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Model Predictive Control of an Autonomous Vehicle

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Abstract-- **This paper presents model predictive control of an autonomous vehicle. Simulation and experimental results have been shown and compared with input-output linearization method. The results obtained show that the MPC is an efficient method that allows for accurate control and navigation of an autonomous vehicle. Model based predictive control is tested in simulations for motion on an inclined plane. This is done to prepare future work regarding the avoidance of the violation of the smoothness condition for exact linearization, while at the same time by modifying the input commands the geometric path planning results are conserved. The approach is presented for the wheel-ground slippage and tip-over avoidance of the three-wheeled vehicle for inclined plane motion. A complete three-dimensional dynamic model using Newtonian dynamics is also presented. Simulation results using a three-wheeled vehicle built in our laboratory illustrate the performance of the proposed controller.**

Index Terms-- **Robotics, Autonomous Vehicle, Model Predictive Control**

I. INTRODUCTION

Autonomous motion of unmanned vehicles requires an operational space control approach which is able to generate and correct the trajectory of the vehicle in order to avoid collisions with unexpected obstacles and takes into account the contact forces between the wheels and the ground such that the slippage and tip-over of the vehicle can be avoided.

In recent years a variety of autonomous vehicles were developed mostly using kinematics based control. At the present time the trend is to further enhance the features for autonomous operation of vehicles in an open quasi-flat field or on the factory floor. Motions on uneven road conditions impose complex requirements for the controller of the vehicle, in particular with regard to vehicle dynamics.

For autonomous motion control of unmanned vehicles, an operational space control approach is needed which is able to generate and correct the trajectory of the vehicle in order to avoid collisions with unexpected obstacles and takes into account the contact forces between the wheels and the ground such that the slippage and tip-over of the vehicle can be avoided.

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For achieving autonomy, a dynamics based control approach is formulated for a three-wheeled vehicle with front wheel driving and steering. Motion control of the vehicle in operational space is greatly facilitated by the exact input-output feedback linearization of vehicle dynamics.[1] The linearization also permits the development of a real-time collision avoidance scheme using artificial potential field approach thus enhancing autonomy of the vehicle. The sufficient smoothness condition for applying feedback linearization has to be however continuously observed and this requires the avoidance of actuators torque saturation, wheel-ground longitudinal and lateral slippage, and tip-over of the vehicle. Also, the smoothness condition has to be observed for motion on horizontal plane as well as inclined surfaces.[2]

This paper presents first the kinematics and a complete three dimensional dynamic model using Newtonian dynamics of a three wheeled autonomous vehicle for a front wheel steering and driving. A three-dimensional dynamic model of the vehicle is strongly recommended instead of using two-dimensional model for the compensation of the inertia of the vehicle. It is followed by a presentation of the dynamics model predictive control approach, based on modification of the input commands such that the geometric path planning result is conserved and the smoothness condition for exact linearization is not violated. The approach presented in this paper is suitable for the wheel-ground slippage and tip-over avoidance of the three-wheeled vehicle for inclined plane motion. Simulation tests presented in the paper have the purpose of verifying the proposed controller for simple situations in preparation for the future work in which corrective actions are taken by the controller to avoid smoothness condition violations.

In order to facilitate the development of the dynamic model and the control law, multiple reference frames should be chosen for wheeled vehicles.[3,4] Two inertial frames and four moving reference frames are chosen for the wheeled vehicle with rigid body structure and wheels moving on an inclined plane which has a slope β (Fig. 1). One inertial frame, M-Q-P, has the plane M-Q placed on the horizontal ground surface, while the second inertial frame, N-Q-R, contains the inclined plane N-Q of the motion of the vehicle. The two inertial frames have a common axis Q and the angle between M-Q and N-Q planes is β. One moving reference frame X-Y-Z is attached to the vehicle structure (X-axis along the vehicle, Y-axis parallel to the rear axle, and Z-axis perpendicular to X-Y plane originated at O in the vehicle's centre of mass).

