

# Dynamic control of the 6WD skid-steering mobile robot RobuROC6 using sliding mode technique

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**Abstract**—A robust dynamic feedback controller is designed and implemented, based on the dynamic model of the six-wheel skid-steering RobuROC6 robot, performing high speed turns. The control inputs are respectively the linear velocity and the yaw angle. The main object of this paper is to elaborate a sliding mode controller, proved to be robust enough to ignore the knowledge of the forces within the wheel-soil interaction, in the presence of sliding phenomena and ground level fluctuations. Finally, a 3D simulation is performed with an accurate physical engine to evaluate the efficiency of this designed control law.

## I. INTRODUCTION

The main objective of this paper is to control precisely a six wheel drive skid-steering vehicle for path following. Nevertheless, vehicle systems are not usually easy to control owing to unknowns about their model and owing to the difficulty to evaluate the forces in the wheel-soil interaction. Many interaction models developed by Bakker [3] or by Pacejka [13] try to represent the complexity of the physical phenomena using empirical models. However, wheel-soil interaction is still one of the great unknowns in mobile robotic systems. The dynamic of skid-steering mobile robots has been studied by Caracciolo in [5], with the use of a dynamic feedback linearization paradigm for a model-based controller that minimizes lateral skidding by imposing the longitudinal position of the instantaneous center of rotation. In [11], Kozłowski designed a new algorithm proved to have a high robustness to dynamic parameters uncertainty. Now, an other strategy that uses a sliding mode controller can be investigated in order to deal with the skid phenomenon that is inherent to this kind of vehicle. This controller, developed by Utkin [17], authorizes a decoupling design procedure, disturbance rejection, insensitivity to dynamic parameters variations, and a simple implementation. That is why this control law has been treated in many ways in the literature. In [10] and in [2] dynamic control laws are studied, but without taking into account the complex dynamical model of the vehicle. In [18] and then in [6] the dynamical model of a unicycle is studied for the design of a controller by using a nonholonomic constraint, considering a null lateral velocity. In [9], it is taken into account that in realistic case, the nonholonomic constraints are not satisfied. But the problem is addressed for a partially linearized dynamical model of a unicycle robot.



Fig. 1. RobuROC6

Here, we suggest an original dynamical model based sliding mode control method for fast autonomous mobile robots, that control the torques applied in the wheels. The main objective is to follow a given path with a relatively high speed by servoing the longitudinal velocity and the yaw angle. The terrains considered here are horizontal in theory and relatively smooth compared to the size of the wheels. If most of the mobile robots motion controllers found in the literature use the hypothesis of rolling without slipping, it is no longer suitable at high speed where wheel slip can not be neglected. Owing to the dynamics of the vehicle and the saturation of admissible forces by the soil, the slippage reduces the robot motion stability. So that we need a controller robust enough.

A 3D simulation is done in a dynamic environment with the robuBOX, a software being developed by the ROBOSOFT company [1] and based on Microsoft Robotics Studio. An interaction wheel-soil model of forces designed by Szostak and al in [16], described in the fifth section, is used to permit a realistic modelization of the system behavior. We will analyze the motion control of a RobuROC6 represented Fig. 1.

It is an electric mobile robot developed by Robosoft, for exemple studied in [12], which consists of three pods steered and driven by two actuated conventional wheels on which a lateral slippage may occur. The rear and the front pods are symmetrically arranged about the central pod. They are attached to this later one by two orthogonal passive rotoid joints providing a roll/pitch relative motion for keeping the wheels on the ground to maintain traction of the pod when traversing irregular surfaces. Note that the pitch mobility can be actuated by hydraulic cylinders. Two ultrasound sensors with a range of 3,4 meters and two bumper sensors are

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located in the front and in the rear of the robot. One inclinometer for each pod and odometric sensors are also available. A GPS and a gyro meter are needed for the control law implementation.

