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Ensuring path tracking stability of mobile robots in harsh conditions: An adaptive and predictive velocity control

Jean-Baptiste Braconnier[1], Roland Lenain[1], Benoit Thuilot[2,3]
[1] Irstea, 9 avenue Blaise Pascal, 63172 Aubière, France
[2] Clermont Université, Université Blaise Pascal, Institut Pascal, BP 10448, 63000 Clermont-Ferrand, France
[3] CNRS, UMR 6602, Institut Pascal, 63171 Aubière, France

firstname.lastname@irstea.fr benoit.thuilot@univ-bpclermont.fr

Abstract— **The aim of a mobile robot path tracking algorithm is to ensure that the desired path is followed as accurately as possible. This problem has been intensively studied in literature with satisfactory results in on-road context. Nevertheless, performances may be depreciated when the expected ideal conditions are no longer satisfied, as it is the case when moving off-road: in such a context, bad grip conditions together with actuator saturations may generate significant perturbations, especially at high speed. Beyond a lack of accuracy, instabilities (such as spin around or non-controllability) may arise. This paper proposes an adaptive and predictive approach in order to preserve the path tracking stability thanks to the modulation of the robot velocity. Relying on the on-line observation of the grip conditions and the reference path properties, the maximal velocity admissible in a near future is computed and applied, if necessary, instead of the desired speed. A steering angle control law, designed to be independent of the robot speed, acts in parallel. The capabilities of this algorithm are tested through actual experiments with a mobile off-road platform.**

I. INTRODUCTION

Recent advances in control of autonomous ground vehicles show important potentialities in many fields of application [13], such as agriculture [3], rescue or even public transportation [11]. Recent exhibitions (such as the DARPA Grand Challenge) demonstrated the capabilities of unmanned ground vehicles to operate autonomously. Nevertheless, fast and accurate control in off-road context remains an open issue. This is particularly true in agricultural applications for instance, where guidance within a few centimeters accuracy is required,without relying on complex perception systems. In off-road context, higly variable grip condiions are encountered and will affect the path tracking performances(see [2]), especially at high speed. In these conditions, wheels slip is non-negligible and basic mobile robot control laws based on the ideal rolling without slipping (RWS) assumption (as presented in [4] or [14]) cannot be used. Indeed the direct application of such approaches in natural environment leads to large tracking errors. Moreover, only the robot motion is addressed by path tracking control laws: stability and path admissibility (e.g. actuators saturations), which depend on the robot speed and the soil properties, are not taken into account.

The problem of preserving the tracking accuracy of a mobile robot subject to sliding effects has been addressed via several approaches. The sliding effects may be either considered as a perturbation [1] to be rejected by robust techniques [5], [7] or on-line estimated within an adaptive approach [8]. In the latter case, the grip conditions are explicitly accounted in the control laws and may moreover feed a partial dynamical model to enable further developments related to the robot behavior. This control strategy is used in this paper (and briefly presented) for two reasons. First, it can achieve a highly accurate tracking despite the harsh dynamics encountered off-road at high speed. Secondly, it permits to consider the lateral and longitudinal motions independently, which will be use in order to address stability preservation. The steering angle computed by the control law may indeed either exceed the actuator physical limits or lead to spin around situations: the amount of sliding at high speed on natural ground may lead to unstable situations, since fast and large variations of the steering angle may then be theoretically required. In order to limit such phenomena without reducing the robot speed, several approaches based on wheel velocity distributions have been investigated (such as ESP in on-road context or [12] for off-road vehicles). Nevertheless, they impose to control each wheel independently and do not consider the path admissibility. The moderation of the robot velocity (as proposed in [6], but limited to saturation detection) is here investigated in order to preserve both path tracking accuracy and robot stability without considering independent wheel control.

