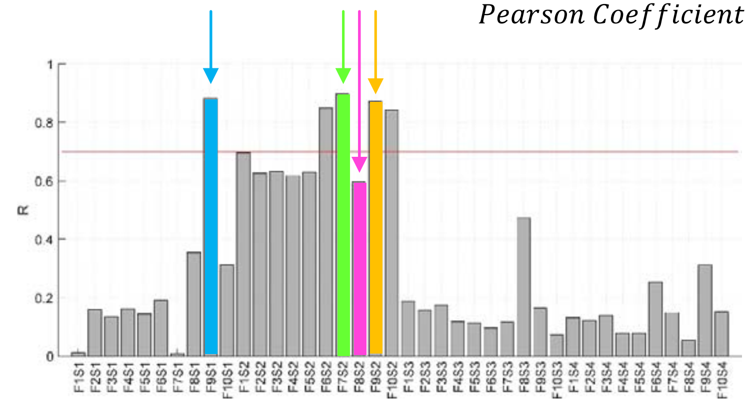
STATISTIC MOMENTS	
S1	Mean
S2	Variance
S3	Skewness
S4	Kurtosis

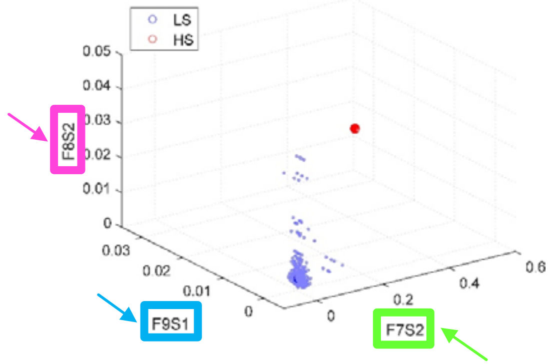
$$WB = m \cdot \frac{SSW}{SSB}$$





Pearson Coefficient



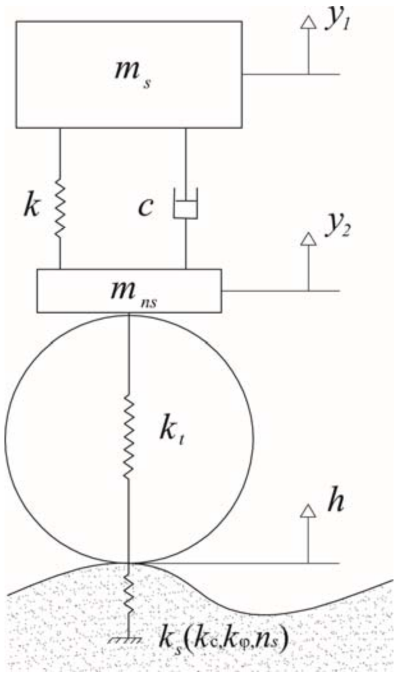


Model-based vehicle dynamic estimation

On-line estimation of vehicle-terrain parameters using model-based observers (e.g., Recursive Least Square, Extended Kalman Filter, Cubature Kalman Filter, etc)

General quarter vehicle model

Reina G , Leanza A., Messina A., "On the vibration analysis of off-road vehicles: Influence of terrain deformation and irregularity", Journal of Vibration and Control, 24 (22), 2018.



Model-based observer

$$\dot{\mathbf{x}} = \mathbf{A}(\mathbf{x})\mathbf{x} + \mathbf{B}\mathbf{u} + \mathbf{G}\mathbf{w}$$