A controller based on a complete three dimensional dynamic modelisation of this kind of articulated system would be difficult to investigate, especially for calculation times if we intend to reach high velocities. That is the reason why the sliding mode controller is particularly adapted. The robustness of this controller, according to the robot dynamic model, permits to stay quite reliable in spite of the sliding phenomenon and the roll and pitch movements of the three pods, due to possible fluctuations of the ground level and of the normal contact.

This paper is organized as follows. In the second section, the system dynamical model is given. In the third section, we describe the design of the sliding mode controller. In the fourth section, the use of the Robosoft Robobox for an efficient implementation of the controller is detailed. In the last section, simulation results using this controller are presented and analyzed.

## II. SYSTEM DYNAMICS MODEL

A dynamic model of a skid-steering vehicle is established in fixed frame  $\mathcal{R}_0 = \{O_0, x_0, y_0, z_0\}$ . We consider  $\mathcal{R} = \{G, x, y, z_0\}$  the frame attached to the vehicle. The vehicle pose vector is given by  $[x, y, \theta]^T$ , where  $[x, y]^T$  is the position of the center of gravity  $G$  and  $\theta$  is the orientation of  $\mathcal{R}$ , both with respect to  $\mathcal{R}_0$ . The representation of the 6WD skid-steering vehicle is described Fig. 2. The absolute velocity  $[\dot{x}, \dot{y}, \dot{\theta}]^T$  become  $[u, v, r]^T$  in the local frame, linked by the

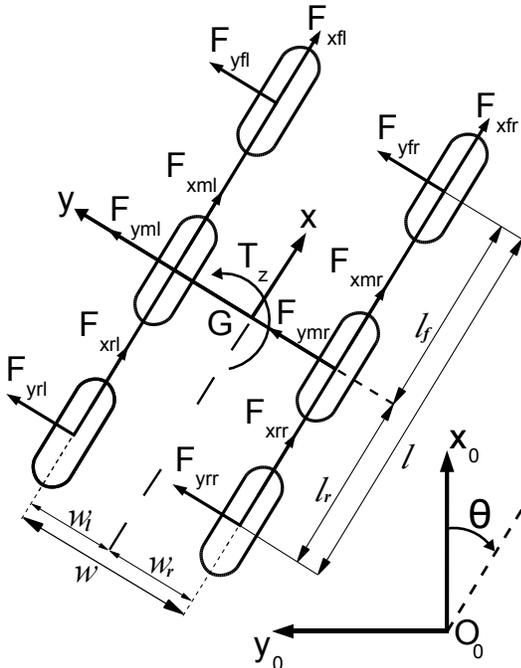


Fig. 2. System dynamics

relationship:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u \\ v \\ r \end{bmatrix} \quad (1)$$

The wheel-ground interaction forces are called  $F_{x**}$  and  $F_{y**}$  for each one of the six wheels in both the longitudinal  $x$  and the lateral  $y$  directions (with  $f, m$  and  $r$  for front, middle and rear, and  $l$  and  $r$  for left and right). Dynamical model of this mechanical system can be expressed in the local frame by the following equations:

$$M(\dot{u} - rv) = F_{xrl} + F_{xrr} + F_{xml} + F_{xmr} + F_{xfl} + F_{xfr} \quad (2)$$

$$M(\dot{v} + ru) = F_{yrl} + F_{yrr} + F_{yml} + F_{ymr} + F_{yfl} + F_{yfr} \quad (3)$$

$$\begin{aligned} J\dot{r} &= -w_l F_{xrl} + w_r F_{xrr} - l_r F_{yrl} - l_r F_{yrr} \\ &\quad - w_l F_{xml} + w_r F_{xmr} \\ &\quad - w_l F_{xfl} + w_r F_{xfr} + l_f F_{yfl} + l_f F_{yfr} \end{aligned} \quad (4)$$

which express the dynamic of the main frame considered as a unique rigid body, and:

$$\begin{aligned} J_w \dot{\omega}_{fl} &= \tau_{fl} - R F_{xfl} & ; & & J_w \dot{\omega}_{fr} &= \tau_{fr} - R F_{xfr} & ; \\ J_w \dot{\omega}_{ml} &= \tau_{ml} - R F_{xml} & ; & & J_w \dot{\omega}_{mr} &= \tau_{mr} - R F_{xmr} & ; \\ J_w \dot{\omega}_{rl} &= \tau_{rl} - R F_{xrl} & ; & & J_w \dot{\omega}_{rr} &= \tau_{rr} - R F_{xrr} & \end{aligned} \quad (5)$$

that correspond to the wheels spin dynamics.