In this paper[1], an algorithm acting on the robot speed in parallel to the path tracking control law (acting on the robot steering angle) is proposed to preserve the robot stability. This velocity control law is based on a partial dynamical model adapted on-line, and is constituted of several steps: at each iteration, the maximal admissible yaw rate in the near future is first computed using the future trajectory properties, the adapted grip conditions and the actuator saturations. Moreover, it depends on the current vehicle behavior (under or over-steering cases). Using this maximal yaw rate, the corresponding admissible velocity, depending on the current

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sliding and the expected steering angle, is then computed. It is finally compared to the desired robot speed, and applied instead if this latter is larger. As a result, the robot decelerates if a risk of instability (spin around or steering actuator saturation) has been predicted.

This paper is decomposed as follows. First, the modeling of the robot motion is investigated, from an extended kinematic point of view and next, from a partial dynamical one. The proposed models are both used for the tracking control law and the velocity moderation algorithm developed in this paper. The adaptation of model parameters and variables, together with the steering control law for path tracking, are then briefly recalled from existing work. The next section then details the proposed approach: the predictive estimation of the maximal admissible speed, based on the adapted dynamical model, is derived. Finally, the efficiency of the proposed approach to preserve the robot path tracking stability is investigated through full-scale experiments.

II. ROBOT MODELING

A. Assumptions and notations

For the path tracking application, the model describing the robot motion is based on the classical bicycle model assumption [15]. In this framework, only motion in the yaw plane of the contact point is considered, such as depicted in Figure 1. As pointed out previously, the ideal RWS assumption cannot be satisfied in off-road conditions. As a result, the effects of sliding are accounted by adding two sideslip angles (β_F and β_R, respectively for the front and rear axles) defined as the difference between the tire direction and the actual speed vector at each wheel [10]. They are kinematically linked to the global sideslip angle β considered at the centre of gravity G, the position of which is described by L_R and L_F (with $L = L_F + L_R$ denoting the robot wheelbase).

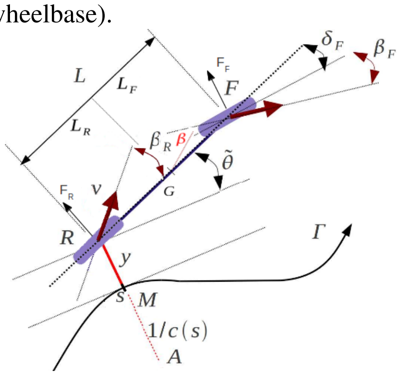


Fig. 1. Robot modelling

In this paper, the objective will focus on achieving accurate and stable path tracking. As a result, the robot motion is described with respect to the reference path Γ. The robot position R (middle of the rear axle) is then characterized in a Frénet frame using as a state vector the curvilinear abscissa s (of the closest point from R belonging to Γ), the tracking error y and the angular deviation $\tilde{\theta}$. The path curvature at the closest point is denoted $c(s)$, while the absolute velocity at point R is named v. These notations permit to derive the extended kinematic model (1). Nevertheless, as pointed out in [8], the motion at high speed requires the knowledge of a partial dynamical model in order to be able to estimate on-line the grip conditions and finally the sideslip angles (as detailed in section III-A). As a result, the lateral forces F_F and F_R for respectively front and rear axles are introduced. They impact on the global robot orientation θ, and more precisely on the variation of the robot yaw rate $\dot{\theta}$.

B. Extended kinematic model

Using these notations, the robot motion equations may be derived as (see [10] for details):

$$\begin{cases} \dot{s} & = & v\frac{\cos(\tilde{\theta}+\beta_R)}{1-c(s)y} \\ \dot{y} & = & v\sin(\tilde{\theta}+\beta_R) \\ \dot{\tilde{\theta}} & = & v[\cos(\beta_R)\lambda_1 - \lambda_2] \end{cases} \tag{1}$$

where:

$$\lambda_1 = \frac{\tan(\delta_F+\beta_F)-\tan(\beta_R)}{L}, \qquad \lambda_2 = \frac{c(s)\cos(\tilde{\theta}+\beta_R)}{1-c(s)y}$$

This model exists under the condition $1 - c(s)y \neq 0$. However the point R is supposed to be close to the trajectory and then never superposed with the curvature centre of the reference path, so that this singularity is never met. Apart from the two sideslip angles β_F and β_R, all the variables in model (1) can be measured or known by a preliminary calibration. Therefore, as soon as β_F and β_R are estimated thanks to the observer described briefly in the next section, a control law can be designed from model (1).