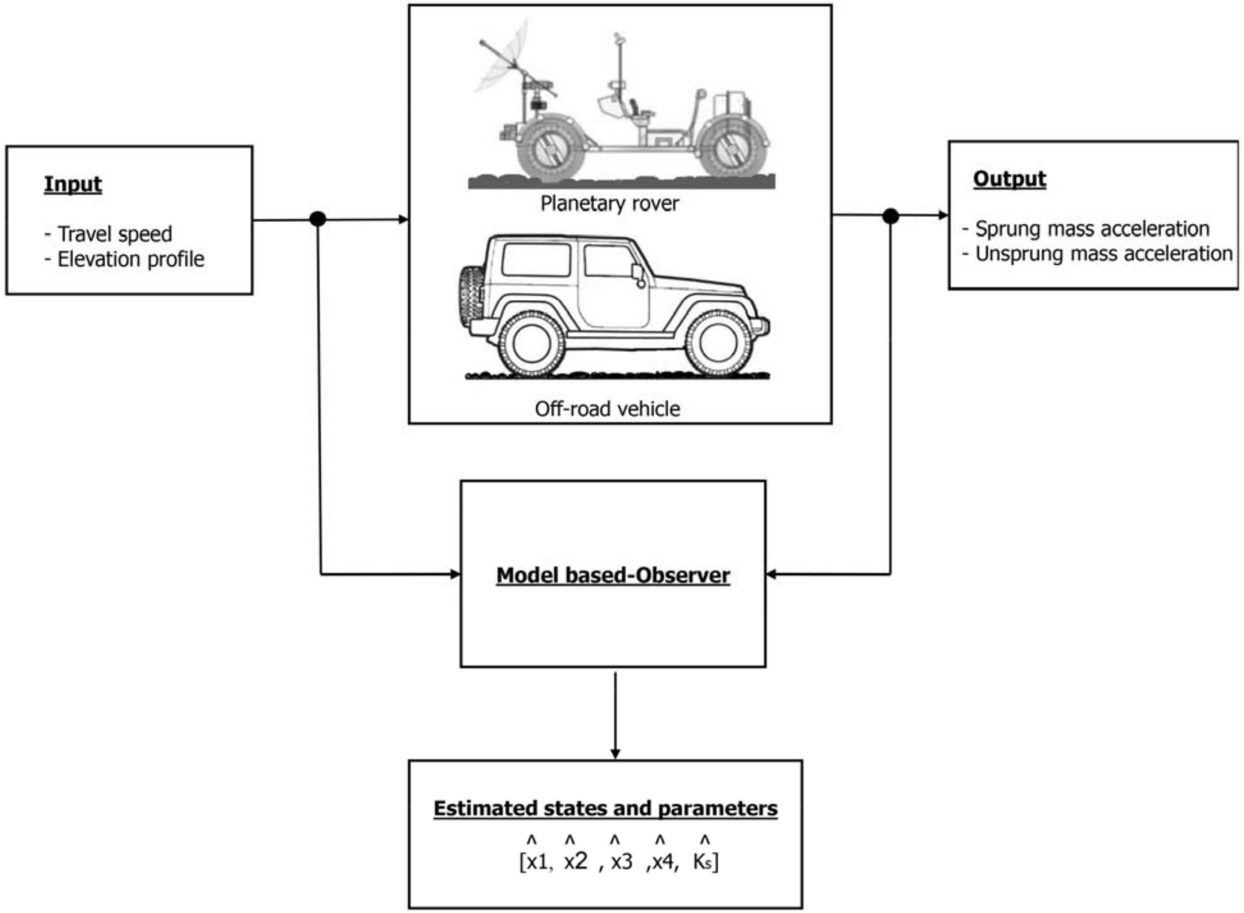
$$\mathbf{z} = \mathbf{C}(\mathbf{x})\mathbf{x} + \mathbf{v}$$