$M$  is the mass of the vehicle,  $R$  the wheel radius,  $J$  the vehicle inertia on  $z$  axis,  $J_w$  the wheel inertia,  $\dot{\omega}_{**}$  the angular acceleration of the wheels,  $\tau_{**}$  the wheel torques,  $w_l$  and  $w_r$  the left and right width and  $l_f$  and  $l_r$  the front and rear length.

## III. CONTROLLER DESIGN

Because the lateral dynamics of the vehicle can not be controlled, we use only the dynamic equations projected along  $x$  and  $z_0$  for a decoupling design procedure.

The longitudinal velocity and the yaw angle of the vehicle are controlled by considering two additional inputs  $\tau_u$  and  $\tau_\theta$ . The torque  $\tau_u$  is applied equally on the six wheels of the robot, whereas the value of the torque  $\tau_\theta$  is of opposite sign for the right and the left wheels.

The control law architecture is depicted Fig. 3.

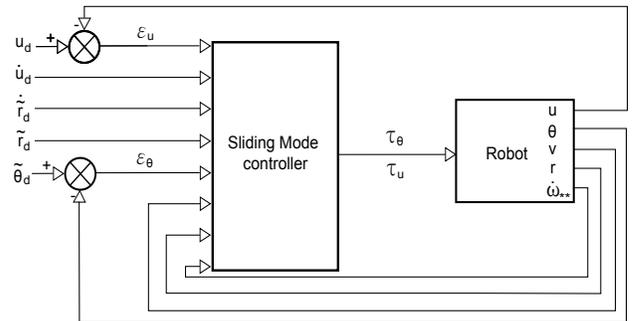


Fig. 3. Control block diagram

### A. Control of the yaw angle $\theta$

1) *Design of the control law:* Introducing the input  $\tau_\theta$ , equations (4) and (5) give us:

$$\dot{r} = \lambda \tau_\theta + \Lambda_\theta \dot{\omega} + \mathbf{D}_\theta \mathbf{F}_y \quad (6)$$

with:

$$\begin{aligned} \lambda &= \frac{3}{2} \frac{w_r + w_l}{JR} ; \\ \Lambda_\theta &= \frac{J\omega}{JR} \begin{bmatrix} -w_l & w_r & -w_l & w_r & -w_l & w_r \end{bmatrix} ; \\ \dot{\omega} &= \begin{bmatrix} \dot{\omega}_{fl} & \dot{\omega}_{fr} & \dot{\omega}_{ml} & \dot{\omega}_{mr} & \dot{\omega}_{rl} & \dot{\omega}_{rr} \end{bmatrix}^T ; \\ \mathbf{D}_\theta &= \begin{bmatrix} l_f & l_f & -l_r & -l_r \end{bmatrix} ; \\ \mathbf{F}_y &= \begin{bmatrix} F_{yfl} & F_{yfr} & F_{yrl} & F_{yrr} \end{bmatrix}^T . \end{aligned}$$

As proposed in [8], to allow the vehicle joins the path, the desired yaw angle  $\theta_d$  has to be modified as:

$$\tilde{\theta}_d = \theta_d + \arctan\left(\frac{d}{d_0}\right)$$

with  $d_0$  a positive gain and  $d$  the distance to the path.

