Experimental study of a fast mobile robot performing a drift maneuver

Eric Lucet*,**, Christophe Grand*, Alexander V. Terekhov*, and Philippe Bidaud*
Institut des Systèmes Intelligents et de Robotique
Université Pierre et Marie Curie (CNRS - UMR 7222)
4, Place Jussieu 75252 Paris Cedex 05, France

***Robosoft*
Technopole d'Izarbel
64210 Bidard, France

In this paper we present a mobile robotic platform designed for experimental analysis of the robot control during sliding at high velocity. We use the developed platform for experimental analysis of the mobile robot performing aggressive 90 degrees steering maneuver at high speed (about 8 m/s) on the highly slippery surface (Coulomb friction coefficient about 0.4). The maneuver is performed in feedforward manner by the controller, which was previously developed using methods of stochastic multiobjective optimization applied to the simplified mathematical model of the robot. The theoretical trajectory of the maneuver assumes significant oversteering associated with large slippage angle (more then 30 degrees), which is kinematically incompatible with no-slipping condition and thus is significantly dependent on actual properties of the wheel-terrain interaction. The experimentally observed trajectory of the robot was qualitatively similar to the one obtained in the model, though the actual angle of turn was less then the desired (about 75 degrees instead of 90 degrees).

Keywords: Autonomous Mobile Robots; Dynamic Model; Aggressive maneuvers.

1. Introduction

The control of high speed mobile systems on natural terrain is an important field of research. The modeling of the forces arising in the interaction of the vehicle wheels with terrain, broadly studied by Bakker,[1] remains an open topic of research because of the variety of the physical effects involved into this interaction. The latter makes impossible to use precise model-based control of the vehicle slippage. Current control approaches mainly aim towards minimization of the slippage and planning trajectories in order to guarantee better adhesion properties. For example, Lhomme-Desages[2] proposed an real time estimation procedure of the wheel-ground slippages, based on terramechanical model. The slippage conditions were included in the trajectory controller in order to improve mobility over difficult terrains.[3] Nevertheless, this approach is mainly developed for slow motion and requires an accurate estimation of vehicle displacement, which can be hardly achieved during the high speed motions.

In contrast Kozlowski[4] designed a control algorithm dedicated to ensure stability of the desired trajectory of a mobile robot in presence of slippage and some model uncertainties. Another approach lies in defining the domain of the vehicle stability in the space of velocity/steering angle by considering the adhesion properties to be known.[5,6] In the same line of research we proposed a control algorithm,[7] which allows to preserve the vehicle controllability even if the sliding is very large. However, none of these control strategy benefits from the slippage phenomena.

An alternative approach consists in planning complicated maneuvers in advance and executing them when it becomes necessary. This allows for taking the phenomena of slipping into account at the planning stage and to obtain more efficient trajectories. For example, the sharp 90 degrees turn can be performed much faster if large slippage angle is admitted, then if the maximum velocity is determined by no-sliding conditions.

The difficulties arise at the stage of solving the optimal control problem for slipping vehicle. The complexity of the vehicle dynamics and wheel-terrain interaction makes it nearly impossible to approach the problem with convenient methods of optimal control. Recently, another approach was proposed.[8] The analysis of the experimentally recorded actions of professional rally racers showed that the steering angle and break/throttle commands can be well approximated as stepwise linear functions of time. Given such approximation the optimal control problem transforms into an order simpler problem of finding optimal parameters of the approximation. It was shown, that solution of the latter optimization problem results in the trajectory and control inputs resembling those used by the professional rally racers.[8]

Recently we have shown that the methods of multiobjective stochastic optimization could be successfully applied to obtain an approximation of the optimal control for the problem of sharp steering.[9] Adopting the stochastic optimization becomes necessary because the problem is non-convex and conventional optimization methods get stuck at local extrema.

The aim of this study is to develop a mobile robotic platform for testing control algorithms for highly slippery movement of the robot; to implement on this platform the previously obtained feedforward control strategy and to compare the experimentally observed behavior of the robot with the one predicted by the model.

2. Platform description

To perform experiment analysis of the vehicle control during aggressive maneuver we developed a robotic platform "fastBot" (see fig. 1). It is a four-wheel vehicle, which basic mass-geometrical characteristics are given in the table 1.

The platform is actuated by electric motors. Its propulsion is performed by a brushless motor, which torque is transmitted to the front and rear axles. Each axle is equipped with differential guaranteeing nearly equal distribution of the torque among its wheels.

The front axle is supplied with Ackerman-style steering system, driven by a DC servo-motor. Both motors, propulsion and steering, are controlled by servo systems, working in velocity tracking and position tracking modes correspondingly.