measure

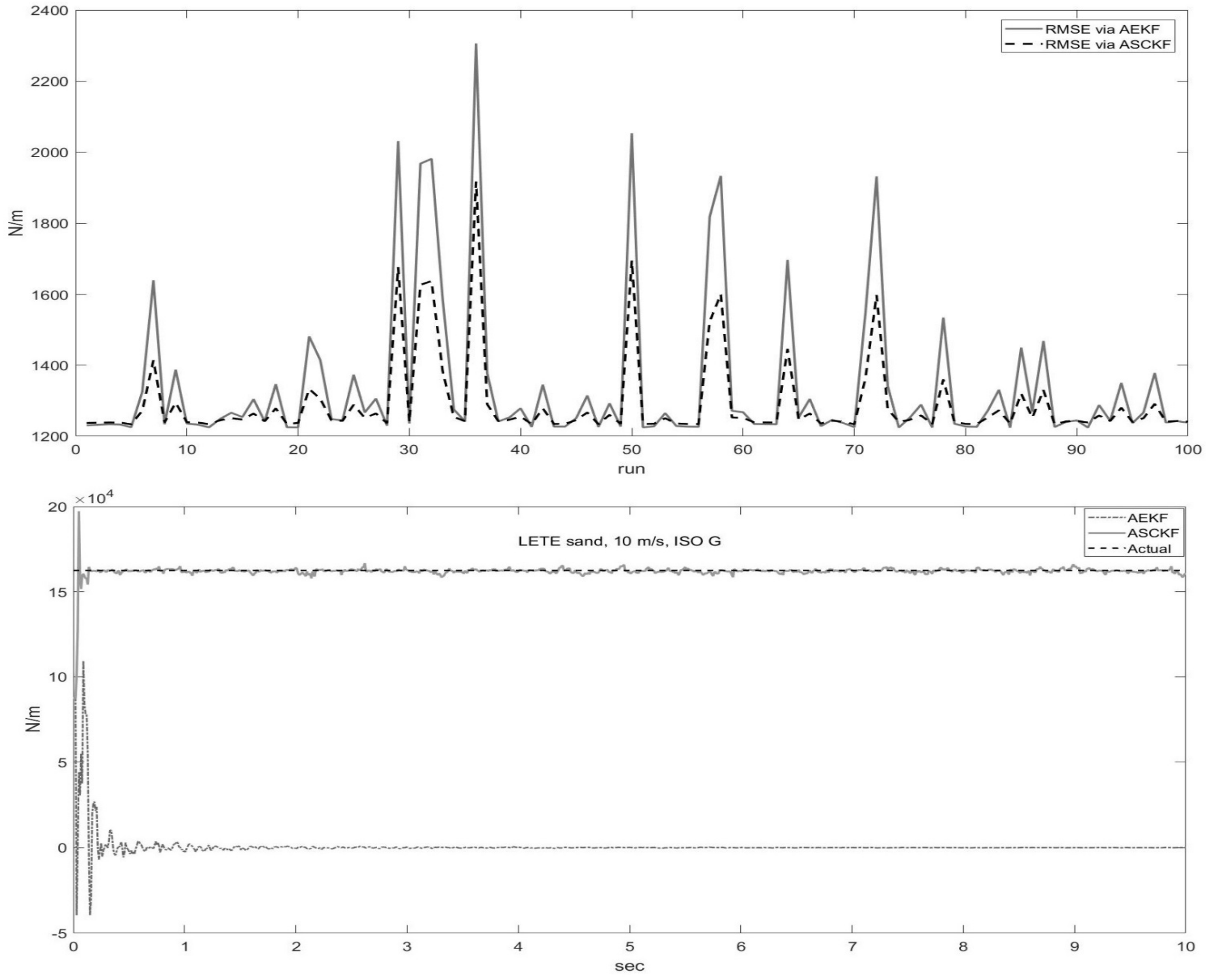
$$\mathbf{x} = \begin{pmatrix} y_1 - y_2 \\ \dot{y}_1 \\ y_2 - h \\ \dot{y}_2 \\ k_{tot} \end{pmatrix} \qquad \mathbf{z} = \begin{pmatrix} \ddot{y}_1 \\ \ddot{y}_2 \end{pmatrix}$$

