CONTROL DESIGN FOR AN OVERACTUATED WHEELED MOBILE ROBOT

Jeroen Ploeg * **John P.M. Vissers** ** **Henk Nijmeijer** ***

* *TNO Automotive, P.O. Box 756, 5700 AT Helmond, The Netherlands, Phone: +31 (0)492 566 536, E-mail: jeroen.ploeg@tno.nl*
** *Vanderlande Industries, Veghel, The Netherlands*
*** *Eindhoven University of Technology, Eindhoven, The Netherlands*

Abstract: In order to simulate road vehicles in a hardware-in-the-loop test set-up, TNO has developed a wheeled mobile robot with independently driven and steered wheels. This robot is overactuated, i.e. the number of actuators exceeds the number of spatial degrees of freedom to be controlled. A position controller based on feedback linearization is presented. This controller takes the overactuatedness into account by using the so-called multicycle approach, which essentially regards the robot as a combination of independent unicycles. As a result, the robot is position controlled while the redundant actuators are used to compensate for weight transfer during acceleration and cornering.

Keywords: Mobile robots, Nonlinear control, Position control, Robotics

1. INTRODUCTION

Nowadays, Wheeled Mobile Robots (WMR's) are widely used in industry as transport devices. As such, the main control objective usually is to let a fixed point on the WMR follow a time dependent spatial reference trajectory. TNO Automotive has developed a specific WMR for use in its VeHIL test facility. VeHIL is a hardware-in-the-loop testbed for the development of road vehicles equipped with driver assistance functionality based on environment sensors, such as Advanced Cruise Control and Collision Warning. The principle of VeHIL is to simulate only the relative motion of other vehicles with respect to the test vehicle. This allows for efficient, safe and reproducible testing (Gietelink *et al.*, 2004). The neighboring vehicles are simulated by two WMR's, equipped with a dummy vehicle body in order to resemble a real vehicle. Figure 1 shows a photograph of such a WMR, without body. This VeHIL WMR or *Moving Base* (MB) differs from most wheeled robots in that it is a high dynamic robot, capable of extreme maneuvers at velocities up to 50 km/hr, exceeding

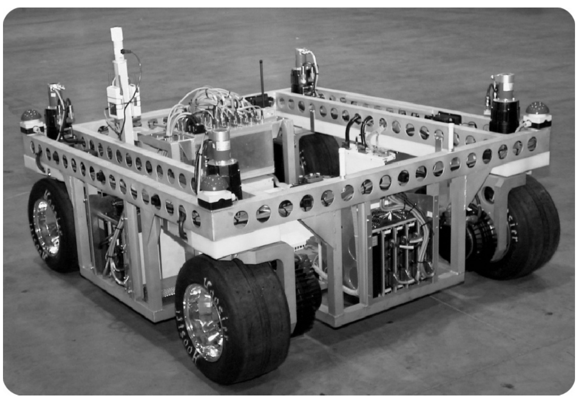

Fig. 1. TNO's mobile robot: the Moving Base

the handling performance of modern road vehicles (Ploeg *et al.*, 2002).

The control objective of the MB is to let its center follow a reference trajectory $\mathbf{q}_{ref}$, consisting of the position in the (horizontal) x, y-plane and the orientation ψ as a function of the time t:

$$\mathbf{q}_{ref}(t) = \left(x_{ref}(t) \ y_{ref}(t) \ \psi_{ref}(t) \right)^{\mathrm{T}} \qquad (1)$$

This is achieved by four independently driven and steered wheels. As a consequence, the MB has eight actuators – four driving and four steering motors – whereas the control objective comprises three degrees of freedom only. The MB can therefore be characterized as being *overactuated*. This paper focuses on the control design for this type of mobile robot.

2. SPECIFICATIONS

In order to develop an adequate position controller for the MB, it is important to know its main characteristics. These are shortly summarized here.

The maximum acceleration and deceleration of the MB is $10\,\mathrm{m/s^2}$ in all directions. The maximum centripetal acceleration is $12\,\mathrm{m/s^2}$. These acceleration levels lead to a considerable weight transfer, given the total mass of the vehicle (570 kg) and the height of the center of gravity (0.35 m). The friction force that a tire can deliver, is approximately proportional to the actual vertical load of the tire (Pacejka, 2002), which in turn is determined by the weight transfer. As a consequence, the wheels should be driven by the motors in accordance with their actual vertical loads in order to obtain a maximum performance of the MB in terms of acceleration and maneuverability. The drive torque distribution across the four wheels should therefore correspond to the actual weight distribution.