C. Partial dynamical model

The previous model (1) is suitable for control law design and sideslip angles estimation at low speed. However, the dynamical effects cannot be neglected at high speed and a partial dynamical model has to be considered to estimate sideslip angles and derive the proposed velocity limitation control law for robot stability preservation. Using the Fundamental Principles of Dynamics, one can derive the following system, representative of the lateral robot dynamics:

$$\begin{cases} \ddot{\theta} & = & \frac{1}{I_z}\left(-L_F F_F \cos(\delta_F) + L_R F_R\right) \\ \dot{\beta} & = & -\frac{1}{v_2 m}\left(F_F\cos(\delta_F-\beta) + F_R\cos(\beta)\right) - \dot{\theta} \\ \beta_R & = & \arctan\left(\tan\beta - \frac{L_R\dot{\theta}}{v_2\cos(\beta)}\right) \\ \beta_F & = & \arctan\left(\tan\beta + \frac{L_F\dot{\theta}}{v_2\cos(\beta)}\right) - \delta_F \\ v_2 & = & v\frac{\cos(\beta_R)}{\cos(\beta)} \end{cases} \tag{2}$$

where v_2 is the linear velocity at the centre of gravity G. In addition to the variables already introduced, the dynamical model (2) requires the knowledge of some dynamical parameters, namely the mass m and the vertical moment of inertia crossing G denoted I_z. This model exists under the assumption that $v_2 \neq 0$ and $\beta \neq \frac{\pi}{2}$, which is supposed to be met in a path tracking application.

III. Observer-based path tracking control

A. Dynamic observer for sideslip angles estimation

In order to rely on model (1), the sideslip angles (β_F, β_R) representative of the non-ideal grip conditions have to be known. Since these angles cannot be directly measured, a mixed kinematic and dynamic observer has been introduced in [9] and is here summarized. It is based on three steps, depicted in Figure 2.

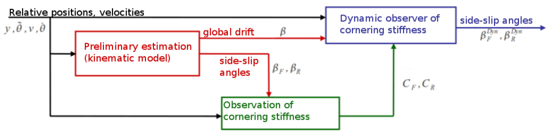


Fig. 2. Diagram of kinematic-dynamic observer

1) First, a preliminary estimation of the sideslip angles is achieved by using the model (1) and the actual position and velocity of the robot supplied by the sensors. It permits to estimate a global sideslip angle β relevant in the steady state periods of the robot motion. Nevertheless, such an estimation is not reactive enough to provide relevant values at high speed during transition phases, since dynamical effects have been neglected.
2) This first estimation of β is then used to feed an adaptation law for the parameters representative of the grip conditions. More precisely, an adapted linear tire model is introduced:

$$\left\{ \begin{array}{lcl} F_F & = & C_F(.)\beta_F \\ F_R & = & C_R(.)\beta_R \end{array} \right. \quad (3)$$

where the cornering stiffnesses $C_F(.)$ and $C_R(.)$ are varying in order to reflect the actual grip conditions. These two parameters are then adapted on-line by imposing the convergence of the observed yaw rate and global sideslip angle to respectively their measured and previously estimated values.
3) Once cornering stiffnesses (C_F, C_R) are adapted, the forces F_F and F_R can be computed. Consequently, the dynamical model (2) is totally known and can be used to derive an estimation of the sideslip angles via a dynamical representation. This last step permits to improve the reactivity of sideslip angles estimation, even at high speed, and to increase the path tracking performances for fast mobile robots in natural environment. In the sequel, such a model will be used to design the stability control algorithm proposed in this paper (detailed in section IV).