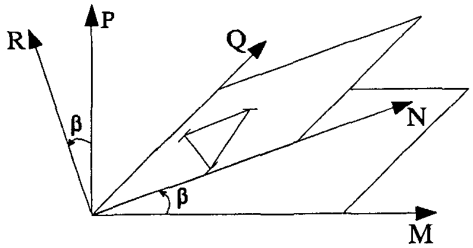

Figure 1. Inertial frame transformation

Three other moving frames, X_i-Y_i-Z_i (i=1,2,3), with origins Oi, are attached to the three wheels, with Zi parallel to Z (Fig. 2).[5]

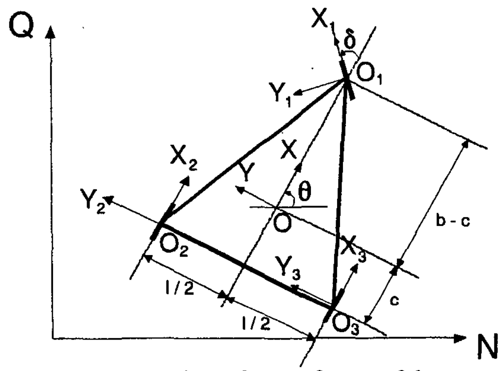

Figure 2. The moving reference frames of the autonomous vehicle

The coordinate transformation gives the position (N, Q, R) in N-Q-R plane of a point defined by the position (X, Y, Z) in X-Y-Z plane where the θ is the orientation angle between N and X axis of the two inertial frames, N-Q-R and X-Y-Z.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \cos\delta & -\sin\delta & 0 \\ \sin\delta & \cos\delta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix}, \begin{bmatrix} N \\ Q \\ R \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \tau \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} M \\ P \\ Q \end{bmatrix} = \begin{bmatrix} \cos\beta & 0 & -\sin\beta \\ 0 & 1 & 0 \\ \sin\beta & 0 & \cos\beta \end{bmatrix} \begin{bmatrix} N \\ Q \\ R \end{bmatrix} \quad (2)$$

To determine the moving reference frame's position and orientation with regard to the inertial frame, the (algebraic) vectors for absolute positions of the origins **R**, $\mathbf{R}_i$(1=1,2,3) and the orientation angles θ of X, X_2, X_3 and θ+δ of the X_1 with regard to N are defined.

For inclined plane motion analysis, only N-Q and X-Y components are needed, i.e., 8 components for the 4 position vectors. The vehicle dynamics for the three wheeled vehicle was derived on the basis of general principles of multi-body systems with assumptions presented in [6,7].

II. MPC CONTROL ALGORITHM

The autonomous vehicle represented in Fig. 2 is analyzed for the inclined plane subject to .wheel slippage and body tip-over avoidance. The vehicle control system is shown in Fig. 3. The control block diagram contains a three-part control scheme for verifying slippage and tip-over conditions. The external loop controller and path planner are included in operational space, and a model predictive controller is implemented for the K_{ext} which represents the proportional control gain for the angular velocity command of the front wheel. The inner loop involves exact input-output linearization controller in curvilinear space (s-δ). The model based predictive control scheme improves the performance of the autonomous vehicle while avoiding slippage and loss of contact with ground.

Feedback linearization is a powerful technique for facilitating the design of the controller. Basically, it consists of applying a nonlinear feedback to the system to compensate its nonlinearity, so that the dynamics of the new composed system appear linear. The linearization procedure requires that all of the necessary variables be estimated accurately. Some conditions must be fulfilled to be able to use feedback linearization, first of all the smoothness of the system.

Unfortunately, almost no real system is smooth outside a limited operating region, in particular almost all real systems have some hard bounds on the inputs. Under feedback control this means that the input signal to the actuator lies between the bounds (i.e., in the unsaturated region), while for the saturated regions the input is either at the maximum or at the minimum value. Feedback linearization tends to increase the dynamic range of the input, and therefore may reduce the unsaturated region and increase the danger of running into the bounds. Reaching the bounds changes the structure of the controlled system, destroys the linearity of the composite system, and, as discussed in [8], can even lead the plant to instability. Therefore, it may be worth limiting the range of allowable reference values so that the state trajectory does not leave the unsaturated region. The sufficient smoothness condition for applying feedback linearization has to be continuously observed and this requires the avoidance of actuators torque saturation, wheel-ground longitudinal and lateral slippage and tip-over of the vehicle for motion on horizontal plane as well as inclined surfaces. Obviously, avoiding these limiting conditions improves also the general performance of the vehicle.

