Systèmes de locomotion hybrides roues-pattes

ISIR – UPMC

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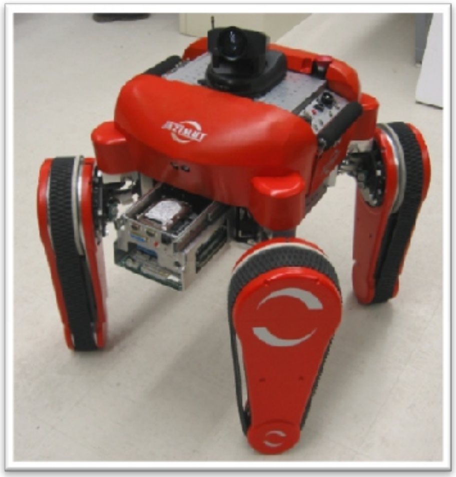
Plan

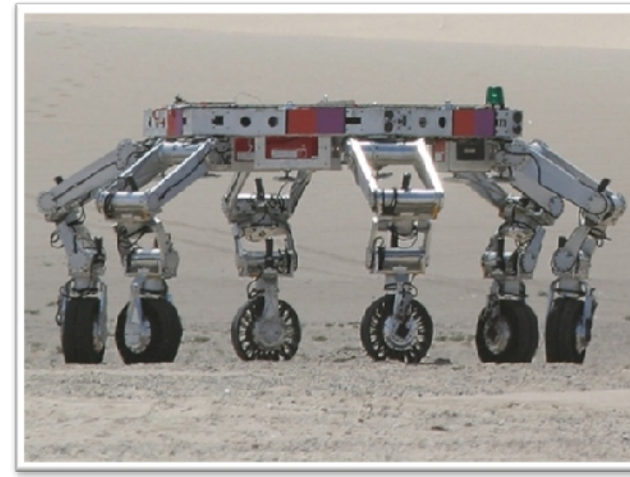
1. Introduction
2. Architecture mécatronique des robots Hylos
3. Modélisation cinémato-statique
4. Commande pour le contrôle de posture
5. Optimisation de la distribution des forces

Introduction



Azimut [Laborius/2004]

Hybtor [HUT / 2001]



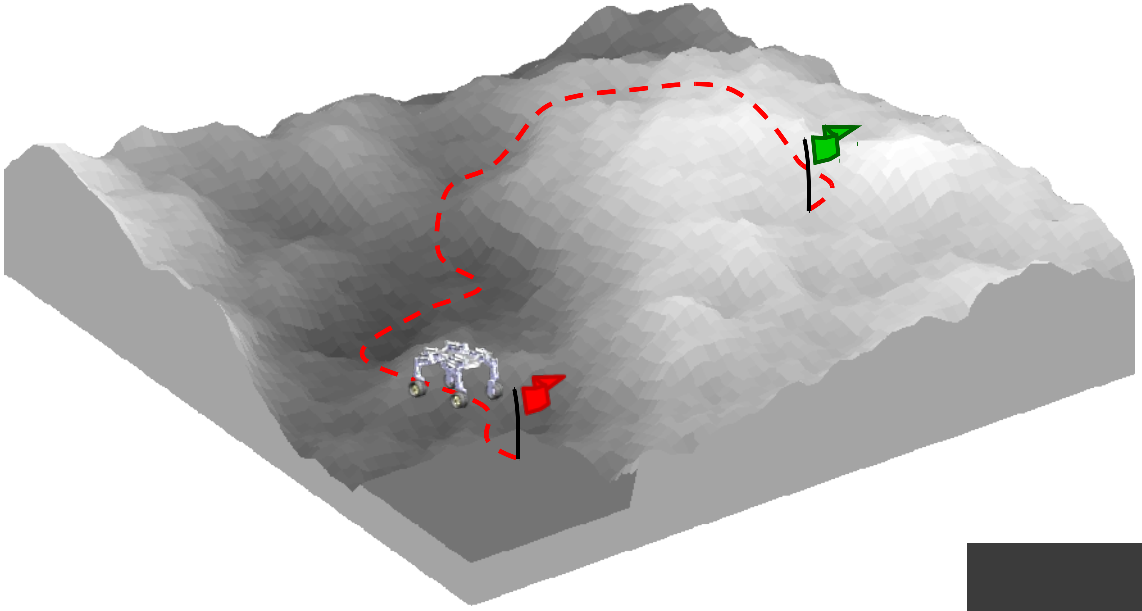
Athlete [JPL / 2004]

HyLoS I [UPMC / 2001]

HyLoS II [UPMC/2005]