state

Terrain properties observer

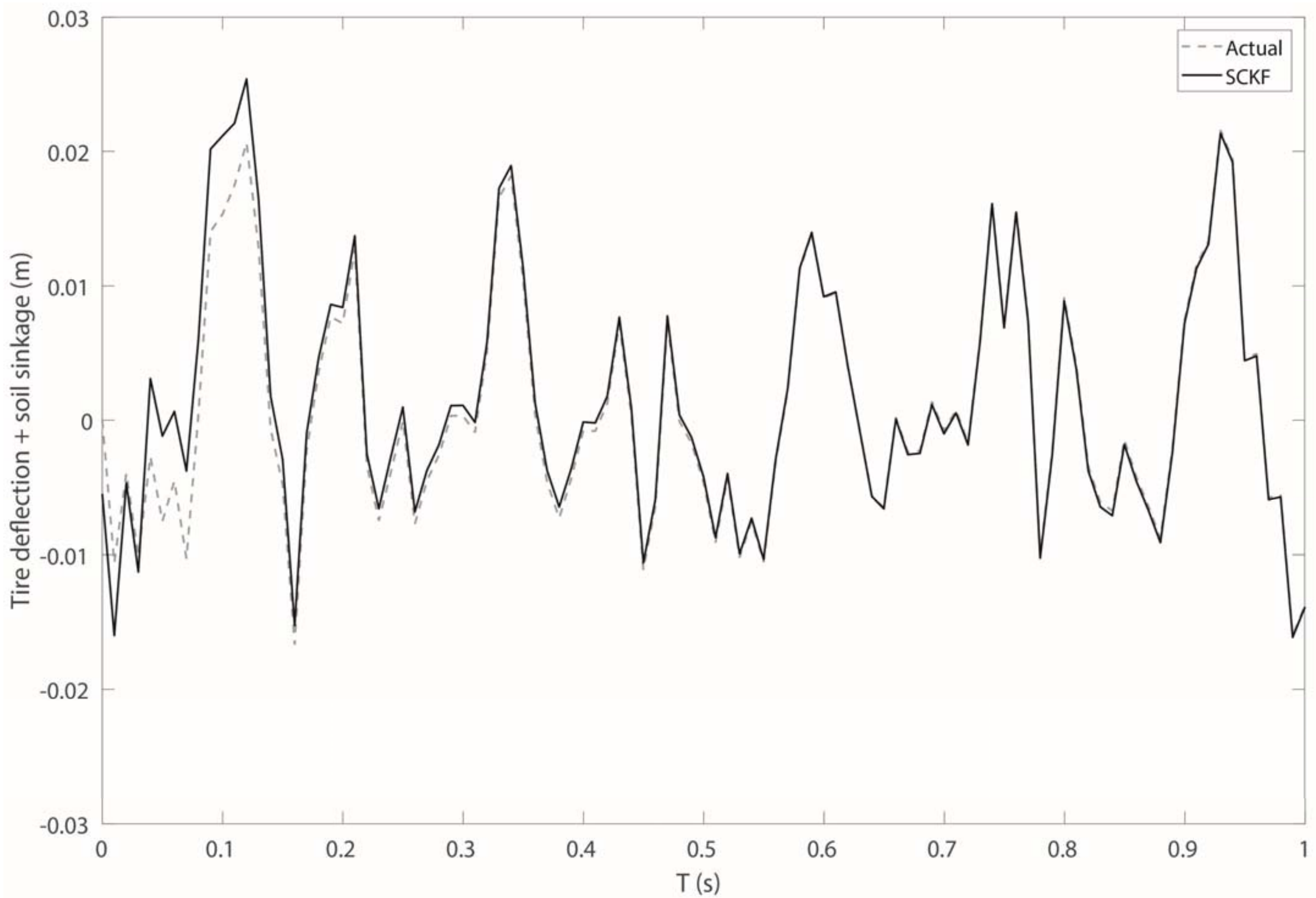


Results

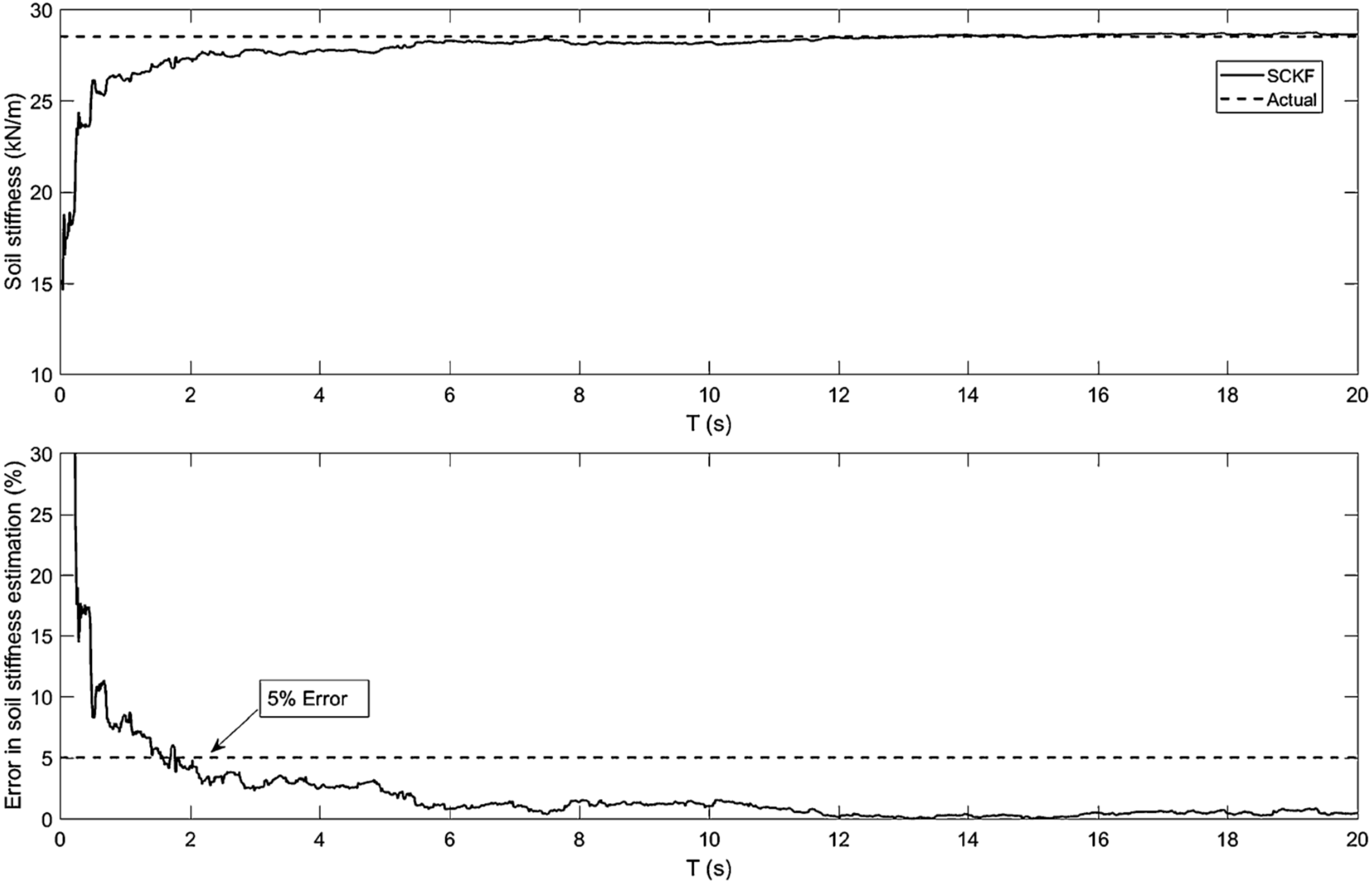


Reina G. , Leanza A., Messina A., "Terrain estimation via vehicle vibration measurement and