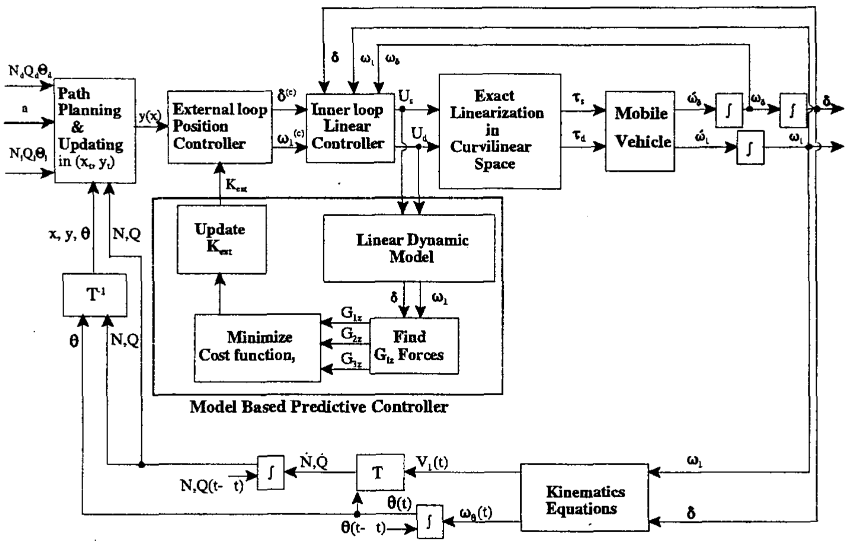

Figure 3. Control block diagram representing over-all system

Model Predictive Control (MPC) provides a unified solution to the problems of free motion, and contact motion controls. In the model predictive control, the knowledge is represented by analytical models of the autonomous vehicle and the environment. These models are used to predict, using current measurements, the motion over a receding horizon extending from the current time over a fixed interval into the future.

The actual control command is decided upon some control objectives over the receding horizon. In order to define how well the predicted process output tracks the reference trajectory, a criterion function is used (Eqn. 3).

$$\Phi_k = \sum_{i=0}^{N_h} \begin{bmatrix} \gamma_1 (N_{d_{k+i}} + N_{k+i})^2 + \gamma_2 (Q_{d_{k+i}} + Q_{k+i})^2 + \\ \gamma_3 (\dot{N}_{d_{k+i}} + \dot{N}_{k+i})^2 + \gamma_4 (\dot{Q}_{d_{k+i}} + \dot{Q}_{k+i})^2 + \\ \gamma_5^* (G_{z1_{k+i}})^2 + \gamma_6^* (G_{z2_{k+i}})^2 + \gamma_7^* (G_{z3_{k+i}})^2 \end{bmatrix} \qquad (3)$$

where, Nh is the receding horizon and γ_i (i =1~7) are weight factors selected during the MPC design.

$$\gamma_5^* = \begin{cases} 0, & \text{for } G_{z1} < 0 \\ \gamma_5, & \text{otherwise} \end{cases}$$

$$\gamma_6^* = \begin{cases} 0, & \text{for } G_{z2} < 0 \\ \gamma_6, & \text{otherwise} \end{cases}$$

$$\gamma_7^* = \begin{cases} 0, & \text{for } G_{z3} < 0 \\ \gamma_7, & \text{otherwise} \end{cases}$$

where, G_{zi} (i=1,2,3) are vertical wheel-ground contact forces of the wheels.

The variables N and Q are defined in Fig. 2.