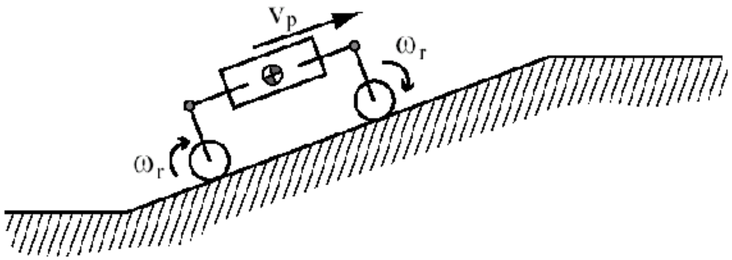
Introduction

Intérêt de la locomotion hybride roues-pattes

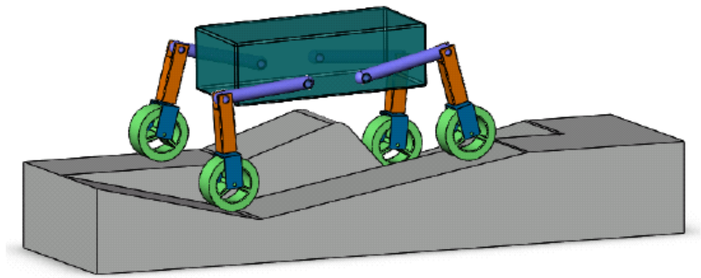


Introduction

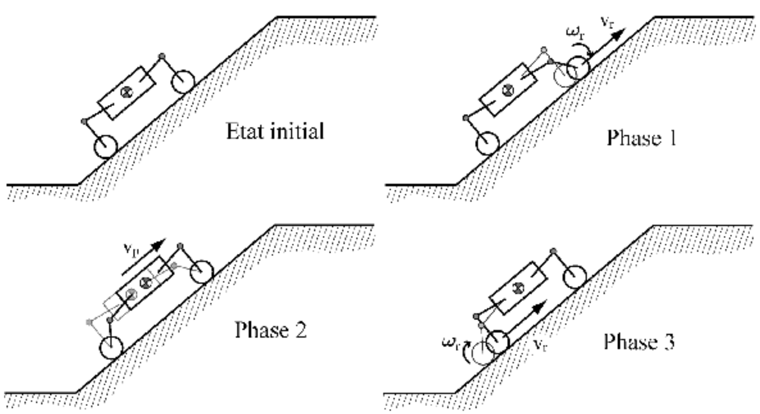
Les modes de locomotion



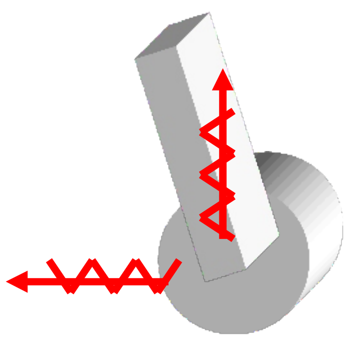
Mode 1 : Roulement simple



Mode 2 : Reconfiguration

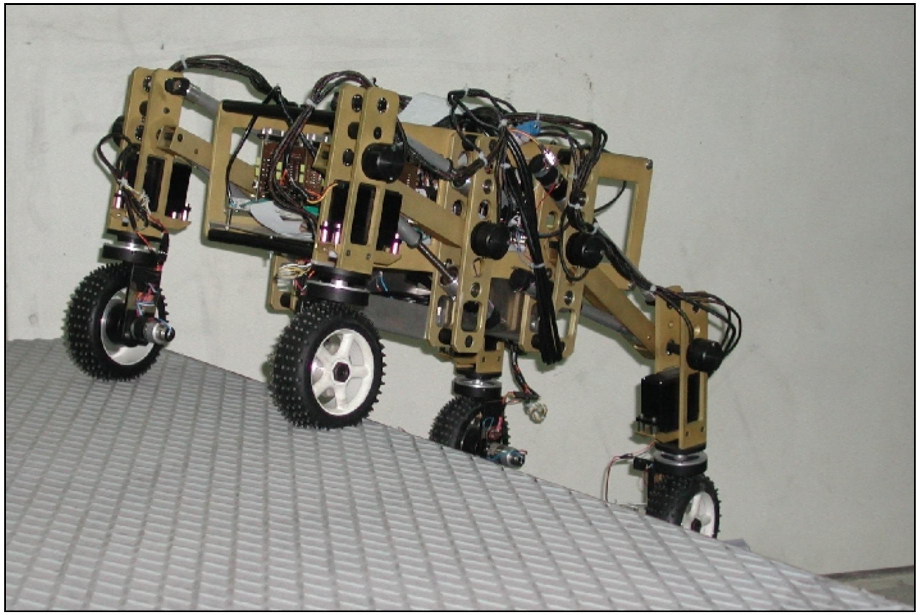


Mode 3 : Péristaltisme



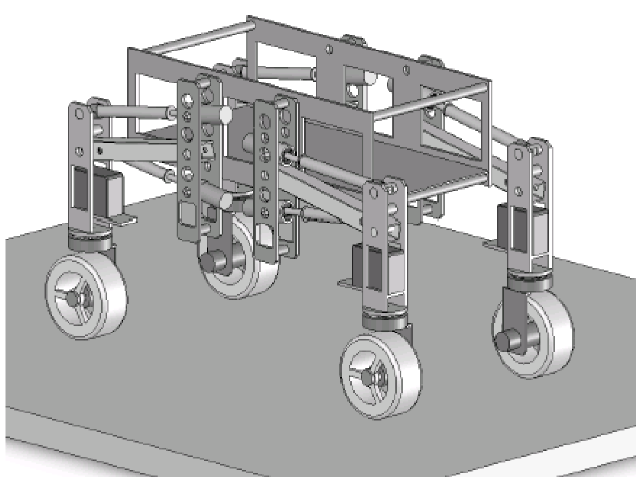
Mode 4 : Franchissement

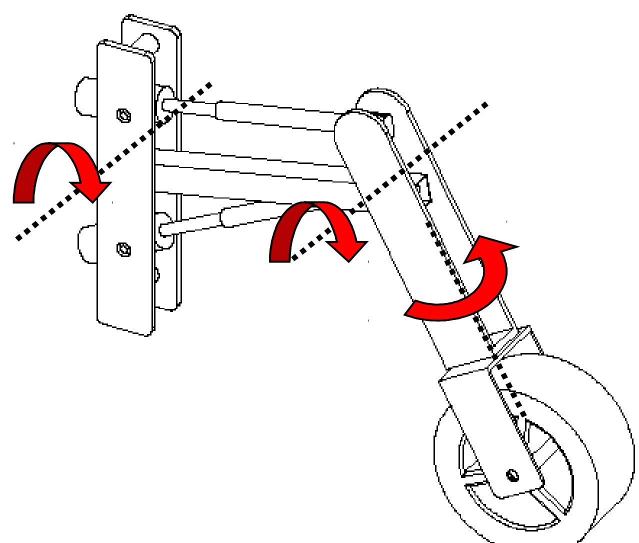
Architecture Hylos 1



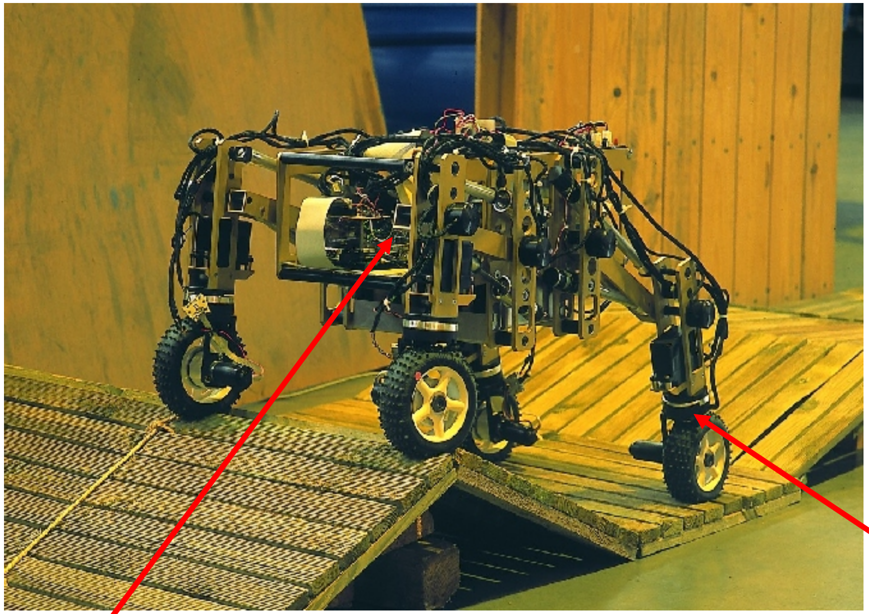
Caractéristiques du robot

Masse	15 kg
Dimensions	70x30x40 cm
Garde au sol	10-30 cm
Vélocité	0.6 m/s
ddl	16
Énergie	Batterie (NiCd)



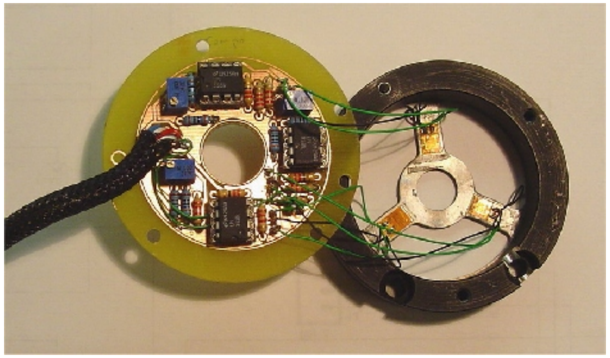


Architecture Hylos 1



Perception

- 1 Inclinomètre 2 axes roulis/tangage
- Potentiomètres articulations
- Codeurs optiques
- 4 capteurs d'effort 3 axes



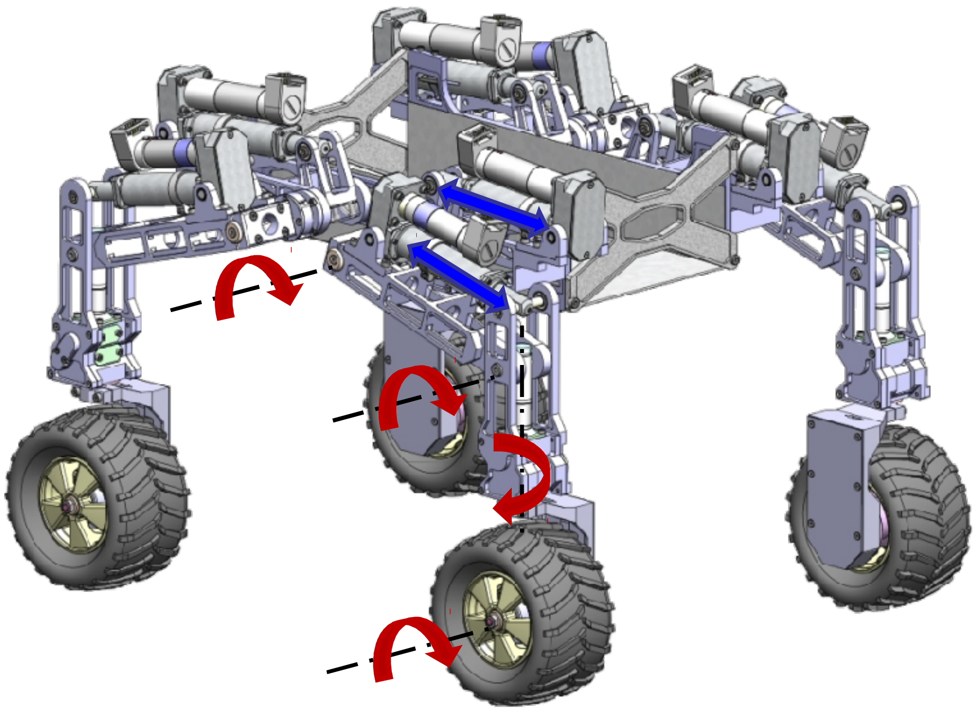
Commande

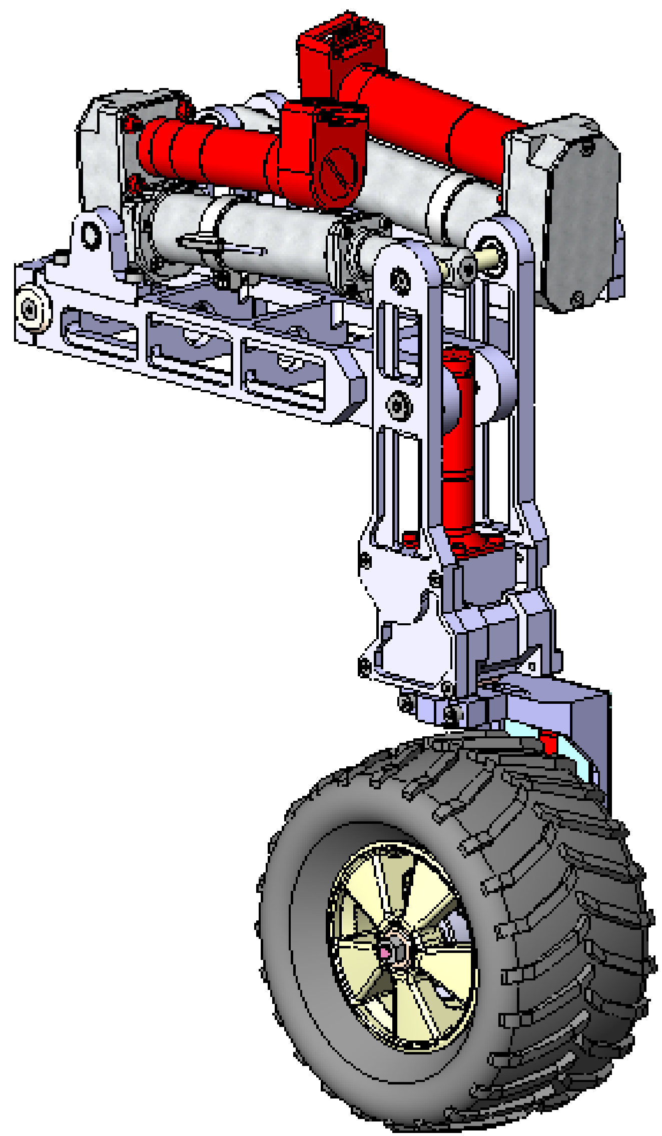
PC104

Bus *CAN*
(1 Mbits/S)

MPC555

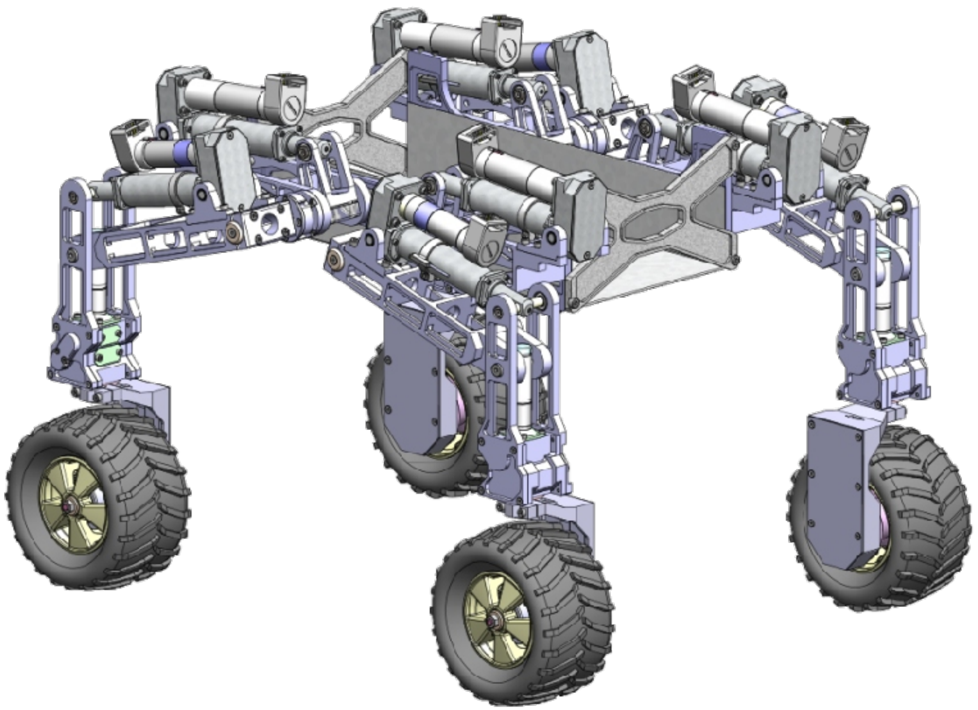
Architecture mécatronique





Masse	25 kg
Dimensions	70 x 50 x 40 cm (L x l x h) 14 cm ($\varnothing_{roue}$)
Variation de la garde au sol	10 cm à 40 cm
Vitesse	2 m/s
ddl	16 (4/patte)