Considering  $c_{d\theta}$  the control law and  $n(\theta, r, \dot{r}, d, \dot{d}, \ddot{d})$  the function of uncertainties about  $\theta$ ,  $r$ ,  $\dot{r}$ ,  $d$ ,  $\dot{d}$  and  $\ddot{d}$  in the dynamic equations, we have the following relationship:

$$\dot{r} = c_{d\theta} - n(\theta, r, \dot{r}, d, \dot{d}, \ddot{d}) \quad (7)$$

We define the yaw angle control law as:

$$c_{d\theta} = \ddot{r}_d + K_p^\theta \varepsilon_\theta + K_d^\theta \dot{\varepsilon}_\theta + \sigma_\theta \quad (8)$$

with:

- $\ddot{r}_d$  the second time derivative of  $\tilde{\theta}_d$ , being an anticipative term;
- $\varepsilon_\theta = \tilde{\theta}_d - \theta$  the yaw angle error;
- $K_p^\theta$  and  $K_d^\theta$  two positive constants that permit to define the settling time and the overshoot of the closed-loop system;
- $\sigma_\theta$  the sliding mode control law.

2) *Error state equation establishment:* If we calculate the second derivative of  $\varepsilon_\theta$ :

$$\begin{aligned} \ddot{\varepsilon}_\theta &= \ddot{r}_d - \ddot{r} \\ &= \ddot{r}_d - c_{d\theta} + n \\ &= \ddot{r}_d - (\ddot{r}_d + K_p^\theta \varepsilon_\theta + K_d^\theta \dot{\varepsilon}_\theta + \sigma_\theta) + n \\ &= -K_p^\theta \varepsilon_\theta - K_d^\theta \dot{\varepsilon}_\theta + (n - \sigma_\theta) \end{aligned} \quad (9)$$

We define the error state vector  $\mathbf{x} = \begin{pmatrix} \varepsilon_\theta \\ \dot{\varepsilon}_\theta \end{pmatrix}$ . So, we have the state equation:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}(n - \sigma_\theta) \quad (10)$$

with:  $\mathbf{A} = \begin{pmatrix} 0 & 1 \\ -K_p^\theta & -K_d^\theta \end{pmatrix}$ ;  $\mathbf{B} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$ .

If  $\sigma_\theta = 0$ , the system is linear and we choose the value of  $K_p^\theta$  and  $K_d^\theta$  as  $K_p^\theta = \omega_n^2$  and  $K_d^\theta = 2\xi\omega_n$  in order to define a second order system.  $\omega_n$  is the pulsation and  $\xi$  the damping factor. To define numerical values, the 5% answer time  $T_r$  is introduced:  $T_r = \frac{4.2}{\xi\omega_n}$ .

3) *Stability analysis:* To guarantee the stability of this closed-loop system, the problem of tracking the desired raw  $\tilde{\theta}_d$  can be solved by using the Lyapunov candidat function  $V = \mathbf{x}^T \mathbf{P}\mathbf{x}$ , with  $P$  a defined positive symetric matrix. Based on the Lyapunov theorem ([15]), the state  $\mathbf{x} = 0$  is stable only if:

$$V(0) = 0 ; \forall \mathbf{x} \neq 0 \quad V(\mathbf{x}) > 0 \text{ and } \dot{V}(\mathbf{x}) < 0 \quad (11)$$

The first two equations are verified. We have to establish the third one. Using the equation 10, we calculate the derivative:

$$\begin{aligned} \dot{V}(\mathbf{x}) &= \dot{\mathbf{x}}^T \mathbf{P}\mathbf{x} + \mathbf{x}^T \dot{\mathbf{P}}\mathbf{x} \\ &= (\mathbf{x}^T \mathbf{A}^T + n\mathbf{B}^T - \sigma_\theta \mathbf{B}^T) \mathbf{P}\mathbf{x} \\ &\quad + \mathbf{x}^T \mathbf{P}(\mathbf{A}\mathbf{x} + \mathbf{B}n - \mathbf{B}\sigma_\theta) \\ &= \mathbf{x}^T (\mathbf{A}^T \mathbf{P} + \mathbf{P}\mathbf{A}) \mathbf{x} + 2\mathbf{x}^T \mathbf{P}\mathbf{B}(n - \sigma_\theta) \end{aligned} \quad (12)$$