B. Adaptive and predictive control law

Thanks to the observer described in the previous section, the model (1) is totally known. It can be use to design a control law ensuring the convergence of the tracking error to zero (i.e $y \to 0$). The two control variables in model (1) are the robot velocity v and the front steering angle δ_F. However, at this step, the velocity is considered as a measured parameter and a control law for the front steering angle is derived to achieve the tracking, whatever the speed and the estimated sideslip angles. It has been shown in [10] that expression (4) ensures an accurate path tracking when moving at low speed.

$$\delta_F = \arctan\left(\tan(\beta_R) + \frac{L}{\cos(\beta_R)}\left(\frac{c(s)\cos\tilde{\theta}_1}{k} + \frac{A\cos^3\tilde{\theta}_1}{k^2}\right)\right) - \beta_F \quad (4)$$

with:

$$\left\{ \begin{array}{lcl} \tilde{\theta}_1 & = & \tilde{\theta} + \beta_R \\ k & = & 1 - c(s)\,y \\ A & = & -K_p y - K_d\,k\,\tan\tilde{\theta}_1 + c(s)\,k\tan^2\tilde{\theta}_1 \end{array} \right. \quad (5)$$

where K_d and K_d are positive gains used to adjust the convergence distance.

However,the previous law is not used directly, because low-level settling time and actuators delays affect the tracking accuracy. In order to anticipate for these delays, a predictive control detailed in [8] is added. More precisely, the expression (4) is split into two terms $\delta_F = \delta_F^{Dev} + \delta_F^{Traj}$. The first part δ_F^{Dev} relies only on the current tracking error and sideslip angles values. It cannot be predicted and is then let unchanged. In contrast, δ_F^{Traj} mainly relies on the known reference path properties (principally the path curvature) and can therefore be anticipated. It is achieved via a Predictive Functional Control approach accounting for the actuators properties. The predicted term attached to the trajectory δ_{Fpred}^{Traj} is eventually applied instead of δ_F^{Traj}, leading to the following control law:

$$\delta_F^{Pred} = \delta_F^{Dev} + \delta_{Fpred}^{Traj} \quad (6)$$

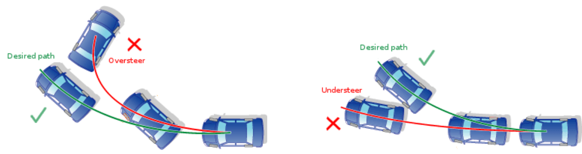
Control law (6) ensures a high accurate path tracking for fast mobile robots moving off-road, as soon as the path is admissible at the desired speed. A given path Γ, manually recorded at low speed, may be admissible. However, the effects of sliding are increased with the robot velocity and may lead to steering angle saturations or a loss of controllability. The path can then be no longer admissible, depending on the robot limitations, its velocity and the grip conditions.

IV. Velocity limitation

The previous control law acts only on one of the two control variables of the robot: the steering angle. Since the control law performances are theoretically independent of the velocity, this latter control variable may therefore be modulated to ensure the tracking stability. The proposed approach acts then in parallel to the first control law dedicated to motion servoing. In this section, the stability conditions are first described considering two different behaviors: over and under-steering. Next, the maximal admissible yaw rate in each case is computed, and finally the maximal admissible velocity is obtained.

A. Computation of the maximal admissible yaw rate

When the ideal RWS assumption is not satisfied, two problematic cases can occur: over and under-steering. They can be distinguished from each other by the value of the difference between the actual yaw rate and the theoretical one (i.e. the yaw rate that would have been obtained if RWS assumptions were satisfied). If this difference is positive, then the robot is over-steering, and if it is negative, the robot is under-steering (see illustration in Figure 3). These phenomena are not an inherent property of a given robot, they also depend on the grip conditions and the robot speed.