Architecture mécatronique



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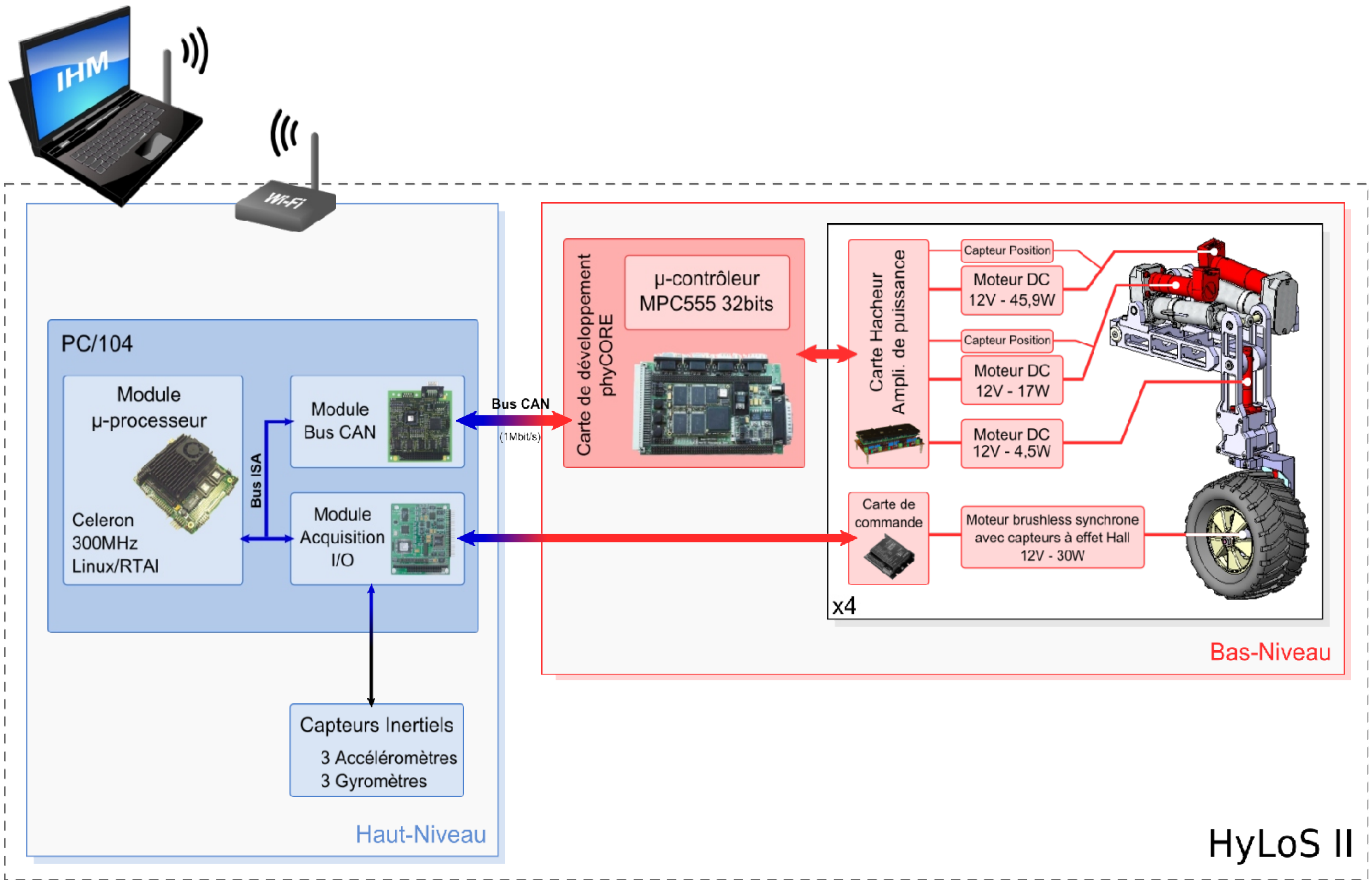
Architecture mécatronique



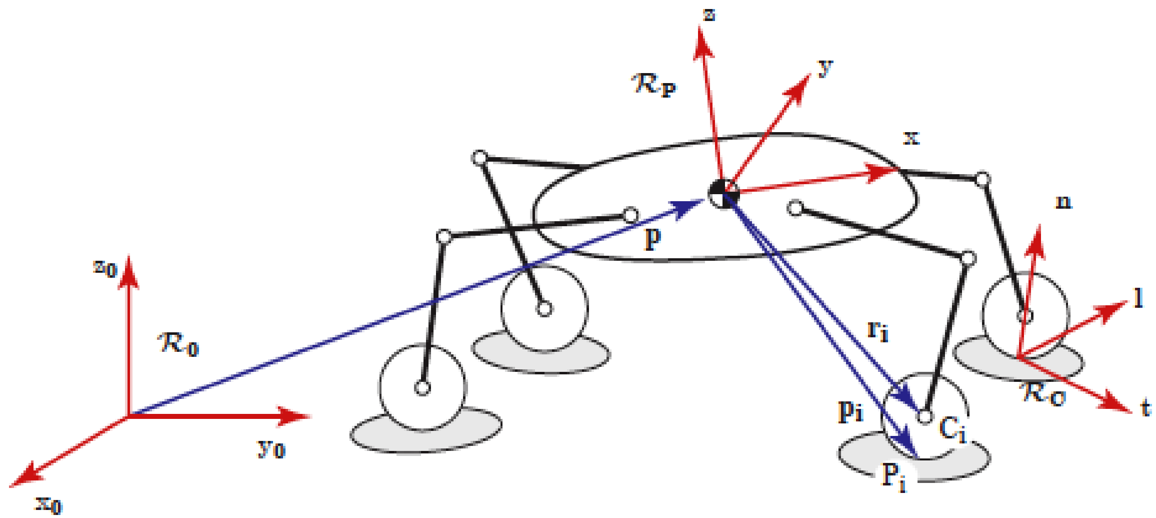
Modélisation cinémato-statique

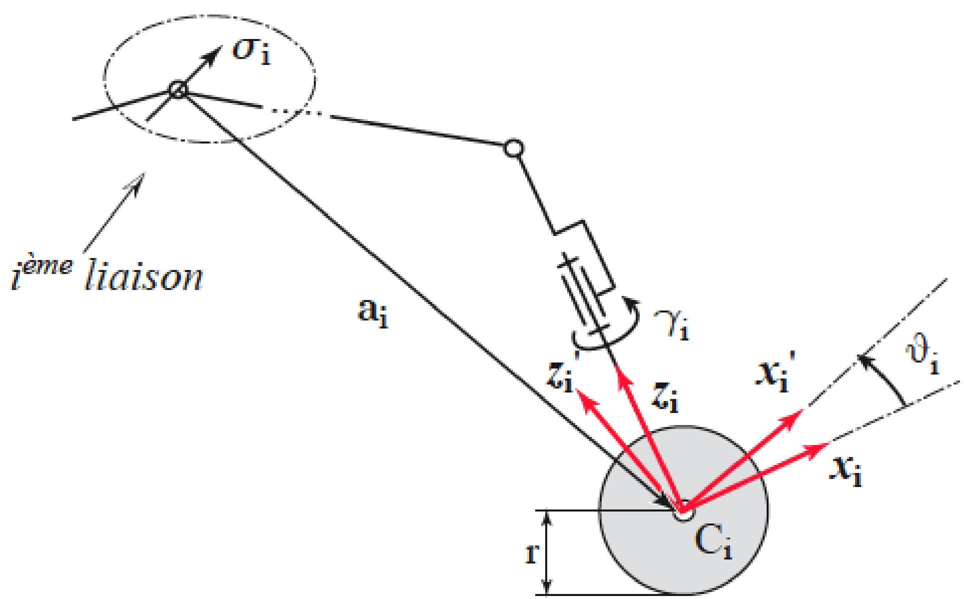
Inertial frame: $\mathcal{R}_0$

Main body frame: $\mathcal{R}_p$

Transformation: $\mathbf{x}^t = (\mathbf{p}^t, \boldsymbol{\phi}^t)$

$$\mathbf{p} = \begin{pmatrix} x \\ y \\ z \end{pmatrix} \qquad \boldsymbol{\phi} = \begin{pmatrix} \varphi \\ \psi \\ \theta \end{pmatrix}$$





Leg parameters: $\boldsymbol{\theta}_i = \begin{pmatrix} \alpha_i \\ \beta_i \\ \dots \end{pmatrix}$

Wheel configuration: $\boldsymbol{\chi}_i = \begin{pmatrix} \gamma_i \\ \vartheta_i \end{pmatrix}$

Global parameters:

$$\mathbf{q}^t = (\mathbf{x}^t, \boldsymbol{\theta}_1^t, \boldsymbol{\chi}_1^t, \boldsymbol{\theta}_2^t, \boldsymbol{\chi}_2^t, \dots)$$

Modélisation cinémato-statique

Wheel-soil contact give a velocity constraint at contact point P_i for each contact (pseudo closed loop) :

$$\mathbf{v_s} \triangleq \mathbf{v_x} + \mathbf{v_p} - \mathbf{v_c}$$

where

$${}^{\mathbf{p}}\mathbf{v_x} \triangleq \mathbf{R}\dot{\mathbf{p}} + \boldsymbol{\omega} \times \mathbf{p_i}$$ is the velocity of P_i due to platform motion

$${}^{\mathbf{p}}\mathbf{v_p} \triangleq \dot{\mathbf{r}}_\mathbf{i} = \mathbf{J}_{\mathbf{p_i}}\dot{\boldsymbol{\theta}}_i$$ is the velocity of P_i due to legs motion

$${}^{\mathbf{i}}\mathbf{v_c} \triangleq r\dot{\vartheta}_i\mathbf{t_i}$$ is the circumferential velocity of the wheel

The platform angular velocity: $\boldsymbol{\omega} = \mathbf{T}_\phi\dot{\boldsymbol{\phi}}$

$$\mathbf{T}_\phi(\boldsymbol{\phi}) = \begin{pmatrix} 1 & 0 & -S_\psi \\ 0 & C_\varphi & C_\psi S_\varphi \\ 0 & -S_\varphi & C_\psi C_\varphi \end{pmatrix}$$

$${}^{\mathbf{p}}\mathbf{v_x} = \mathbf{L_i}\dot{\mathbf{x}} \qquad \mathbf{L_i} = \left[\begin{array}{cc} \mathbf{R} & -\widetilde{\mathbf{p}}_\mathbf{i}\mathbf{T}_\phi \end{array}\right]$$

Modélisation cinémato-statique

Equations projected in each **contact frame** $\mathcal{R}_i = (P_i, \mathbf{t}_i, \mathbf{l}_i, \mathbf{n}_i)$

$$\mathbf{v_s} \triangleq \mathbf{v_x} + \mathbf{v_p} - \mathbf{v_c} \quad \longrightarrow \quad \mathbf{v_s} = \mathbf{R_i}^t \mathbf{L_i} \dot{\mathbf{x}} + \mathbf{R_i}^t \mathbf{J_{p_i}} \dot{\boldsymbol{\theta}}_i - r \dot{\vartheta}_i \mathbf{t_i}$$