Then, we calculate  $P$  in order to obtain the Lyapunov equation:

$$\mathbf{A}^T \mathbf{P} + \mathbf{P}\mathbf{A} = -\mathbf{Q} \quad (13)$$

with  $\mathbf{Q}$  a defined positive symetric matrice. Equation (12) becomes:

$$\dot{V} = -\mathbf{x}^T \mathbf{Q}\mathbf{x} + 2\mathbf{x}^T \mathbf{P}\mathbf{B}(n - \sigma_\theta)$$

To maintain the stability,  $\dot{V}$  has to be negative. The first term is negative and the second one is null if  $\mathbf{x}$  belongs to the kernel of  $\mathbf{B}^T \mathbf{P}$ . We define the sliding variable  $s = \mathbf{B}^T \mathbf{P}\mathbf{x}$ .  $s = 0$  is the sliding surface. If  $s = 0$ , the error state vector  $\mathbf{x}$  becomes null.

The sliding mode controller  $\sigma_\theta$  is defined as  $\sigma_\theta(s = 0) = 0$  and for  $s \neq 0$ ,  $\sigma_\theta = \mu \frac{s}{\|s\|}$ , with  $\mu$  a positive scalar large enough to allow the stability of the controller. That allows to have:

$$s^T (n - \sigma_\theta) = sn - \mu \frac{s^2}{\|s\|} = sn - \mu \|s\| \leq \|s\| (\|n\| - \mu)$$

If we make the hypothesis that the modelisation error is bounded:  $\|n\| \leq n_{Max} < \infty$ , the selection of  $\mu > n_{Max}$  allows to verify the Lyapunov theorem hypothesis.

4) *Resolution of the Lyapunov equation:* To solve the equation (13), the matrice  $\mathbf{Q}$  is chosen as:

$$\mathbf{Q} = \begin{pmatrix} a & 0 \\ 0 & b \end{pmatrix}$$

with  $a > 0$  and  $b > 0$ .

Knowing the value of the parameters of the matrice  $\mathbf{A}$ , the matrice  $\mathbf{P}$  is:

$$\mathbf{P} = \begin{pmatrix} \frac{1.05 \cdot b}{\xi^2 \cdot T_r} + \frac{5 \cdot a \cdot \xi^2 \cdot T_r}{21} + \frac{a \cdot T_r}{16.8} & \frac{a \cdot \xi^2 \cdot T_r^2}{35.28} \\ \frac{a \cdot \xi^2 \cdot T_r^2}{35.28} & \frac{b \cdot T_r}{16.8} + \frac{a \cdot \xi^2 \cdot T_r^3}{296.352} \end{pmatrix} \quad (14)$$

B. *Control of the longitudinal velocity  $u$*

Introducing the input  $\tau_u$ , equations (2) and (5) give us:

$$\dot{u} = \gamma \tau_u + \Lambda_u \sum \dot{\omega} + rv \quad (15)$$

with:

$$\begin{aligned} \gamma &= \frac{6}{RM} ; \\ \sum \dot{\omega} &= \dot{\omega}_{fl} + \dot{\omega}_{fr} + \dot{\omega}_{ml} + \dot{\omega}_{mr} + \dot{\omega}_{rl} + \dot{\omega}_{rr} ; \\ \Lambda_u &= \frac{-J\omega}{RM} . \end{aligned}$$

As previously,  $c_u$  is the control law and  $m(u, \dot{u})$  the function of uncertainties about  $u$  and  $\dot{u}$  in the dynamic equations. We have the following relationship:

$$\dot{u} = c_u - m(u, \dot{u}) \quad (16)$$

The longitudinal velocity control law is:

$$c_u = \dot{u}_d + K_p^u \varepsilon_u + \sigma_u \quad (17)$$

with:

- $\dot{u}_d$  an anticipative term;
- $\varepsilon_u = u_d - u$  the velocity error;
- $K_p^u$  a positive constant that permits to define the settling time of the closed-loop system;
- $\sigma_u$  the sliding mode control law.