Usually the control objectives are given in terms of the minimization of an optimization criterion defined over the receding horizon (Eqn. 4).

$$u^* = \arg\min_{u} \Phi_k \qquad (4)$$

The controller output sequence $u^* = K_{ext}^*$ over the prediction horizon, Nh, is obtained by minimization of Φ_k with respect to $u = K_{ext}$. Then u^* is optimal with respect to the criterion function that is minimized. This unified approach of MPC is based on the concept found in [9].

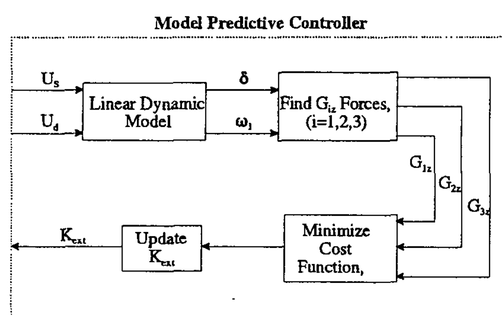

Figure 4. Detailed schematic block diagram for Model Predictive Control

In this paper the Model based Predictive Control, as shown in Fig. 4, is used for avoidance of wheel-ground longitudinal and lateral slippage and loss of wheel-ground contact of the vehicle for motion on horizontal plane as well as inclined surfaces. The input commands were modified such that the geometric path planning result is conserved and the smoothness condition for exact linearization is not violated.

III. RESULTS

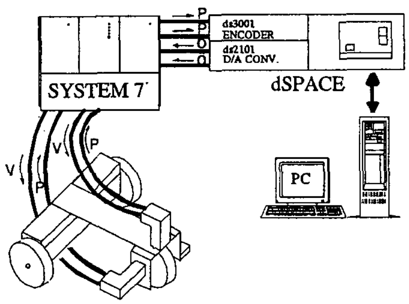

Figure 5. Schematic diagram of the experimental setup of the autonomous vehicle driven by two direct drive motors

The schematic diagram shown in Fig. 5 illustrates the components used in the experimental study. The autonomous vehicle, dSPACE digital signal processor, SYSTEM 7 direct drive motor driver, A/D, D/A, and encoder cards, batteries, analog filters, and a PC are the components needed to perform the experiment. The dSPACE DSP runs on a TMS320C30 processor chip. It is connected to the personal computer by an expansion PHS-bus

There are two versions of the autonomous vehicle designed and constructed in our laboratory. Both versions have a tricycle configuration equipped with a driving and steering front wheel and two idle rear wheels. These designs are inspired by the base frame configuration of HERO1 Mobile robot.

The first version has been developed for experimental testing of the sensor fusion of odometers and accelerometers in case of vehicle slippage. In the first version, two direct drive (brushless) DC motors made by Parker Hannifin Ltd. in U.K. were installed at the front wheel of the robot, one on top of the steering assembly structure for steering purpose and the other on right hand side of the wheel for driving. A counter balancing mass is attached on the other side of the driving motor.

This version of autonomous vehicle has a frame with dimension of 0.4 x 0.3 x 0.4 m. The vehicle was connected to System 7 motor driver which was supplied with the motors by the manufacturer.(Fig. 5) The signals establish communication with the dSPACE DSP (digital signal processor). The dSPACE DSP generated the analogue torque commands outputs(τ_d, τ_s) by DS2101 D/A converter control board while communicating with PC and receives the angular displacement signals (θ_d, θ_s) from DS3001 incremental encoder board.

The servomotor type is an important factor in autonomous vehicle design. Desirable servos are lightweight, compact, easily integrated, efficient, controllable, and maintenance free. Especially, for unmanned vehicle, easy servo maintenance is a desirable feature. Although the direct drive motor outperforms the DC motor with brush as far as torque control is concerned, it is noted that it is not suitable for autonomous vehicle application because of its heavy and balky motor driver unit that increases the size and weight of the vehicle. It was also registered that the thickness of vehicle frame affects the dynamic characteristics of the rigid body assumption. The thickness of the vehicle frame of above version is only 3 mm. These two main factors gave enough reasons to construct the second generation vehicle with thicker and more sturdy frames and DC motors replacing direct drive motors.