The maximum velocity of the MB is 50 km/hr in all directions. It is important for the controller to work well over the whole range from 0 – 50 km/hr. Motors capable of steering the wheels in a range of $-350\,^\circ$ till $+350\,^\circ$ are implemented on all four wheels. These large steering angles are necessary in view of the trajectories driven in VeHIL. Table 1 summarizes the main MB specifications.

Table 1. Moving Base specifications

Vehicle mass (without body)	570 kg
Wheel base	1.4 m
Track width	1.4 m
Center of gravity height	0.35 m
Maximum velocity	50 km/hr
Maximum acceleration	$10\,\mathrm{m/s^2}$
Max. centripetal acceleration	$12\,\mathrm{m/s^2}$
Installed power	52 kW
Steering angle range	$[-350\,^\circ, +350\,^\circ]$

3. CONTROL CONCEPT

The control method is inspired by the idea presented by Borenstein (Borenstein, 1995), which is to decentralize the tracking problem, the latter being defined as the realization of a desired position and orientation of the vehicle's center, according to (1). To this end, the reference vector $\mathbf{q}_{ref}$ needs to be converted to reference positions x_{ijref} and y_{ijref} ($i = f(ront), r(ear)$, $j = l(eft), r(ight)$) for the four corners where the wheels are attached; refer to figure 2 depicting the MB co-ordinate systems. The reference orientation angles ψ_{ijref} of the wheels are calculated using a kinematic approach, i.e. the orientation angles correspond to the direction of the local reference velocities $\dot{x}_{ijref}$ and $\dot{y}_{ijref}$. As a result, the wheels are oriented such that an instantaneous center of rotation (ICR) is present, being the point where the perpendiculars to the plane of each wheel, drawn from the center of the wheel, are concurrent as illustrated in figure 2. Note that tire slip is thus ignored. Consequently, the reference positions for the MB corners are:

$$\begin{aligned} x_{flref} &= x_{ref} + L_d \cos(\psi_{ref} + \arctan(W/L)) \\ y_{flref} &= y_{ref} + L_d \sin(\psi_{ref} + \arctan(W/L)) \\ x_{frref} &= x_{ref} + L_d \cos(\psi_{ref} - \arctan(W/L)) \\ &\cdots \end{aligned} \qquad (2)$$

where L and W are half the vehicle length and width; $L_d = \sqrt{L^2 + W^2}$ is the distance from the center to a corner. According to the kinematic approach, the reference wheel orientation angles ψ_{ijref} ($i = f, r$, $j = l, r$) are:

$$\psi_{ijref} = \arctan\left(\frac{\dot{y}_{ijref}}{\dot{x}_{ijref}}\right) \qquad (3)$$

where the time derivatives $\dot{x}_{ijref}$ and $\dot{y}_{ijref}$ are determined by differentiation of equation (2).

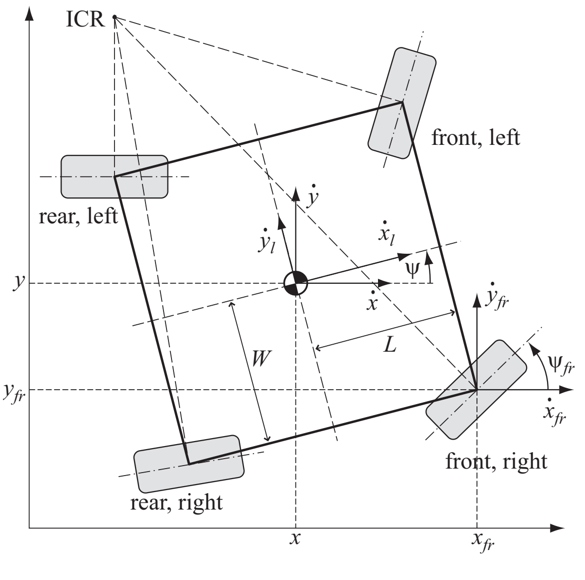

Fig. 2. The Moving Base co-ordinate systems