The platform is capable to move at rather high velocity: the maximum velocity is about 15 m/s and acceleration is about 5 m/s^2. To minimize the transmission of the possible shocks caused by collisions, the trunk of the

Fig. 1. FastBot

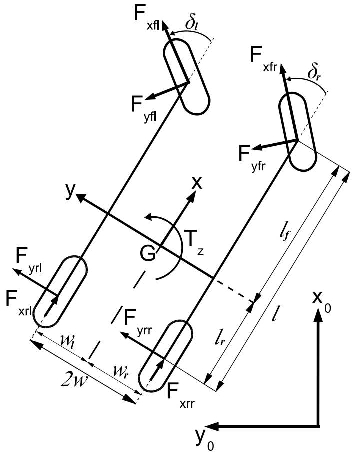

Fig. 2. Schematic representation of the robot

Description	Symbol	Value
Length	l	$0.40m$
Width	$2w$	$0.35m$
High of G	h	$0.15m$
Mass	M	$7.40Kg$
Wheel radius	R	$0.75m$

platform is connected to axles by a suspension system having rather low stiffness and damping characteristics. In addition, a safety hood is added to the trunk in order to protect electronic devices installed in the trunk.

The global control of the vehicle is performed by an embedded computer PC104 with Ubuntu Linux operating system. The communication is performed via WiFi adapter, installed on the top of the trunk, using SSH protocol. In addition, the robot is equipped with XSens inertial measurement unit, which combines three-axial accelerometers, gyroscopes and magnetometers.

The computer executes the control application, responsible for collecting information from XSens, sending control commands to servo controllers and logging information. These operations are performed in the control loop, running at 100 Hz frequency and driven by external clock from XSens IMU.

3. Feedforward control

The control of the developed platformed is performed by assigning desired propulsion velocity and steering angle. We assume that the servo controllers track the desired values perfectly as long as they do not exhibit sudden changes. In order to obtain the feedforward commands for velocity and steering we used the previously described method,[9] which was inspired by the work of Velenis et al.[8] Shortly the method is the following.

At the first step we obtained simplified mathematical model of the platform, in which we assumed that the wheels never loose the contact with the ground and accounted for the planar motion only. Wheel-terrain interaction was modeled using brush model.[10] The mass-inertial and geometric parameters of the model matched those of the real robot; the dry friction coefficient was taken equal to the experimentally estimated value, given below.

The model takes the steering angle and the velocity as inputs. We parametrize them as the piecewise linear functions of time (see fig. 3) and

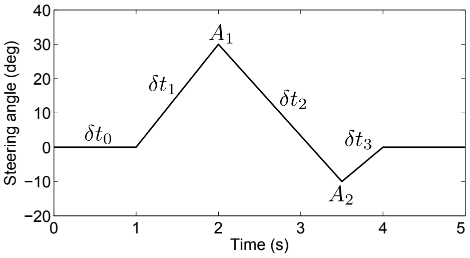

Fig. 3. Schematic illustration of parametrization used for the steering angle control input

then search for the optimal values of the parameters, allowing the maneuver execution. In the search we performed simulations, in which the robot had initial velocity of 8 m/s and was supposed to make 90 degrees turn 8 meters in front of its initial position (see fig. 5, left). The task was to perform the maneuver as fast and as accurate as possible. Since these two demands are clearly conflicting we used methods of stochastic multiobjective optimization to obtain the set of all compromises between them. The particular solution was then selected manually. The fig. 5 presents the model trajectory corresponding to the selected solution.

4. Experimental study

Experiments were performed outdoor on a dedicated horizontal surface. For better slippage we covered the surface of the wheels with plastic tape in order to decrease the adhesive properties of the wheels.

4.1. *Coordinates and velocities estimation*

The position and velocity of the robot are estimated offline using the outputs of the XSens IMU. For this purpose we implemented basic algorithm of inertial navigation. Roughly, the algorithm works as following:

(1) zero values of the gyroscopes and accelerometers are estimated using two seconds of recordings for immobile robot, preceding every experimental trial;
(2) the orientation of the robot relatively to initial reference frame is estimated by integrating the difference between the outputs of the gyroscopes and their initial values;
(3) the outputs of accelerometers are projected on the axes of the absolute reference frame, estimated at the previous step, the initial values of

the accelerometers are subtracted and the difference is integrated for velocity and twice integrated for coordinate.

To estimate the error of this algorithm we performed special trials, in which the experimenter picked the robot up, shacked it for about 10 seconds and then put it back to the initial location place. The error was defined as the difference between the initial value of position/velocity and the final value estimated by the described algorithm. The resulting error was relatively small; for velocity it was about 0.4 m/s in the horizontal plane and 0.2 m/s for the vertical axis; for position these values were 1 m and 0.2 m correspondingly.

4.2. *Coulomb friction coefficient*

The optimal trajectory of the maneuver highly depends on the properties of the wheel-terrain interaction. The most basic characteristic of the adhesion between the wheel and the ground and thus, of the expected slippage, is given by the Coulomb friction coefficient. In order to estimate its value we performed simple experiment in which the robot slowly accelerated to the velocity of about 5 m/s and then performed sudden breaking (see fig. 4).