A second autonomous vehicle, the CLAMOR, was constructed by Victor Lonmo, 1996. The vehicle has a dimension of 0.51 x 0.51 x 0.53 m and mass of 24.5 kg with two batteries installed. The servomotors are DC motors (Pitmo 14202 series, Pittman Corporation) with separate position and torque control loops. These DC servomotors have 75.1:1 planetary gears and have a torque output of max. 10 Nm. Power for the motors is supplied by two 12 V, 10 Ah batteries connected in series. Each servomotor has a built-in optical incremental encoder which has 1000 steps per revolution at motor shaft resulting in 75100 steps per revolution for output shaft. The frame is made of ½" x 3" aluminum stock for strength. The plate metal used for the box near the rear wheels is made of 3/32" thick aluminum. The dSPACE controller is DSP based (TMS320C30) and contains D/A and incremental encoder boards. The dry friction of the DC motors was identified as approximately 1.1 Nm.

Figure 6 shows the planned path and the trajectory of the vehicle when K_{ext} is equal to 3.0 for initial posture of N_i=0(m), Q_i=0(m), and θ_i=-15°, and desired posture of N_d=2.0(m), Q_d=2.0(m), and θ_d = 90°.

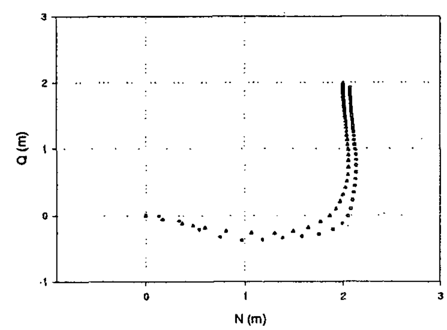

Figure 6. Planned path (▴) and the trajectory (∘) of the vehicle with K_{ext} = 3.0 and a=1.0

The figure shows a curved trajectory followed by the vehicle, parallel to the planned one. Figure 6 also shows that the vehicle didn't reach the target. This result can be explained by the fact that only one control variable, in this case $\omega_1^{(c)}$, can be closed loop controllable while the other variable $\delta^{(c)}$ is open loop controllable because of the non-holonomic constraint. $\omega_1^{(c)}$ is function of the curvilinear position error.

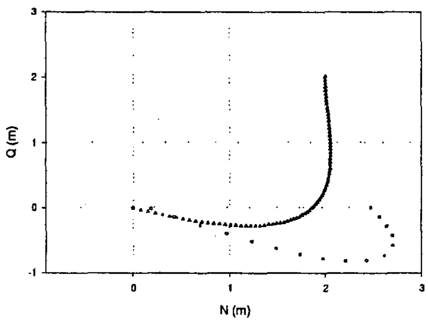

Figure 7. Planned path (▲) and the trajectory (○) of the vehicle with $K_{ext} = 4.0$ and a=1.0

Figure 7 shows the planned path and the trajectory of the vehicle for K_{ext} increased to 4.0 while other conditions are same as before. The figure shows a prematurely stopped trajectory of the vehicle when attempting to follow the same planned path. The trajectory of the vehicle had stopped abruptly when one of the vertical forces of the three wheels changed sign and become negative. This phenomenon means that loss of contact had occurred. The figure 7 shows that the vehicle negotiated the first sharp corner but the centrifugal forces of the vehicle are already out of range of the safe region of not being tipped-over. Eventually tipping over on the other side occurs, and the end position is far from the desired one.

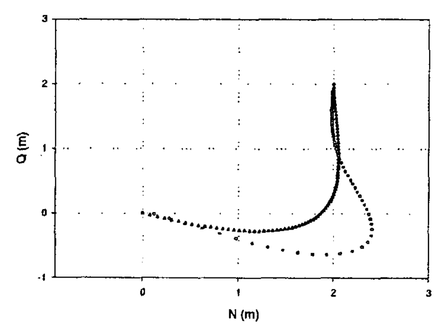

Figure 8. Planned path (▲) and the trajectory (○) of the vehicle with $K_{ext} = 4.0$ and a=1.0 using MPC

The result shown in figure 8 was obtained with MPC and IOL and compared to the results shown in figure 7 for IOL only. It represents a clear improvement in the performance of the vehicle tracking the planned path.