(a) Over-steering (b) Under-steering

Fig. 3. Illustration of over- and under-steering

The maximal admissible yaw rate, ensuring controllability and path admissibility, is computed below, first in the under-steering case, and next in the over-steering case.

1) Under-steering case: In this case, the sliding effects tend to reduce the yaw rate (i.e. despite the steering control, the robot tends to go straight). Consequently, the actual yaw rate can never exceed the value that would be obtained if the steering angle value was kept equal to maxima steering angle (with the same sign as the current steering angle value). This maximal yaw rate can be predicted by integrating the dynamical model (2), previously used in subsection III-A for sideslip angles estimation: injecting $\delta_F = \pm\delta_{Fmax}$ (depending on the current sign of δ_F) in model (2)-(3) and assuming small sideslip angles, model (2) equations can be linearized as follows:

$$\dot{X} = A\,X + B\,(\pm\delta_{Fmax}) \tag{7}$$

with

$$A = \begin{bmatrix} -\frac{C_F L_F^2 \cos(\delta_{Fmax}) + C_R L_R^2}{I_z v_2} & \frac{C_R L_R - C_F L_F \cos(\delta_{Fmax})}{I_z} \\ \frac{(C_R L_R - C_F L_F \cos(\delta_{Fmax}))}{m v_2^2} - 1 & -\frac{(C_R + C_F \cos(\delta_{Fmax}))}{m v_2^2} \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{C_F L_F \cos(\delta_{Fmax})}{I_z} \\ \frac{C_F \cos(\delta_{Fmax})}{m v_2} \end{bmatrix}, \qquad X = \begin{bmatrix} \dot{\theta} \\ \beta \end{bmatrix}$$

and the maximal reachable yaw rate $\dot{\theta}_{max1}$ in under-steering situation can then be obtained by integrating system (7) over a small horizon of prediction H :

$$X_{t+dt} = X_t + (\,A\,X_t + B\,(\pm\delta_{Fmax})\,)dt \quad \text{until } t = t_{current} + H \tag{8}$$

To perform this integration, the cornering stiffnesses $C_{F,R}$ are considered constant during the prediction interval and equal to the current values supplied by the observer described in section III-A. Moreover, v_2 is assumed to be different from 0 (satisfied in path tracking applications).

2) Over-steering case: In this second case, the sliding effects tend to increase the yaw rate (the actual yaw rate is indeed larger than the theoretical value that can be computed when assuming RWS) and this may end with a spin around situation. To preserve the robot stability in such a situation, the steering control law is supposed to instantaneously counter-steer. The maximal counter-steering action is obtained when the steering angle value sent to the actuator is equal to maxima opposite steering angle of the current value. Relying on the first term in the third equation in (1), it can be computed that the maximal admissible yaw rate when counter-steering is:

$$\dot{\theta}_{max2} = v\,\cos(\beta_R)\,\frac{\tan(\beta_F \pm \delta_{Fmax}) - \tan(\beta_R)}{L} \tag{9}$$

Consequently, an actual yaw rate value superior to $\dot{\theta}_{max2}$ has to be considered as a risky situation: in that case, if the robot was starting spinning around, then counter-steering would be unproductive (since it cannot deliver a yaw rate superior to $\dot{\theta}_{max2}$), so the robot would go on spinning and the controllability would be lost. Therefore, in such situations, the robot velocity has to be reduced in order to recover controllability.

It should be noted, that in that case, the dynamical model (2) cannot be used to deliver a predicted value of $\dot{\theta}_{max2}$, since it cannot be assumed that the cornering stiffnesses are constant during a counter-steering maneuver.