Using the Lyapunov candidat function  $V = \frac{1}{2} \varepsilon_u^2$ , it can be immediately verified that the stability of the system is guaranteed by the choice of the sliding mode control law  $\sigma_u = \rho \frac{\varepsilon_u}{\|\varepsilon_u\|}$ , with  $\rho$  a positive scalar, large enough.

### C. Expression of the global control

In practice, uncertainties about the dynamic of the system to control have for consequence an unknown about the real sliding surface  $s = 0$ . As a consequence  $s \neq 0$  and the sliding control law  $\sigma$ , which has a behavior similar to a sign function, induces oscillations by trying to reach the sliding surface  $s = 0$  with a null time in theory. These high frequency oscillations around the sliding surface, called chattering, increase the energy consumption and can damage the actuators. In order to reduce them, we can replace the sign function by an *arctan* one or, as chosen here, by adding a parameter with a small value  $\beta$  in the denominator.

Finally, the following torques are applied to each one of the six wheels:

$$\begin{aligned} \tau_{fl} = \tau_{ml} = \tau_{rl} = \tau_u - \frac{\tau_\theta}{2} ; \\ \tau_{fr} = \tau_{mr} = \tau_{rr} = \tau_u + \frac{\tau_\theta}{2} \end{aligned} \quad (18)$$

with  $\tau_u$  and  $\tau_\theta$  defined by:

$$\tau_u = \frac{1}{\gamma} \left( \dot{u}_d + K_p^u \varepsilon_u + \rho \frac{\varepsilon_u}{\|\varepsilon_u\| + \beta_u} - \Lambda_u \dot{\omega} - rv \right) \quad (19)$$

$$\begin{aligned} \tau_\theta = \frac{1}{\lambda} \left( \dot{r}_d + K_p^\theta \varepsilon_\theta + K_d^\theta \dot{\varepsilon}_\theta + \mu \frac{B^T P \mathbf{x}}{\|B^T P \mathbf{x}\| + \beta_\theta} \right. \\ \left. - \Lambda_\theta \dot{\omega} - \mathbf{D}_\theta \mathbf{F}_y \right) \end{aligned} \quad (20)$$

To estimate the value of the lateral forces  $\mathbf{F}_y$ , a Pacejka [13] theory could be used by considering the slip angle. But, owing to the fact that the sliding mode control is robust, we can consider that  $\mathbf{F}_y$  is a perturbation to reject, and not include it in the control law. A slip angle measure being in practice not very efficient, this solution is better.

## IV. USING ROBUBOX TO IMPLEMENT THE CONTROLLER

The sliding mode controller is implemented with Robosoft robuBOX [14], a software package that allows re-usable development and deployment of robotic applications. It is built on top of Microsoft Robotics Studio (MSRS) and is provided by all Robosoft robots, but can also be used without any hardware platform, with the realistic simulations as all the robuBOX software can run indifferently on real robotic platforms or in simulation. Using reference designs of architectures provided with robuBOX, the controller algorithm is easily encoded and tuned. Then, with the RobuBOX, we can re-use all existing services in a new architecture.

For the simulation, the RobuROC6 robot is provided with 3D models including the graphic 3D meshes and the physics and dynamics properties. All the joints of this multi-body mobile robot are properly encoded.



Fig. 4. Graphic model of the RobuROC6

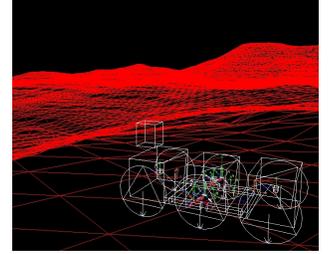


Fig. 5. Physical model of the RobuROC6

Complex environments using a height field entity for the ground are also modeled to be used in the simulation.

## V. SIMULATION

The simulation is executed with the RobuBOX, using MSRS and Ageia PhysX [7], an highly realistic 3-dimensional dynamic environment. An advanced tire slip based friction model is used in this simulator. It separates the overall friction force into longitudinal and lateral components. It is represented by the function depicted Fig.6, the force being in N and the composite slip, taking into account the longitudinal slip of the tire and the slip angle, without unity. The stiffness factor is the base amount of “grip” the tire has in the specified direction.