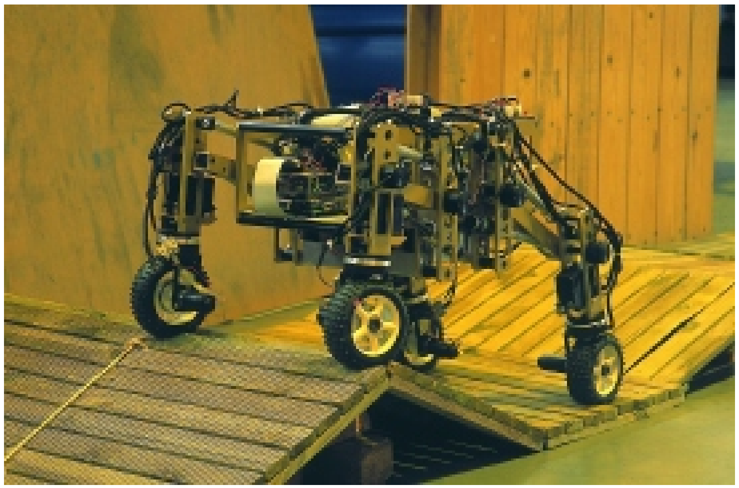
$$\mathbf{L}\dot{\mathbf{x}} + \mathbf{J}\dot{\boldsymbol{\Theta}} = \mathbf{v_s}$$

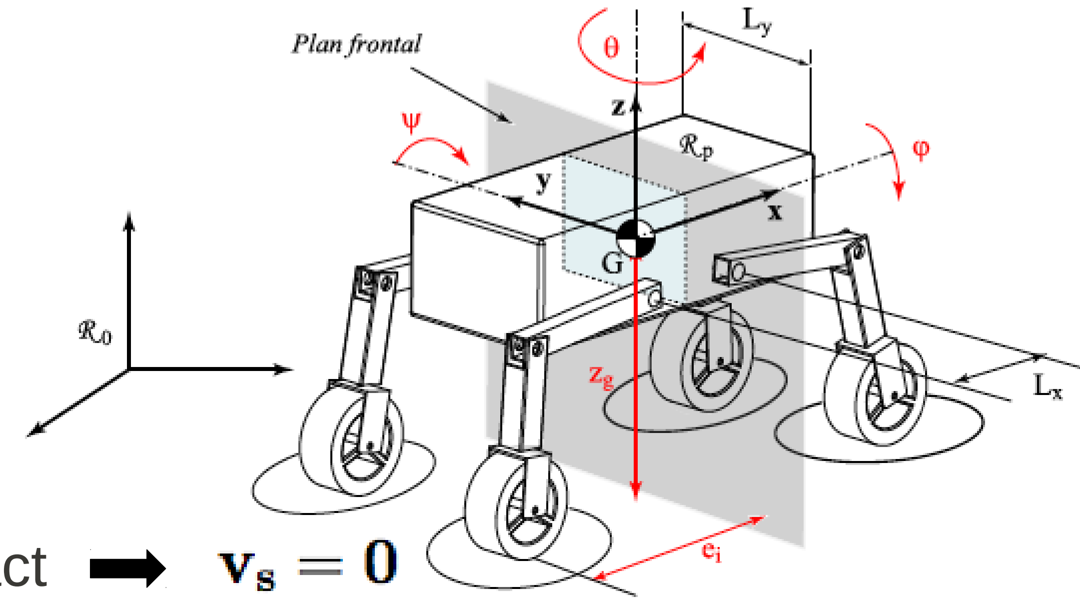
For n contact points
$3n$ scalar velocity constraints
m joint velocities

$$\mathbf{v}_{s_i} = \begin{pmatrix} s_{t_i} \\ s_{l_i} \\ s_{n_i} \end{pmatrix} \qquad \boldsymbol{\Theta} = \begin{bmatrix} \boldsymbol{\theta}_1 \\ \boldsymbol{\chi}_1 \\ \boldsymbol{\theta}_2 \\ \boldsymbol{\chi}_2 \\ \vdots \\ \boldsymbol{\theta}_n \\ \boldsymbol{\chi}_n \end{bmatrix}_{n\,m \times 1}$$

$$\mathbf{L}(\mathbf{x}, \boldsymbol{\Theta}, \mathbf{n}) = \begin{bmatrix} \mathbf{R}_1^t \mathbf{L}_1 \\ \mathbf{R}_2^t \mathbf{L}_2 \\ \vdots \\ \mathbf{R}_n^t \mathbf{L}_n \end{bmatrix}_{\mathbf{3n \times 6}} \qquad \mathbf{J}(\boldsymbol{\Theta}, \mathbf{n}) = \begin{bmatrix} \mathbf{J}_1 & \mathbf{0} & \dots & \mathbf{0} \\ \mathbf{0} & \mathbf{J}_2 & & \mathbf{0} \\ \vdots & & \ddots & \\ \mathbf{0} & \mathbf{0} & & \mathbf{J}_n \end{bmatrix}_{3n \times n\,m} \qquad \mathbf{J}_i = \begin{bmatrix} \mathbf{R}_i^t \mathbf{J}_{\mathbf{p}_i} & \begin{bmatrix} -r \\ 0 \\ 0 \end{bmatrix} \end{bmatrix}_{3 \times m}$$

Analyse de la mobilité





<u>Hypothesis</u>: no sliding in the contact ➡ $\mathbf{v_s} = \mathbf{0}$

Hylos is a 4 wheel-legged robots with 4 dof for each one:

$n = 4$ and $m = 16$

$\mathbf{L}\dot{\mathbf{x}} + \mathbf{J}\dot{\mathbf{\Theta}} = \mathbf{0}$ ➡ correspond to 4x3 = 12 scalar equations

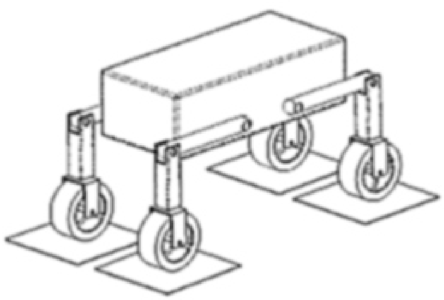
6 operational and 16 joint dof(s) ➡ 22 velocity parameters

Mobility index = 10

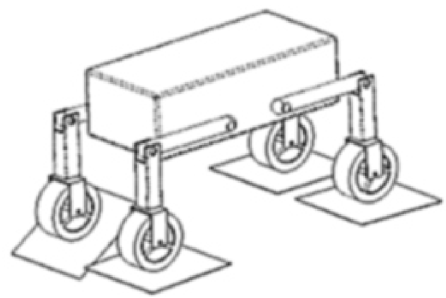
Analyse de la mobilité

$$\mathbf{L}\dot{\mathbf{x}} + \mathbf{J}\dot{\mathbf{\Theta}} = 0 \iff \mathbf{A}\dot{q} = 0 \quad \text{with} \quad \mathbf{A} = [\mathbf{L} \mid \mathbf{J}] \text{ and } \dot{q} = [\dot{\mathbf{x}}\ \dot{\mathbf{\Theta}}]^t$$

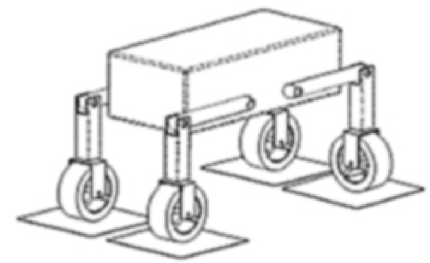
$$m_r = \dim(\mathbf{q}) - \mathbf{rank}(\mathbf{A})$$



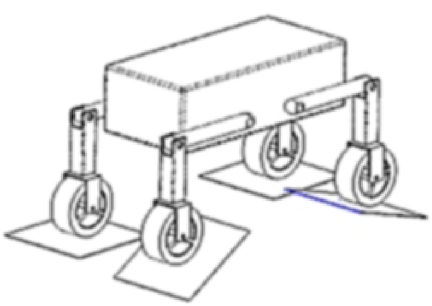
$m_r = 12$



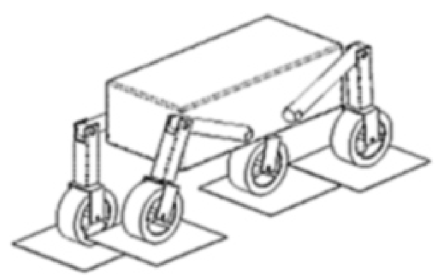
$m_r = 11$



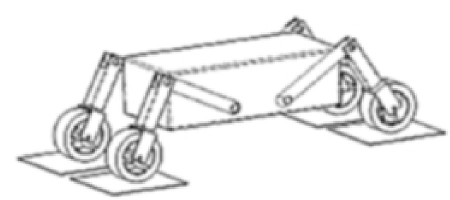
$m_r = 11$



$m_r = 10$

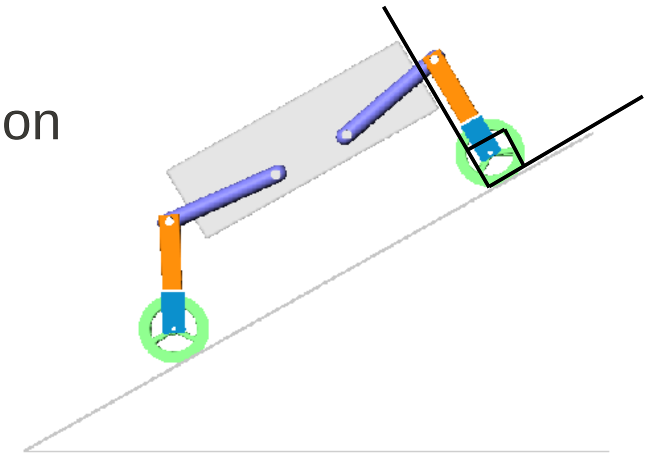


$m_r = 10$



$m_r = 10$

Contrôle de posture



Hypothesis: the steering angle velocity as limited effect on the instantaneous robot velocity

⇨ Remove $\dot{\gamma}_i$ in velocity equations ($\mathbf{u} = \mathbf{B_j}\dot{\Theta}$) and use non-holonomic conditions to solve γ_i

$$\begin{cases} \mathbf{t_i^t v_{s_i}} = \mathbf{0} \\ \mathbf{n_i^t v_{s_i}} = \mathbf{0} \\ \mathbf{B_x L \dot{x}} + (\mathbf{B_x J B_j^t})(\mathbf{B_j}\dot{\Theta}) = \mathbf{0} \end{cases}$$

⇨ 8 scalar equations

$$\mathbf{B_x} = \begin{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} & & \mathbf{0} \\ & \ddots & \\ \mathbf{0} & & \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{bmatrix}_{2n \times 3n}$$

$$\begin{cases} \mathbf{l_i^t v_{s_i}} = \mathbf{0} \\ \mathbf{B_\gamma L \dot{x}} + (\mathbf{B_\gamma J B_j^t})(\mathbf{B_j}\dot{\Theta}) = \mathbf{0} \end{cases}$$