B. Computation of the maximum longitudinal velocity

In order to account for the two possible situations (i.e. under or over-steering), let us define $\dot{\theta}_{max}$ as the lowest value between $\dot{\theta}_{max1}$ and $\dot{\theta}_{max2}$. Clearly, $\dot{\theta}_{max}$ constitutes the maximal admissible value for the robot actual yaw rate: if $\dot{\theta}$ exceeds $\dot{\theta}_{max}$, then the robot stability may be jeopardized, and consequently its velocity has to be reduced. The maximal admissible velocity v_{max} can be computed relying again on the first term in the third equation in (1):

$$\dot{\theta} = v\,\cos(\beta_R)\,\frac{\tan(\beta_F + \delta_F) - \tan(\beta_R)}{L} \tag{10}$$

v_{max} can be obtained by injecting in (10) the current sideslip angles supplied by the observer described in section III-A, the maximal admissible yaw rate $\dot{\theta}_{max}$ and the future steering angle issued from control law (6) (so v_{max} can also be anticipated). The same horizon of prediction H is used for the computation of δ_F^{Pred} and of $\dot{\theta}_{max1}$. Finally, v_{max} is compared to the current desired speed $v_{Desired}$ and the velocity v_c to be applied is the minimum between the desired and the admissible speed:

$$v_c = min\left(v_{Desired}, \frac{L\,\dot{\theta}_{max}}{\cos(\beta_R)(\tan(\delta_F^{Pred} + \beta_F) - \tan(\beta_R))}\right) \tag{11}$$

The velocity v_c permits to reduce, if needed, the actual yaw rate $\dot{\theta}$ and keep it under the on-line adapted threshold $\dot{\theta}_{max}$. As a result, the sideslip angles, and therefore the steering angle, are reduced and this latter stays below the actuator physical limits, ensuring the controllability and consequently the accuracy of the path tracking application.

V. Experimental Results

A. Configuration of the experiments

Experiments have been conducted with the "RobuFast" mobile robot depicted in Figure 4 and manufactured by Robosoft company. This experimental platform is a four independently-driven wheeled robot, with a wheelbase $L = 1.2\ m$. Its weight is $420\ kg$ and its maximal velocity is 7 $m.s^{-1}$. Actuators are electrically powered and their characteristics are settling times of $1.0s$ and $0.4s$ respectively for the longitudinal velocity and the steering angle. The physical limits for the steering angle are $\pm 22.5°$.

Fig. 4. The RobuFast robot

The robot is equipped with an Xsens Mti IMU providing three linear accelerations and three angular velocities, mainly used to measure the yaw rate $\dot{\theta}$. Besides, the robot position, orientation and velocity are provided by an RTK-GPS receiver (Magellan Proflex 500). It supplies a position accurate within to 2 cm at a 10 Hz frequency and its antenna is settled above the point R (middle of the rear axle).

B. Path tracking results with and without limitation algorithm

The algorithm presented in section IV has been tested in combination with the kinematic path tracking control law described in section III-B. A reference path has been previously recorded via a learning procedure at a constant velocity of 1.5 $m.s^{-1}$ and during this manual driving task, the maximal front steering angle was $12°$. The trajectory thus obtained, considered as the reference path Γ, is depicted in black dashed line in Figure 5. Since the steering range is $\pm 22.5°$, this path is clearly admissible, at least at the speed used for the learning procedure.

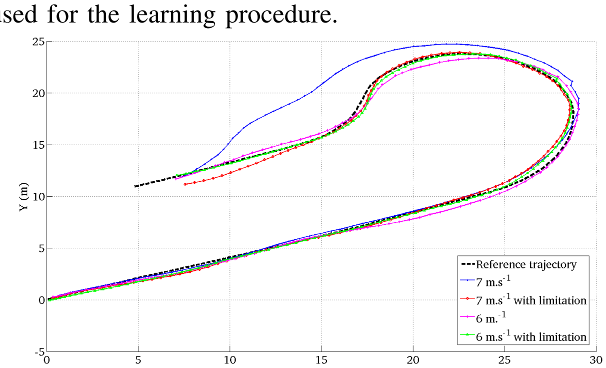


Fig. 5. Reference and actual trajectories followed by the robot

In order to investigate the capabilities of the proposed velocity limitation control law, the trajectory tracking has been achieved with the desired speeds $v_{Desired} = 6\ m.s^{-1}$ and $v_{Desired} = 7\ m.s^{-1}$, with and without the velocity limitation for each considered velocity. The maximal value δ_{Fmax} for the steering angle in the velocity limitation algorithm has been set to $14°$ and the prediction horizon for the steering angle injected in the velocity limitation algorithm was $H = 2s$. The actual trajectories achieved during the four different tests are presented in Figure 5.