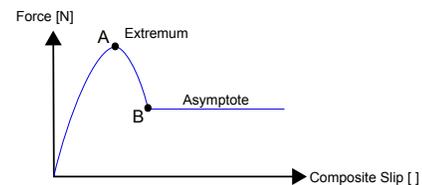


Fig. 6. Friction Model

We use here the following parameters:

- Coordinates of the Extremum point A: (1.0;0.02);
- Coordinates of the point B, beginning of the Asymptote: (2.0;0.01);
- Longitudinal stiffnessFactor = 10000.0;
- Lateral stiffnessFactor = 10000.0.

The controller parameters are chosen as:  $K_p^u = 1.00s^{-1}$ ,  $K_p^\theta = 12.00s^{-2}$ ,  $K_d^\theta = 0.10s^{-1}$ ,  $\xi = 0.70$ ,  $T_r = 2s$ ,  $\beta_u = 0.01ms^{-1}$ ,  $\beta_\theta = 0.01$ ,  $a = 0.10$  and  $b = 0.10$  ( $a$  and  $b$  being the two positive constants defining the matrix  $Q$ , solution of the Lyapunov equation). The value of the torques applied in the axis of the wheels are figured with the control law designed in section III.

TABLE I  
ROBOT PARAMETERS

Description	Symbol	Value
Length	$l$	1.5m
Width	$w$	0.80m
Height	$h$	0.474m
Mass	$M$	140Kg
Inertia	$J$	188Kg · m <sup>2</sup>
Radius of the wheels	$R$	0.234m
Mass of the wheels	$M_w$	3Kg
Inertia of the wheels	$J_w$	0.351Kg · m <sup>2</sup>

#### A. Path following with a horizontal ground

The first simulation consists of following a curved path on a horizontal ground. In this test, the vehicle is commanded to travel at  $3m \cdot s^{-1}$ . The sliding mode control law gains are so settled:  $\rho = 1.0ms^{-2}$  and  $\mu = 18.00$ . The displacements of the RobuROC6 are displayed Fig.7. Time evolution of the exerted torques  $\tau_u$  and  $\tau_\theta$  are displayed in Nm Fig.8 and Fig.9 and the evolutions of resulting  $\varepsilon_\theta$  and  $\varepsilon_u$  with the sliding mode controller are displayed Fig.11 and Fig.10. With a kinematic controller, the vehicle has some difficulties to join the desired path because of the sliding phenomenon in the wheel-soil interaction, not taken into account.

As a consequence, the skidding robot joins the path slowly after a curve.

Adding the sliding mode controller, the path is well followed, the torques being continuously corrected. Nevertheless, we can see Fig.11 some oscillations in the yaw angle error plot, what is the chattering phenomenon which can also be seen Fig.10. To reduce steady state error, we can increase the value of the sliding mode controller gains, which increases the value of the robust control input term. But, increasing these gains, the chattering phenomenon increases and the process could present non acceptable vibrations. The best behavior with a good following of the path and with acceptable chattering is plotted for the values reported here. A maximal yaw angle error absolute value of 0.2rad when turning and the longitudinal speed error absolute value always less than  $0.4ms^{-1}$  remind quite acceptable. Notice that this controller is quite robust because the friction is not constant and some phenomena (like the elasticity of the tire

for example) are not taken into account.