⇨ 4 scalar equations

$$\mathbf{B_j} = \begin{bmatrix} \begin{bmatrix} \mathbf{I} & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} & & \mathbf{0} \\ & \ddots & \\ \mathbf{0} & & \begin{bmatrix} \mathbf{I} & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{bmatrix}_{(l-n) \times m}$$

Contrôle de posture

System redundancy:

$\dot{\mathbf{q}}^t = (\dot{\mathbf{x}}^t, \ \mathbf{u}^t)$ — 6 + 12 dof(s)

$\mathbf{B_x L \dot{x}} + \left(\mathbf{B_x J B_j^t}\right)\mathbf{u} = \mathbf{0}$ — 8 velocity constraints

➡ 10 degrees mobilities

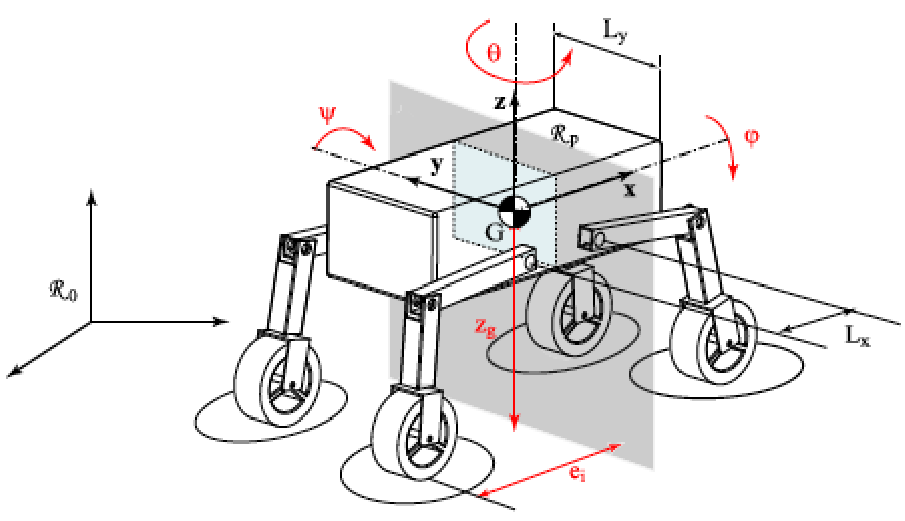
Operational space velocity $\dot{\mathbf{x}}$ ➡ 6 state parameters

Internal parameters **e** ➡ 4 state parameters $\dot{\mathbf{e}} = \mathbf{J_e}(\Theta)\mathbf{u}$

$$\xi^t = (\mathbf{x}^t, \mathbf{e}^t)$$

$$\begin{bmatrix} \mathbf{B_x L} \\ -\mathbf{I} \end{bmatrix} \begin{bmatrix} \dot{\mathbf{x}} \\ \dot{\mathbf{e}} \end{bmatrix} + \begin{bmatrix} \mathbf{B_x J B_j^t} \\ \mathbf{J_e} \end{bmatrix} \mathbf{u} = \mathbf{0}$$

➡ $$\boxed{\widetilde{\mathbf{L}}\dot{\xi} + \widetilde{\mathbf{J}}\mathbf{u} = 0}$$



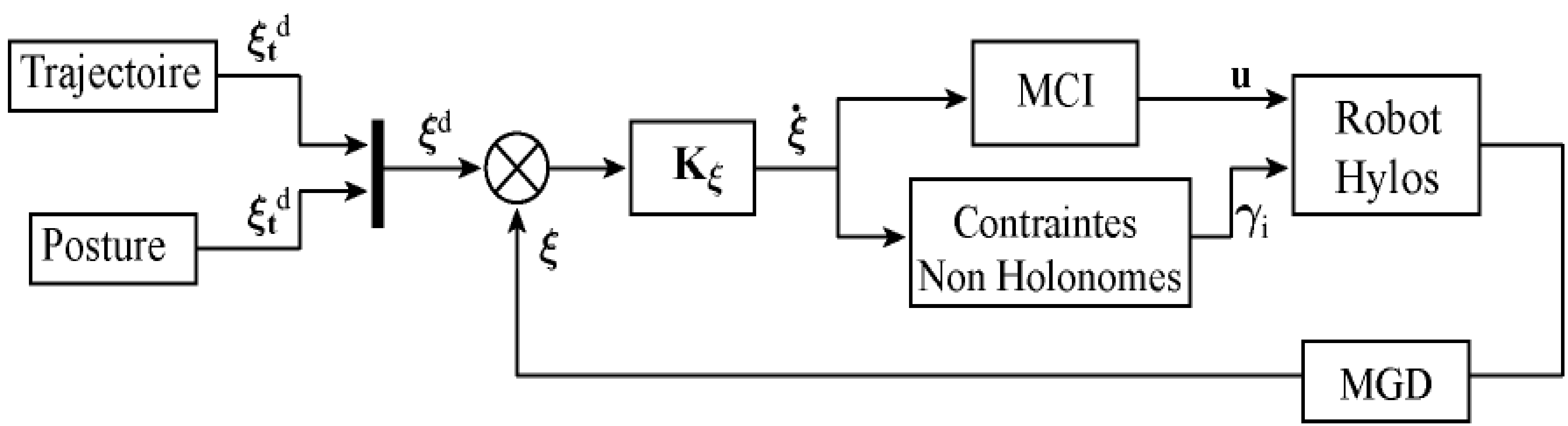
Contrôle de posture

$\widetilde{\mathbf{J}}$ is a square 12x12 matrix and it is singular only for few identified cases:

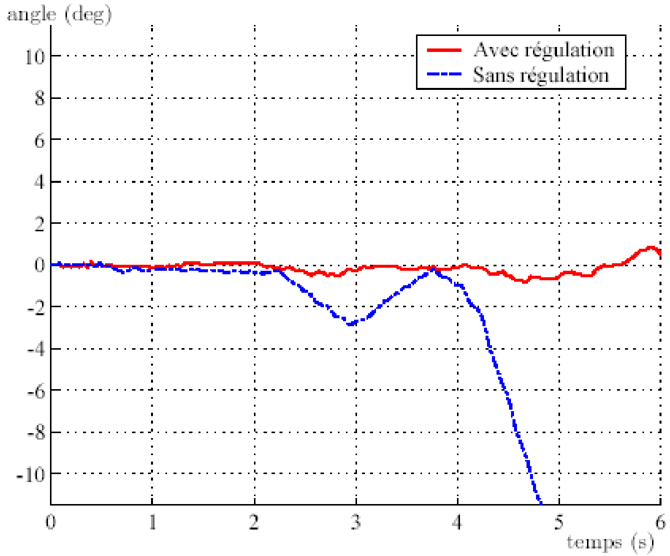
Joint velocities: $\mathbf{u} = -\widetilde{\mathbf{J}}^{-1}\widetilde{\mathbf{L}}\dot{\xi}$

$$\boldsymbol{\xi}^{\mathrm{t}} = (\mathbf{x}^{\mathrm{t}}, \mathbf{e}^{\mathrm{t}}) \quad \Rightarrow \quad \begin{cases} \boldsymbol{\xi}_{\mathbf{p}} = (z,\ \varphi,\ \psi,\ e_1,\ e_2,\ e_3,\ e_4)^{\mathrm{t}} \\ \boldsymbol{\xi}_{\mathbf{t}} = (x,\ y,\ \theta)^{\mathrm{t}} \end{cases}$$

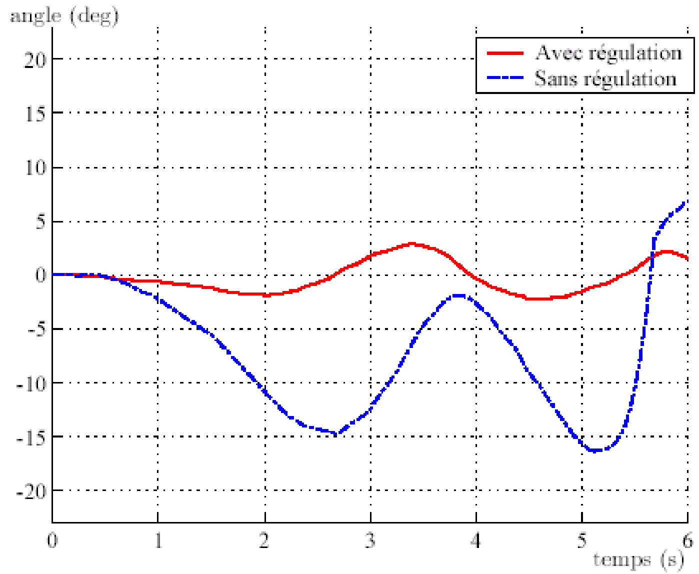
State-feedback control law: $\dot{\boldsymbol{\xi}} = \mathbf{K}_{\mathbf{p}}(\boldsymbol{\xi}_{\mathbf{p}}^{d} - \boldsymbol{\xi}_{\mathbf{p}}) + \mathbf{K}_{\mathbf{t}}(\boldsymbol{\xi}_{\mathbf{t}}^{d} - \boldsymbol{\xi}_{\mathbf{t}})$