First of all, it can be seen that when the velocity limitation algorithm is used, both trajectories are quite close to the

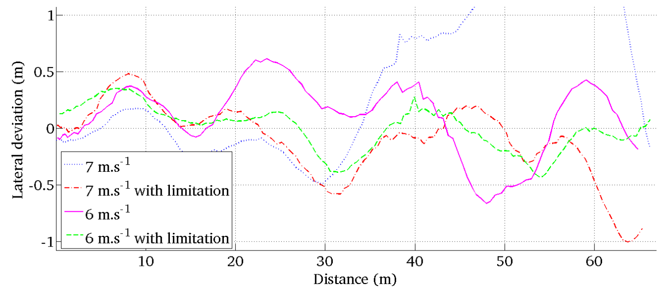


Fig. 6. Lateral deviation

reference trajectory. Figure 6 compares the tracking errors thus obtained and shows that they stay within $\pm 0.5\ m$ when the limitation is active. On the contrary, when the limitation is inactive, the maximal errors are around 0.6 m at 6 m^{-1} and are greater than 1m when applying the maximal velocity 7 $m.s^{-1}$. This is due to the fact that the robot is largely under-steering in the experimental conditions and steering angle saturation occurs. This leads to limited overshoots at 6 $m.s^{-1}$, since the steering angle computed by the tracking control law (6) stays close to the physical limit $22.5°$. When the robot moves faster, the sideslip angles are larger and the steering angle computed from (6) is beyond this limit. As a result, the robot cannot follow the trajectory anymore and a growing drift is recorded and eventually reaches 2.5 m.

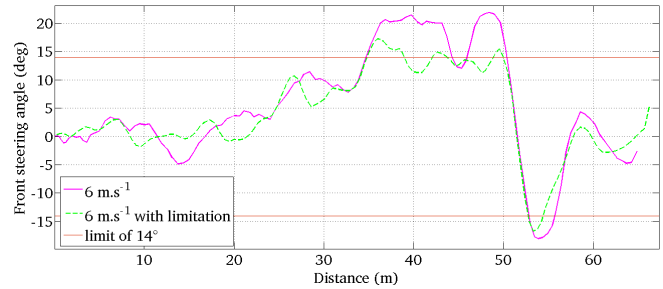


Fig. 7. Steering angle at 6 $m.s^{-1}$

To illustrate this fact, the steering angle computed from (6) during the tests with and without limitation when $v_{Desired} = 6\ m.s^{-1}$ are compared in Figure 7 (for clarity the experimental results at 7 $m.s^{-1}$ are not shown on the followings figures as they exhibit the same features). It can be seen that without limitation, the steering angle during the curve (from curvilinear abscissae 30 to 50m) reaches values larger than the maximal desired value $\delta_{Fmax} = 14°$ and even larger than the physical limit $22.5°$. Contrariwise, when the velocity limitation is activated, the steering angle stays close to the maximal desired value $\delta_{Fmax} = 14°$.

This has been made possible thanks to the robot deceleration achieved when the limitation is active. This can be observed in Figure 8, where the velocities in both trials are compared. While the velocity recorded without limitation oscillates around 6 $m.s^{-1}$, with limitation the velocity is reduced during the bend in order to guarantee the path admissibility with the maximal desired value $\delta_{Fmax} = 14°$. The robot slows down in order to limit the current yaw rate to the maximal admissible yaw rate $\dot{\theta}_{max}$ computed in section IV-A.