cubature Kalman filtering", Journal of Vibration and Control, 2020.

Results

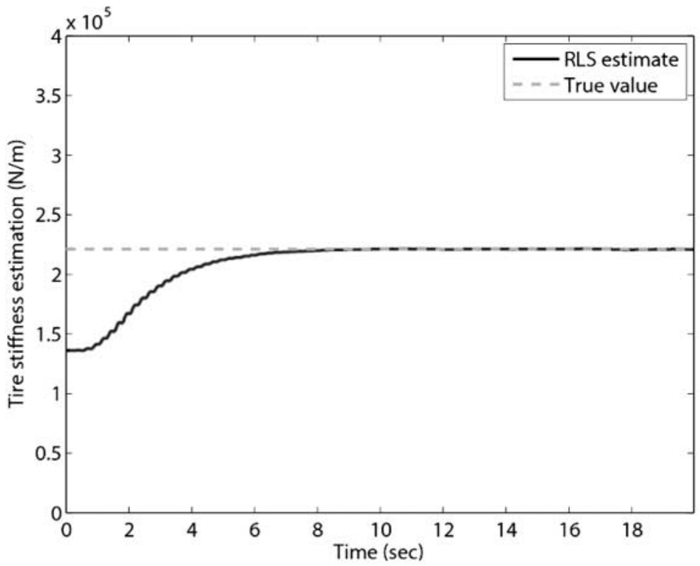

Actual
SCKF
Tire deflection + soil sinkage (m)
T (s)
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