Contrôle de posture

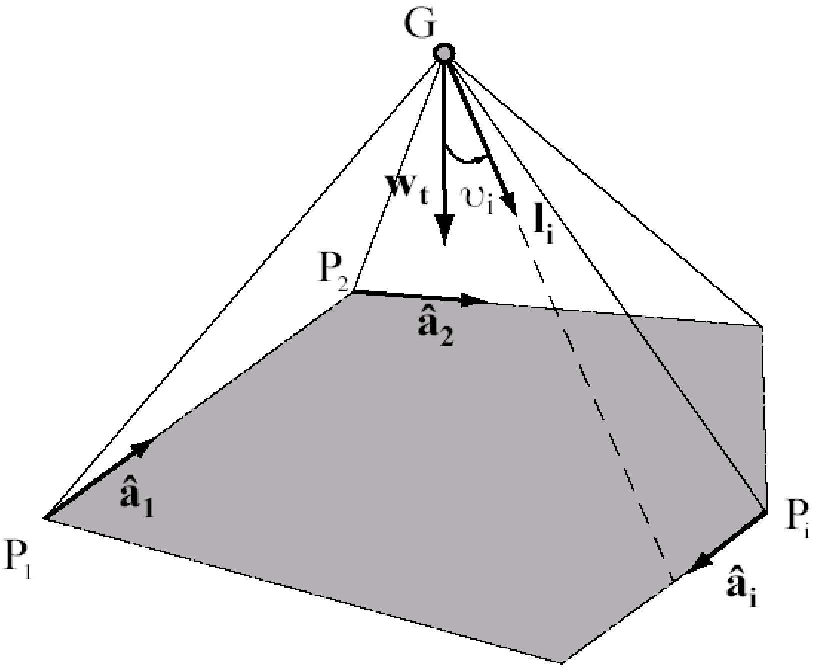


(b) Angle de roulis

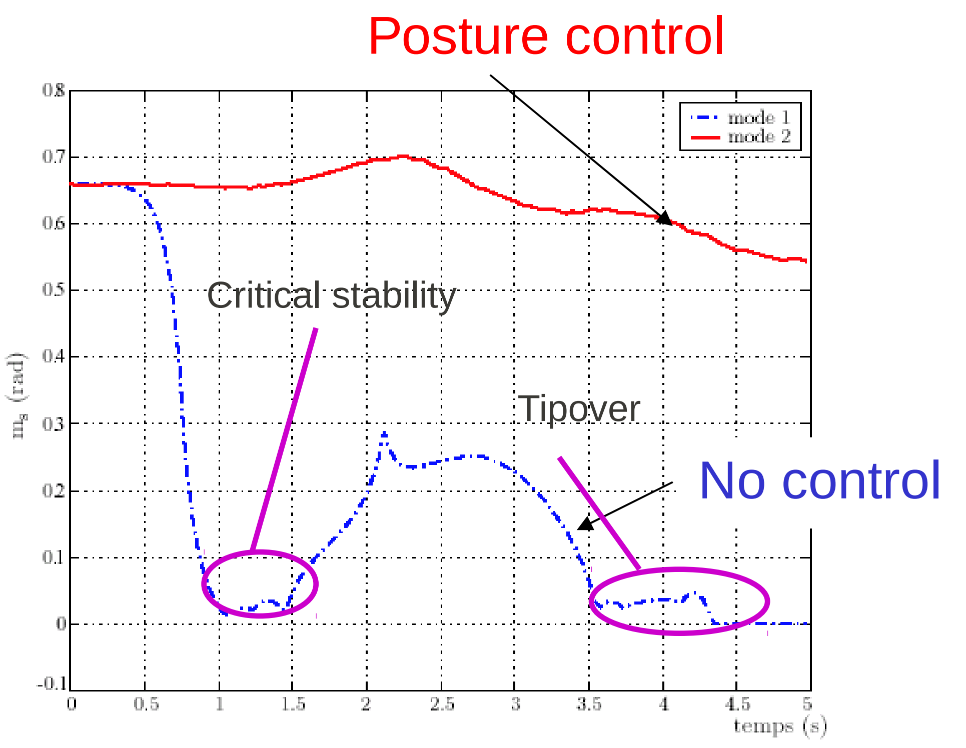


(a) Angle de tangage

Contrôle de posture

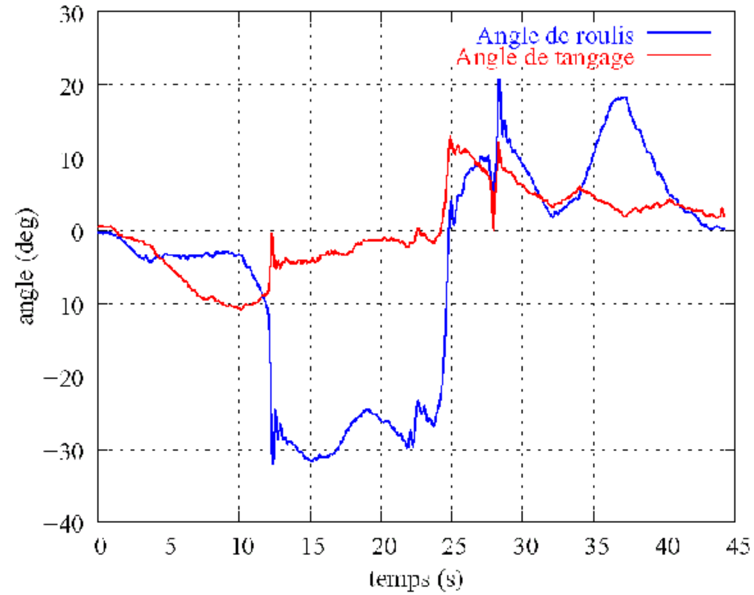


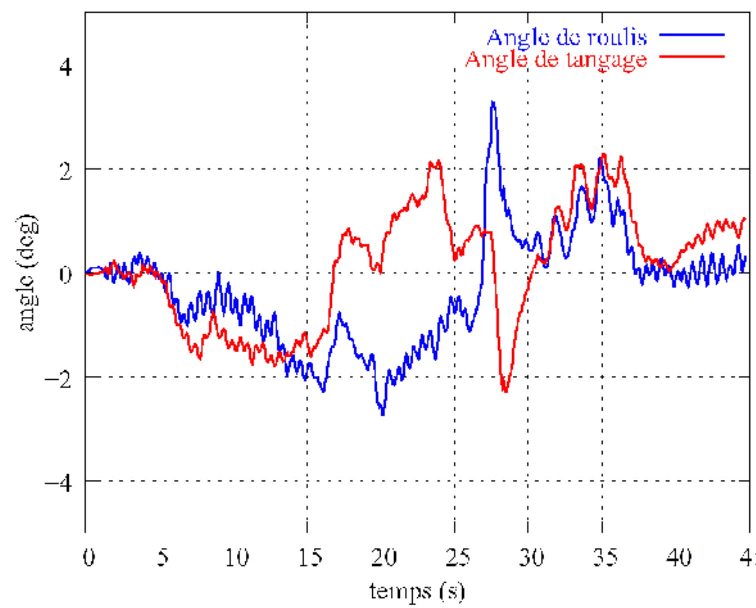
$$M_s = \min(\upsilon_i) \quad i = \{1, \ .., \ n\}$$



3 dimensional pseudo-dynamic stability measure[1]

Contrôle de posture





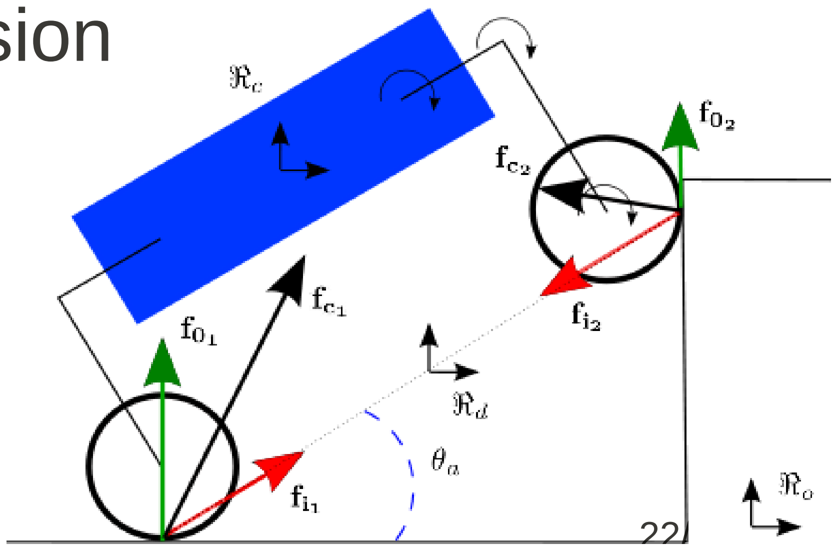
Distribution des forces

Objectifs

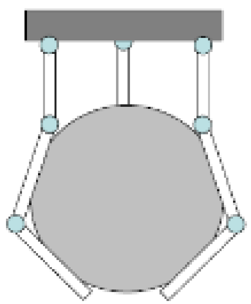
- Franchissement d'obstacle de type marche
- Utilisation des efforts internes pour optimiser la distribution des efforts de contact
- Maximiser les frottements de Coulomb

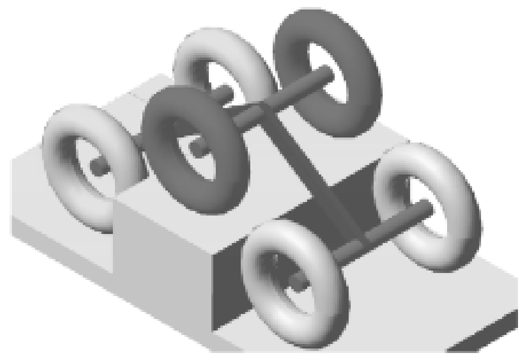
Approche

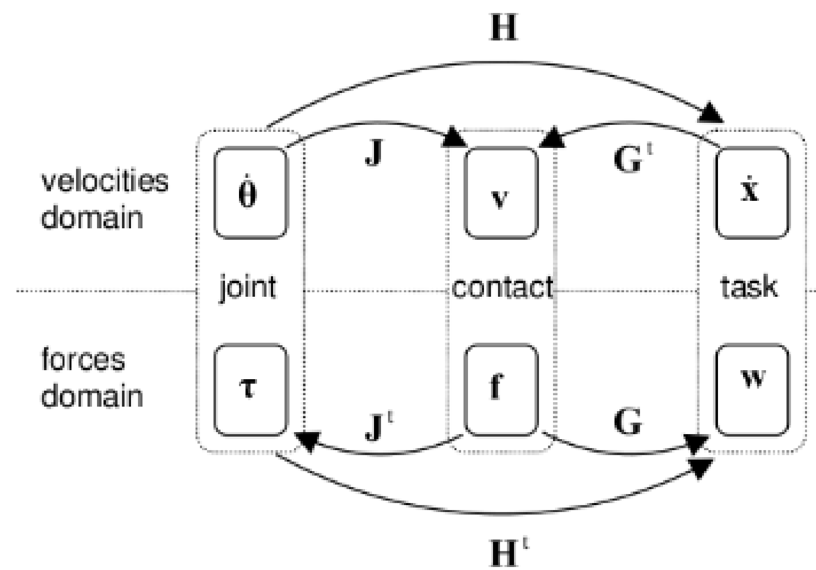
- Analogie locomotion / préhension
- Optimisation sous la forme *minimax*