The computed maximal yaw rate $\dot{\theta}_{max}$ obtained when the

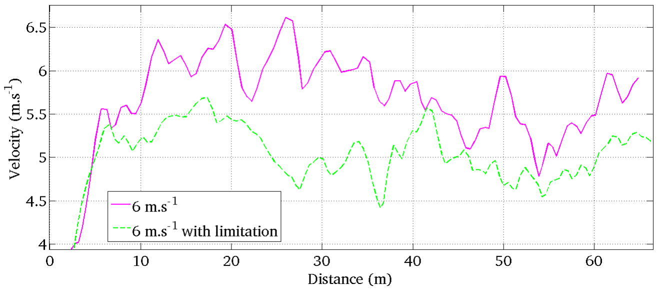


Fig. 8. Linear Velocity at 6 $m.s^{-1}$

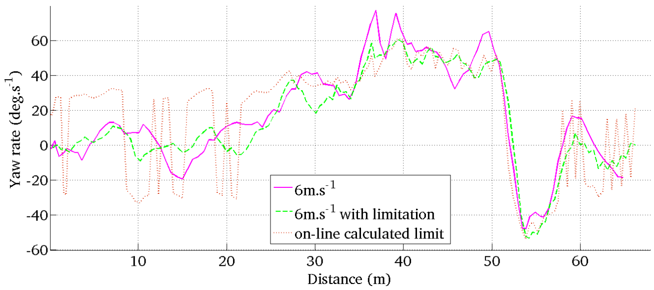


Fig. 9. Yaw speed at 6 $m.s^{-1}$

limitation is active is reported in Figure 9 in red dotted line. The actual value of the yaw rate recorded during the test with the limitation is, as expected, below or equal to $\dot{\theta}_{max}$, so that the saturations can be avoided. On the contrary, when neglecting the possible saturations, the recorded yaw rate is above the limit (between 35m and 45m and at 49m) and consequently the steering angle is above the maximal desired value $\delta_{Fmax} = 14°$ (see Figure 7).

This demonstrates that the proposed algorithm permits to relevantly limit the velocity to preserve the path tracking stability with respect to the physical limitations. In the proposed experiments, the computed velocity indeed permits to keep the steering angle within the desired range without being conservative. Since the actuator limits are not reached, the tracking accuracy is consequently preserved, as the admissibility of the trajectory is ensured.

A video of the both experiments at 7 $m.s^{-1}$ is joined.

VI. Conclusion and Future Work

This paper addresses the problem of stable and accurate trajectory tracking for mobile robots in harsh conditions. The objective is to prevent the robot from actuator saturations or spin around situations thanks to a speed control acting in parallel to the steering control law. An adaptive approach is first applied in order to estimate the grip conditions, allowing to feed a partial dynamical model. Such a model is used, not only to compute the steering angle control law (thus allowing an accurate tracking), but also to estimate the maximal admissible yaw rate. This maximal yaw rate is computed predictively, with respect to the physical limitations of the robot actuators and to the future path curvature. Considering the steering angle values provided by the steering law, the maximal longitudinal velocity is then deduced and applied if smaller than the desired one. As a result, when achieving aggressive maneuvers, the robot slows down to prevent the actuators saturations, preserving the path admissibility and finally the tracking accuracy.

The capabilities of the approach have been tested through actual experiments, showing its efficiency. The proposed control strategy is nevertheless based on the assumption that lateral and longitudinal dynamics may be considered separately. Such an assumption is valid when the robot slows down smoothly. When important accelerations are required, such an hypothesis is no more satisfied and punctual overshoots may be recorded. As a consequence, future work is focused on developing an unified control strategy, coupling longitudinal and lateral dynamics. The objective is to handle these interactions in order to achieve harsh maneuvers, such as emergency obstacle avoidance, without loss of stability.

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