The Model Predictive Controller is used for finding safe K_{ext} by predicting the violation of the loss of contact condition in combination with the Input-Output Exact Linearization controller. A smooth trajectory with a little more curvature is generated by the vehicle with the Model Predictive Controller (Fig. 8) while for Input-Output Exact Linearization scheme (Fig. 7) the vehicle was shown to be in danger of being tipped-over.

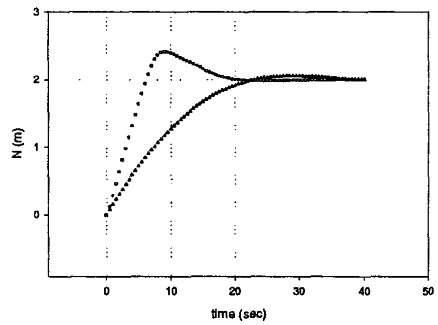

Figure 9. The time behavior of N position (planned (▲) and generated (○))

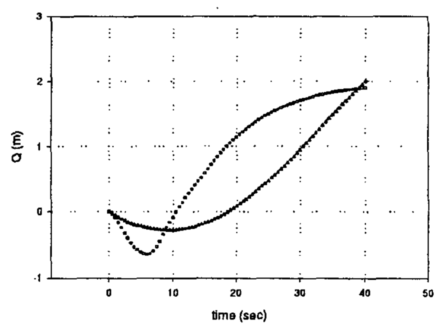

Figure 10. The time behavior of Q position (planned (▲) and generated (○))

Results, shown in figures 9 to 12, confirm the improvement achieved by combining MPC and IOL control. Since all the vertical forces of the wheels to the ground stay in positive area, no loss of contact occurs.

Figures 9 and 10 show the same phenomenon in function of time and the position of the vehicle. From figures 11 and 12, the orientation angle (θ) and the steering angle (δ) of the vehicle, show the smooth variation and reaching the

desired values which are quite smoother than the ones with the Input-Output Linearization control scheme only.
All the other results also show the improvement of the performance of the vehicle in comparison with the corresponding results of the former case.

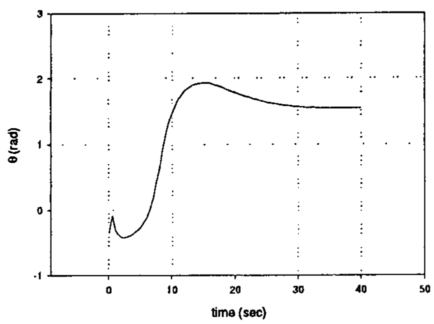

Figure 11. The time behavior of the orientation angle (θ) of the vehicle for figure 7

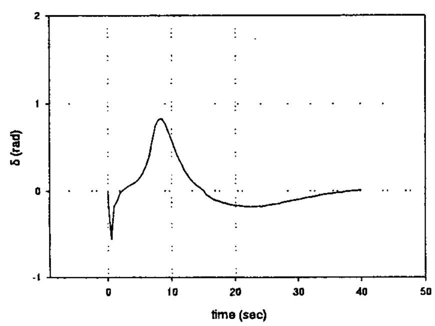

Figure 12. The time behavior of the steering angle (δ) of the vehicle for figure 7

IV. CONCLUSIONS

The dynamic model and the simulation results for a wheeled vehicle moving on an inclined plane show that the events of wheel slippage and vehicle tip-over can be predicted for various vehicle designs and control law parameters. These simulation results are useful for improving the structural design of the vehicle and for the development and tuning of the controller by testing the dynamic behaviour of the vehicle for various conditions of the road and in particular for various slopes. This simulation model can be used for the development of future Moon-Mars autonomous mobile vehicles and for off-road teleoperated vehicles design. The predictive control approach will be applied for enhancing the autonomy of the mobile vehicle.

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