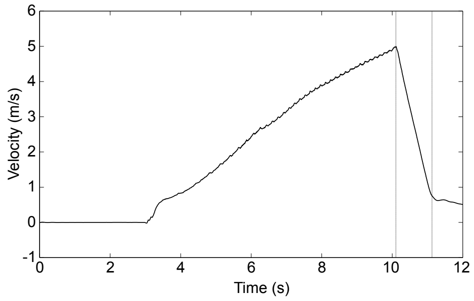

Fig. 4. Empirical estimation of the Coulomb friction coefficient

The value of the Coulomb friction coefficient, μ, was estimated using the formula:

$$\mu = \frac{|a|}{g} \approx 0.4,$$

where a is the acceleration during the breaking (the region between two vertical lines in the fig. 4) and g is gravitational acceleration.

The estimated value of the dry friction coefficient was used when solving the optimal control problem described in the section 3.

4.3. *Experimental results*

Experimental trails have the following structure. The robot accelerates for 2 seconds to 8 m/s velocity, keeps it for 0.5 s and then executes previously computed feedforward commands of the maneuver. Before the commands execution the heading angle of the robot is stabilized by a PID controller using the yaw velocity, provided by XSens. During the maneuver the feedback is switched off.

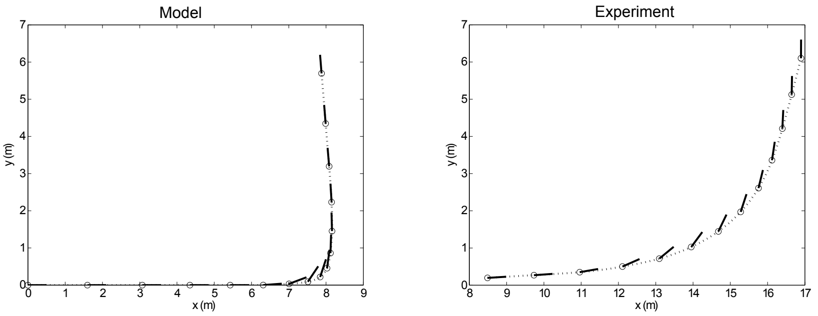

Fig. 5. Position and orientation of the robot computed with the model and in real conditions

An example of the experimental trial is presented in the fig. 5, left. It can be seen that the robot steers with significant slippage angle (more then 30 degrees), however, the resulting turn is about 75 degrees instead of desired 90 degrees. The latter is not surprising since the implemented controller is purely feedforward and thus it is very sensitive to the uncertainties of the model. The more important thing in our opinion is that the robot is able to perform the maneuver with significant oversteering and to exit the maneuver with nearly zero angular velocity, e.g. to continue the strait motion after the maneuver execution.

We also tried to adjust the values of parameters parameters manually. However after tens of trials we did not manage to make the robot exit the maneuver with straight motion. In most cases the robot started spinning around and we had to interrupt the execution.

5. Conclusions

In this paper we presented the new robotic platform "fastBot" designed for experimental verification of control algorithms for fast moving vehicle. We implemented on the platform our previous results on the maneuver planning and compared experimental results with simulation. Though in the experiment the actual angle of turn did not coincide with the desired one, on the whole the trajectory of the robot was similar to simulations. We see the main direction of our further work in developing feedback controller for maneuver performance using the methods, which allowed us obtain the current feedforward controller, and in experimental verification of the controllers on the developed platform.

Acknowledgments

This research work is made in the frame of the REI-FastNav project, supported by DGA grant REI 2008.34.0018.

References

1. E. Bakker, L. Nyborg and H. Pacejka, *International congress of Society of Automotive Engineers, Warrendale, Pensylvania, USA* , 2190 (1987).
2. D. Lhomme-Desages, C. Grand, F. Ben Amar and J. Guinot, Doppler-based ground speed sensor fusion and slip-control for a wheeled rover, in *IEEE/ASME Transactions on mechatronics*, (4)2009.
3. D. Lhomme-Desages, C. Grand and J. Guinot, Trajectory control of a four-wheel skid-steering vehicle over soft terrain using a physical interaction model, in *Proceedings of ICRA'07 : IEEE/Int. Conf. on Robotics and Automation*, 2007.
4. K. Kozlowski and D. Pazderski, *International journal of applied mathematics and computer science* **14**, 477 (2004).
5. M. Spenko, Y. Kuroda, S. Dubowsky and K. Iagnemma, *Journal of Field Robotics* **23**, 311(May 2006), cited By (since 1996) 9.
6. S. Peters and K. Iagnemma, Mobile robot path tracking of aggressive maneuvers on sloped terrain *2008 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS* 2008. cited By (since 1996) 0.
7. E. Lucet, C. Grand, D. Salle and P. Bidaud, Stabilization algorithm for a high speed car-like robot achieving steering maneuver, in *IEEE International Conference on Robotics and Automation (ICRA)*, (Pasadena, CA, USA., 2008).
8. E. Velenis and P. Tsiotras, Optimal velocity profile generation for given acceleration limits: theoretical analysis, in *American Control Conference. Proceedings of the 2005*, 2005.
9. A. Terekhov, J.-B. Mouret and C. Grand, Stochastic multi-objective optimization for aggressive maneuver trajectory planning on loose surface, in *7th Symposium on Intelligent Autonomous Vehicles, IFAC*, 2010.
10. H. B. Pacejka, *Tyre and vehicle dynamics* (Ed. Elsevier Butterworth-Heinemann, 2nd edition, 2005).