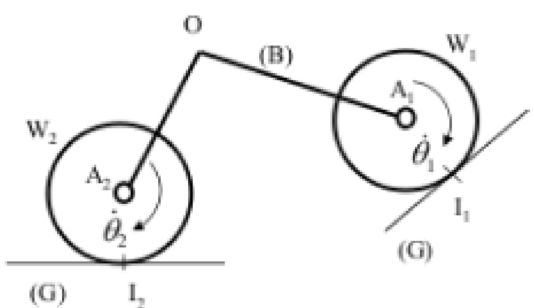


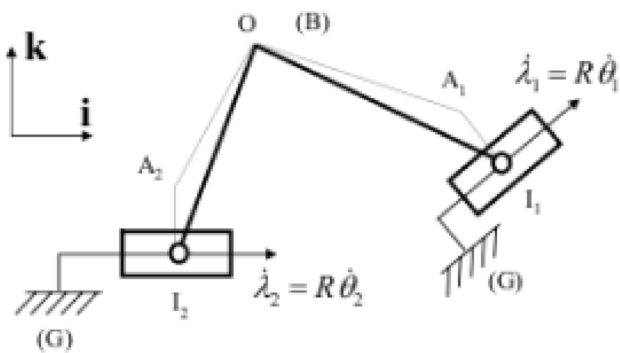
Distribution des forces











$$\mathbf{v} = -\mathbf{G}^t \dot{\mathbf{x}} = \mathbf{J}\dot{\theta}$$

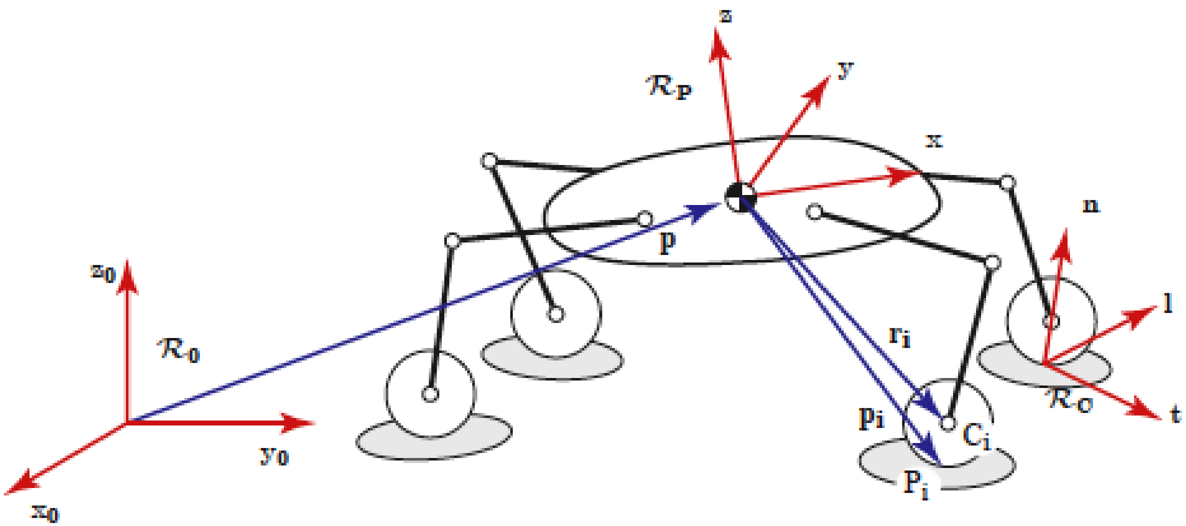
$$\begin{cases} \mathbf{G}\,\mathbf{f} = \mathbf{w} \\ \mathbf{J}^t\mathbf{f} = \tau \end{cases}$$

Distribution des forces

$$G\ \mathbf{f} = \mathbf{F}$$

$$\mathbf{G} = \begin{bmatrix} I_{3\times3}\ R_{c_1} & \dots & I_{3\times3}\ R_{c_n} \\ \tilde{\mathbf{p}}_1\ R_{c_1} & \dots & \tilde{\mathbf{p}}_n\ R_{c_n} \end{bmatrix}$$

$$J^t\ \mathbf{f} = \boldsymbol{\tau}$$

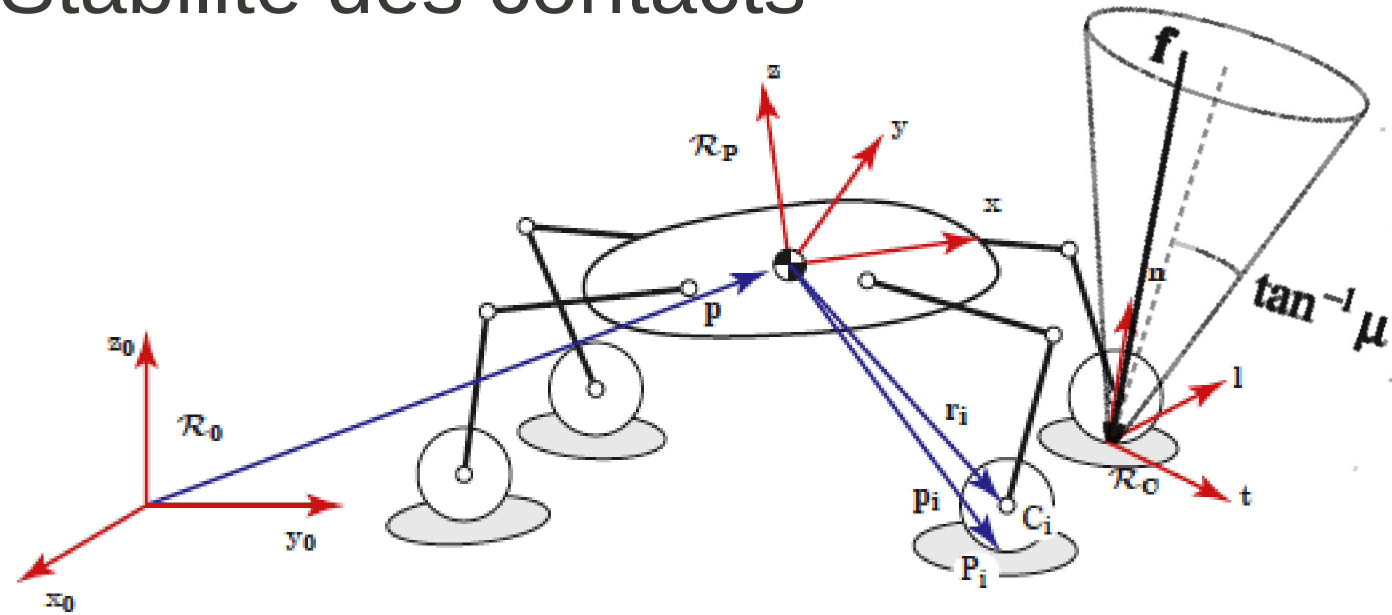


where

- f is the column vector of contacts forces
- F is the 6x1 vector of total wrench applied to the robot CoG
- p_i is position vector of each contact point P_i
- G is the equivalent grasping matrix

Distribution des forces

Stabilité des contacts

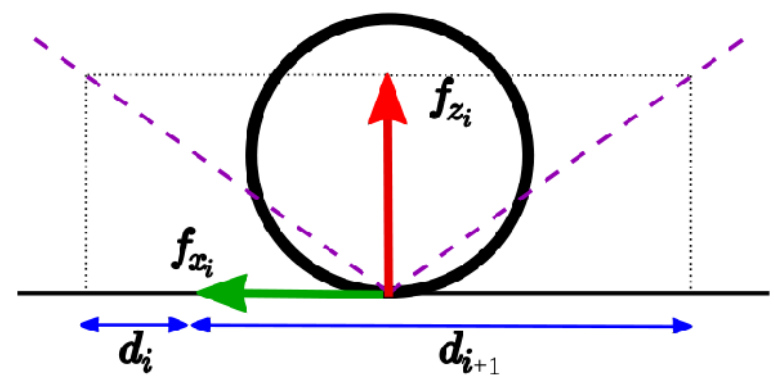


$$\begin{cases} f_{n_k} > 0 \\ \mu^2 f_{n_k}^2 > f_{t_k}^2 \end{cases}$$

Approximation:

$$\mathbf{d} = A\ \mathbf{f} \qquad A_i = \begin{bmatrix} \frac{\mu_i}{\sqrt{2}} & 1 & 0 \\ \frac{\mu_i}{\sqrt{2}} & -1 & 0 \\ \frac{\mu_i}{\sqrt{2}} & 0 & 1 \\ \frac{\mu_i}{\sqrt{2}} & 0 & -1 \end{bmatrix}$$

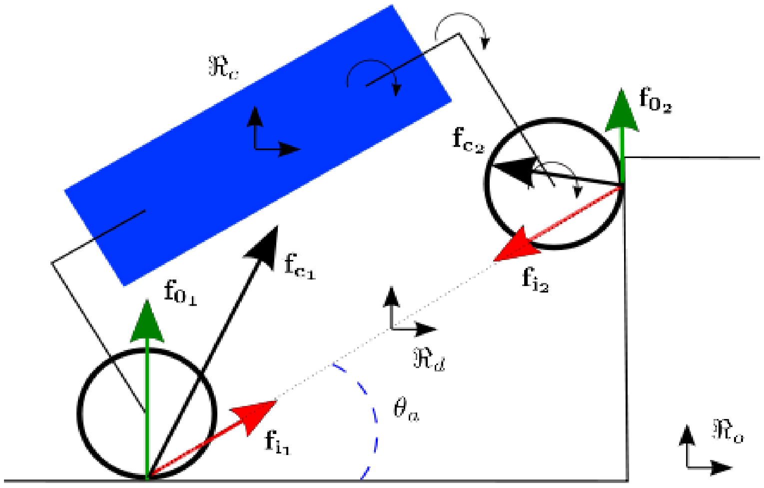
$$A = blockdiag(A_i)$$



$$\phi(\mathbf{f}) = \min(A\ \mathbf{f})$$

Distribution des forces

Optimisation du franchissement :



Find $\mathbf{f} \in \mathbb{R}^{3n}$ maximizing $\phi(\mathbf{f})$

Subject to:

$$\begin{aligned} G\mathbf{f} &= \mathbf{F} \\ J^T\ \mathbf{f} &< \tau_{max} \\ -J^T\ \mathbf{f} &< \tau_{max} \end{aligned}$$

Distribution des forces

Gestion de la redondance:

$$G\ \mathbf{f} = \mathbf{F} \qquad \text{avec } \dim(G) = 6 \times 12$$

Solution :

$$\mathbf{f} = \mathbf{f_p} + \mathbf{f_h}$$

$$\mathbf{f_p} = G^{+}_{Norm}\ \mathbf{F} \quad \text{et} \quad G\ \mathbf{f_h} = \mathbf{0}$$

$$\text{Ker}(G) = \text{vect}\left(\{\mathbf{b_i}\}_{i \in [1,m]}\right) \quad \rightarrow \quad N_f = [\mathbf{b_1}\ \ldots\ \mathbf{b_m}]$$

$$\mathbf{f} = G^{+}_{Norm}\ \mathbf{F} + N_f \mathbf{x_f}$$

→ *Efforts internes* ($N_f \mathbf{x_f}$)

Distribution des forces

Optimisation des forces internes:

Find $\mathbf{x_f} \in \mathbb{R}^m$ maximizing

$$\min\left(A[G^{+}\mathbf{F} + N_f\ \mathbf{x_f}]\right)$$

Subject to:

$$J_f^T\ \mathbf{x_f} < \mathbf{a_f}$$

with:

$$J_f = \left[\begin{array}{cc} N_f^T\ J & -N_f^T\ J \end{array}\right]^T$$

$$\mathbf{a_f} = \left[\begin{array}{cc} (\tau_{max} - J^T\ G^{+}\ \mathbf{F})^T & (\tau_{max} + J^T\ G^{+}\ \mathbf{F})^T \end{array}\right]^T$$