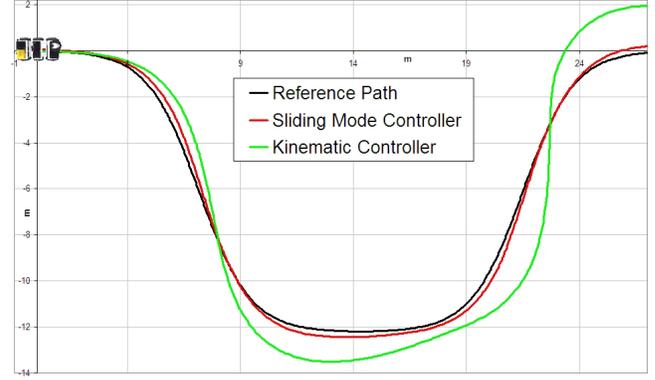


Fig. 7. Robot Position

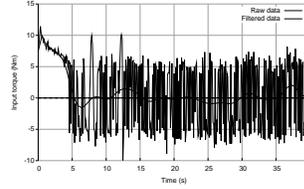


Fig. 8. Torque  $\tau_u$

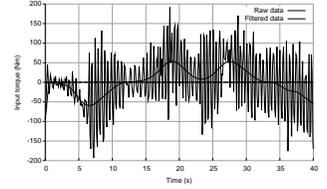


Fig. 9. Torque  $\tau_\theta$

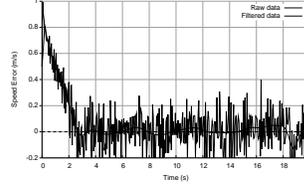


Fig. 10. Longitudinal Speed Error

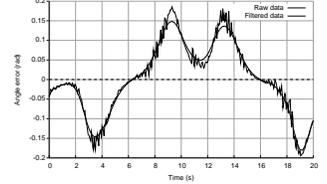


Fig. 11. Yaw Angle Error

#### B. Path following with a sinusoidal ground

In this simulation, we suggest to follow the same path as previously with the same velocity, but with a ground no more horizontal in order to investigate the robustness of our controller according to this kind of disturbance. The ground chosen has a sinusoidal shape with an amplitude of 0.2m, a little less than the half of the RobuROC6 height, and a period of 2m, a little more than its length, as it can be seen Fig.12.

As a result, the path is approximately followed as well as before. The difference between the position errors of the two simulations, with and without horizontal ground, is plotted Fig.13.

We can see that the curve of the position error with a sinusoidal terrain reaches higher values, due to the added disturbances. But the fluctuations are not significant compared to the vehicle dimensions. So, the controller has about the same efficiency as previously with a position error increasing



Fig. 12. RobuROC6 on a sinusoidal ground

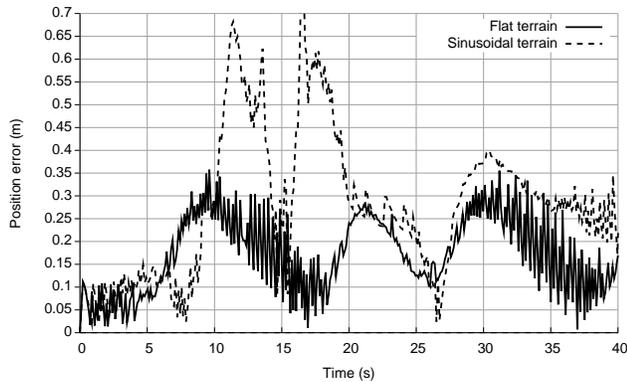


Fig. 13. Position errors

when the robot is turning. Finally, we can conclude that the sliding mode controller is a robust one for the RobuROC6 system, that has proved his efficiency, even with disturbances due to fluctuations of the level of the ground.

## VI. CONCLUSIONS AND FUTURE WORKS

A sliding mode controller was designed and implemented on the simulated RobuROC6 robot. Using RobuBOX and MSRS, it became easy and fast to develop his own control algorithms and include them in an existing re-usable architecture. The simulations performed with an accurate physical engine have shown the robustness of the control law even without any knowledge about the forces in the wheel-soil interaction and with some fluctuations of the ground level. Next, we will experiment this controller in real conditions. Furthermore, it could be tested in an unstructured environment to evaluate the limits of the controller robustness. In this paper, we have not studied the possibility of making varying the sliding mode control law gains. So, we will investigate this possibility, based on stability criteria like the lateral law transfer (LLT), for exemple already used by Bouton in [4].

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