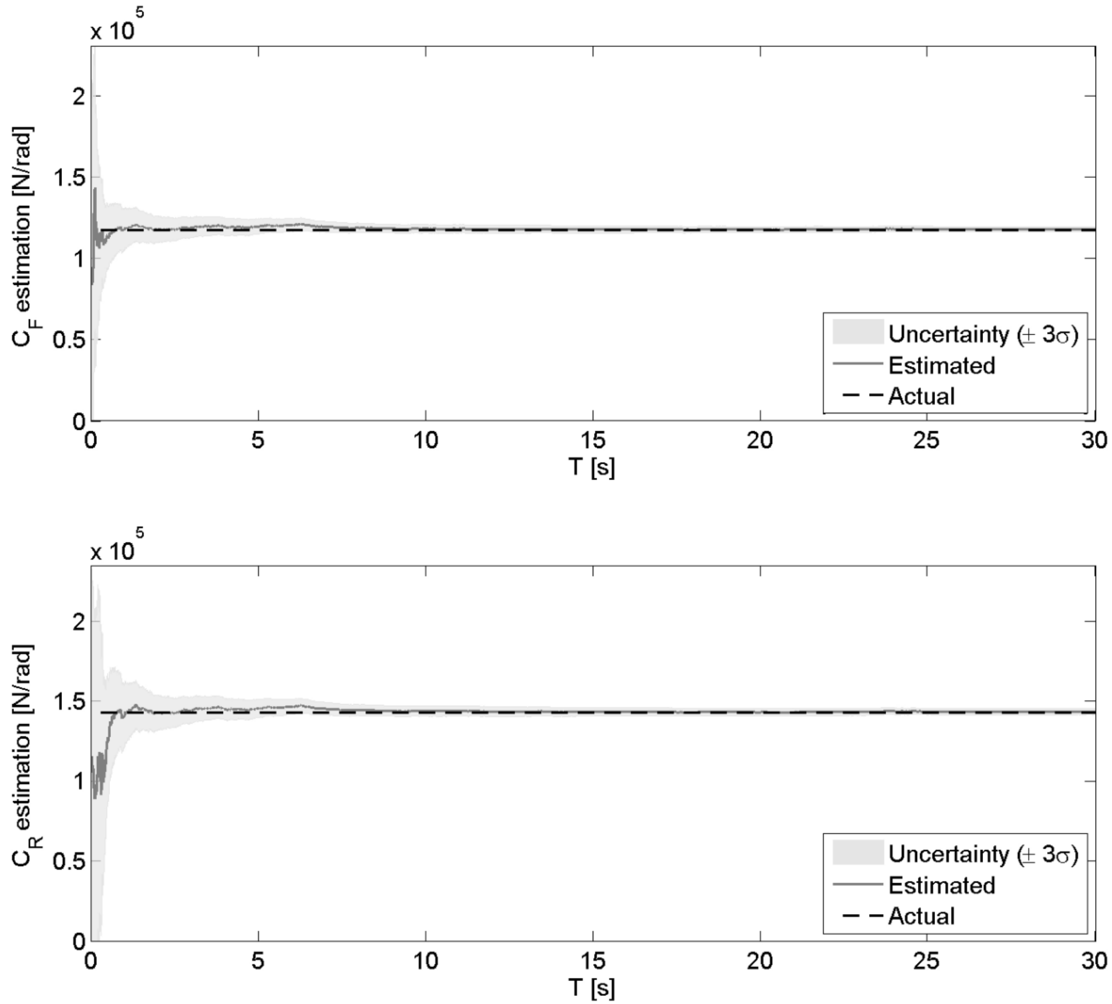
Regolith estimation with a Moon buggy



Cornering stiffness

Tire pressure





Muchas gracias por la atención !!!!

Feel free to drop me an email: giulio.reina@poliba.it

check progress @ www.vagostudio.com/giulio/

$$E = \sqrt{X_e^2 + Y_e^2}$$

$$E[\%] = 100\frac{E}{D}$$

On-line tuning technique