Distribution des forces

Reconfiguration : position CdM

$$\mathbf{f_p} = \mathbf{c_x}\ X + \mathbf{c_z}\ Z + \mathbf{f_0}$$

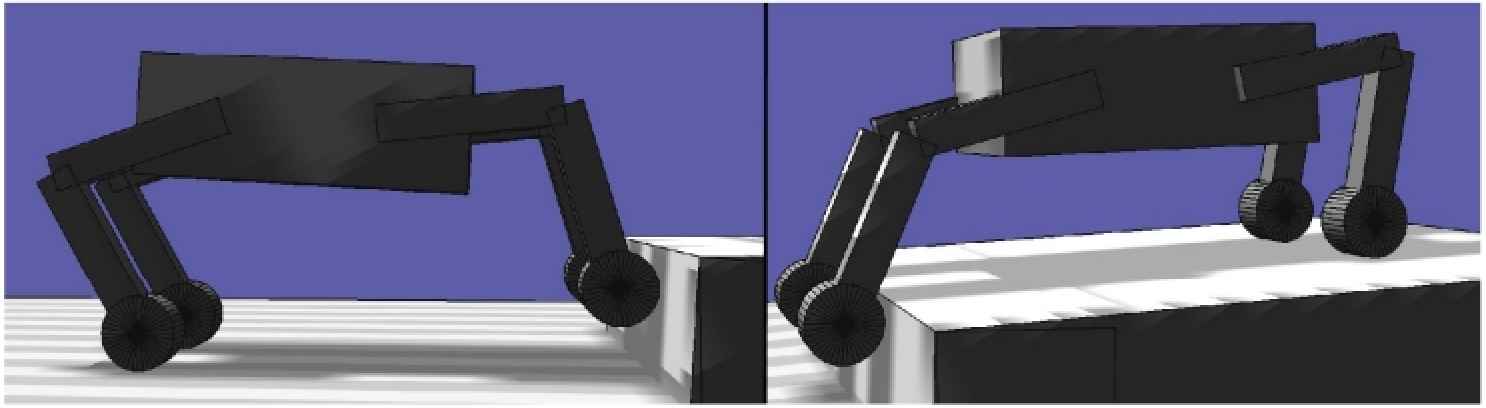
$$\mathbf{f} = \mathbf{f_0} + N\ \mathbf{x}$$

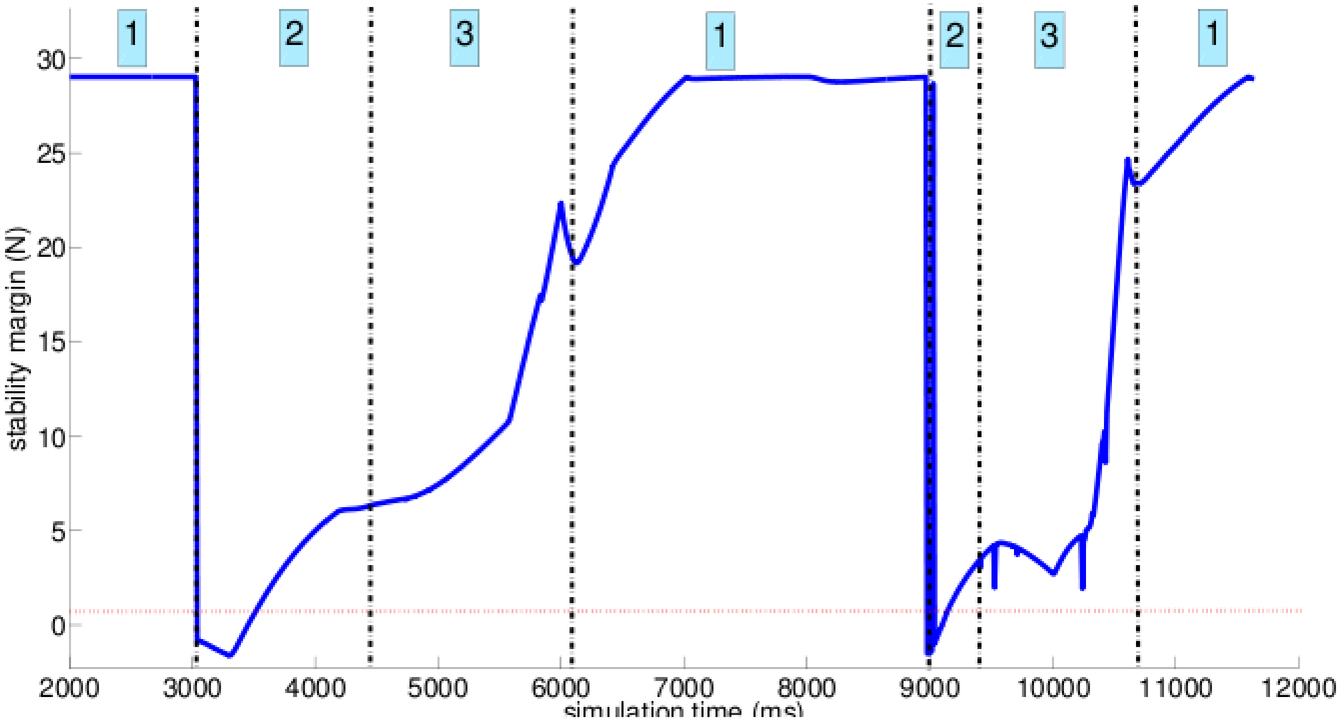
with $N = \left[\begin{array}{ccc} N_f & \mathbf{c_x} & \mathbf{c_z} \end{array}\right]$ and $\mathbf{x} = \left[\begin{array}{cc} \mathbf{x_f}^T & \mathbf{x_p}^T \end{array}\right]^T$

Distribution des forces

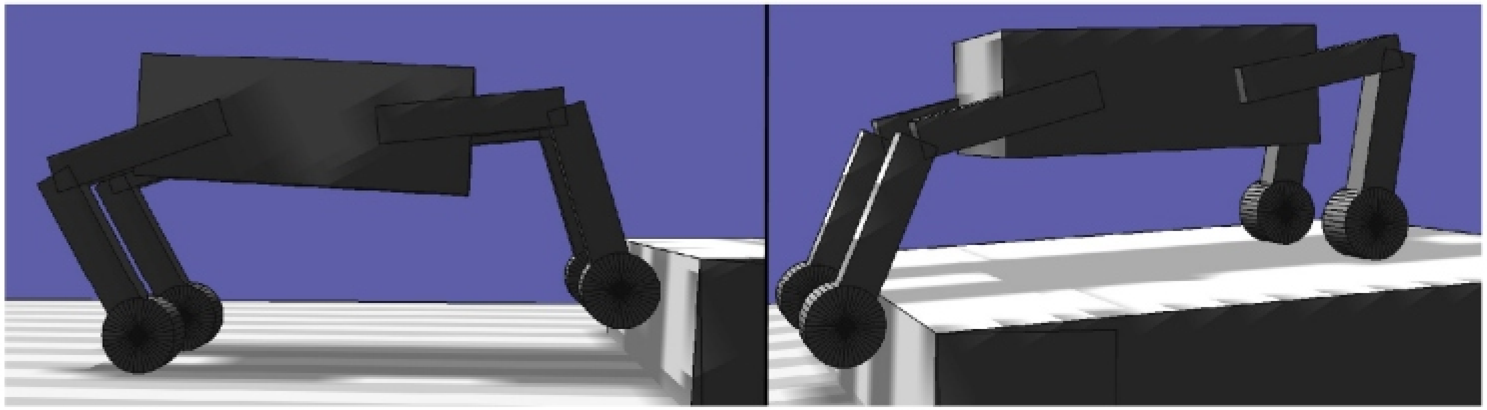
Simulation

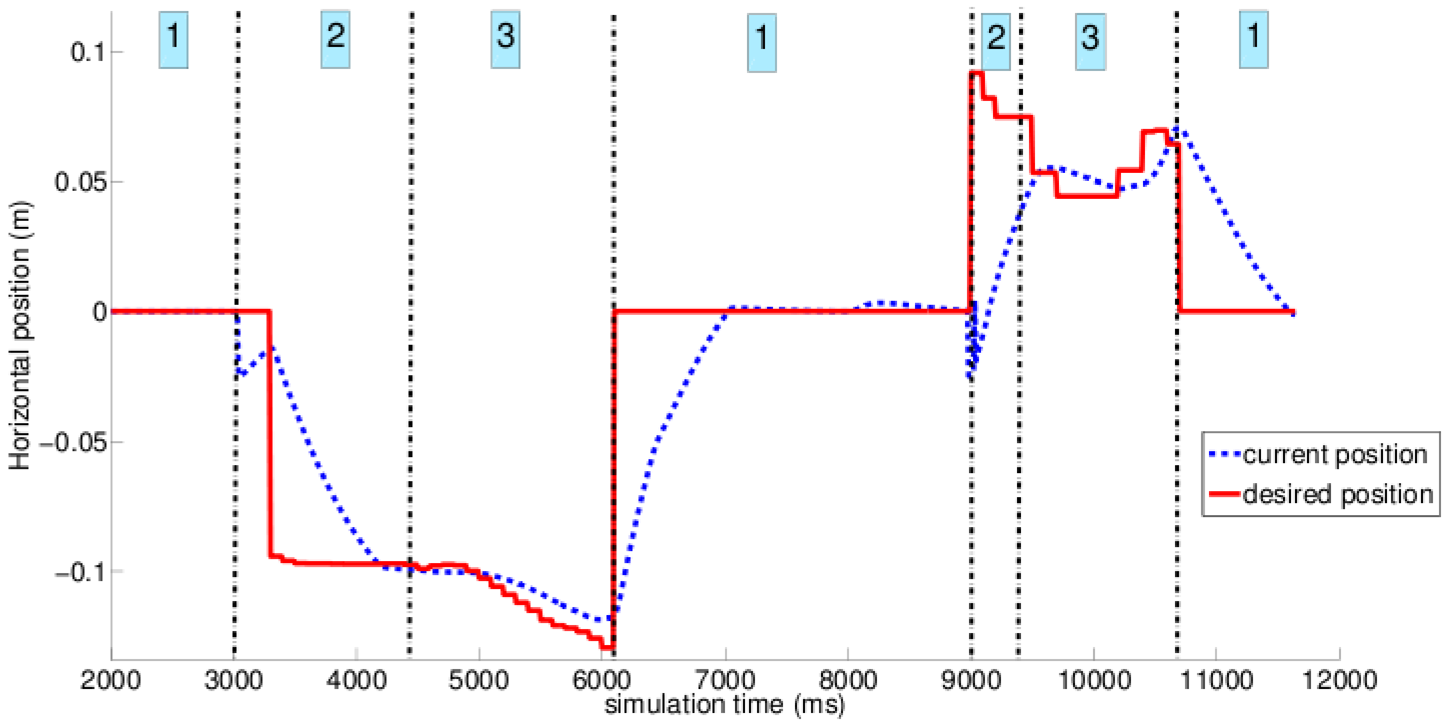
Distribution des forces





Distribution des forces





Distribution des forces

Simulation