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Optimal Trajectory Tracking Control for Automated Guided Vehicles ⋆

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Abstract: This work presents a control strategy for the trajectory tracking problem of an Automated Guided Vehicle (AGV). In contrast to the current methods, this design strategy remains invariant and flexible to arbitrary number of wheels. A three-stage cascade control strategy is proposed in which the control design for the vehicle chassis is separated from the wheel-tire modules. For a given vehicle reference trajectory, the outer controller determines the required forces and moment inputs to the vehicle chassis in a time-receding fashion. At the second stage, the required forces and moment inputs are optimally allocated for each wheel and tire. At each wheel-tire module, a nonlinear controller is used to determine the actual control input for the wheel actuators. The performance of the presented control strategy is illustrated through simulation results with a realistic driving scenario for a six-wheeled vehicle. We demonstrate that the proposed controller architecture is configurable for an arbitrary number of wheels and capable of handling large steering angles efficiently.

Keywords: Trajectory Tracking and Path Following, Decentralized Control and Systems, Autonomous Vehicles, Motion control

1. INTRODUCTION

Recently, there has been a rapid increase in the applications of Automated Guided Vehicles (AGVs). An AGV is a load or people carrier which drives along a predefined path without any human intervention. Its control software uses a sensor-based guidance system to drive the vehicle along the desired path. In comparison to a traditional ground vehicle configuration, an AGV typically incorporates more than 4 wheels in which, moreover, each wheel can be equipped with in-wheel actuators for driving-braking and steering. Various developments are underway to utilise these salient features of AGVs to improve their driving accuracy and performance. The autonomous corner module (Zetterstrom, 2002) and the steer by wire system (Tavoosi et al., 2014) are few examples of electromechanical modules that provide reconfigurable architecture of actuation and improved energy consumption. In the light of the path-following task of an AGV, our goal is to develop a control algorithm for accurate reference tracking by utilising optimal actuation of each available actuator. To this end, we propose a model-based cascade-like controller architecture that delivers optimal and anticipative path tracking of the vehicle. We aim to demonstrate 3 main features of the proposed controller, namely, a) viability of a controller design for AGV with an arbitrary number of wheels, b) its ability to handle cornering maneuvers with large steering angle and c) its capability of anticipating suitable control actions using the prior knowledge of the reference trajectory. We assume that the information about the desired path is known a priori.

In the context of reference tracking of vehicles, several studies and methods have been proposed. For example, Ren et al. (2016) proposed an MPC algorithm to ensure yaw stability based on a simplified bicycle model considering only active front steering. Fredriksson et al. (2004) proposed a reconfigurable control scheme with optimization based control allocation. Feng et al. (2014) utilised a 2 DOF linear vehicle model to design a high level 'pseudo control' followed by distribution of control signals over each wheel. However, in these approaches, compensation of slip dynamics is not included and steering angles are either directly interpreted by the driver or approximated with a small angle. Wang and Longoria (2006) considered slip behaviour using a renowned 'Magic Formula' model. This approach linearises steering angles based on the mapping from the vehicle body frame to the wheel frame and, is therefore, only applicable for small steering angles.

The flexibility in incorporating additional wheels is one of the main issues while developing the trajectory tracking control framework for an AGV. To this end, the physical description of an AGV is described by a multi-body structure where the chassis is connected with multiple wheel-tire dynamical models. We propose to develop a control architecture as a cascade structure where the outer controller compensates the chassis dynamics and determines the control inputs to be applied on the center of mass of the chassis. The control inputs from the outer controller is distributed over each active wheel. Then at each wheel there is a local controller that tracks the

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desired tire forces by finding the actuation command for in-wheel actuators. In each local controller, the steering angle is included as a relevant state of the dynamics and the transient response of the longitudinal slip is taken into account. This approach solves the problem of compensating slip dynamics and large steer angles under cornering maneuvers. As an additional advantage, the outer controller has the capability to anticipate possible changes in the vehicle motion on the basis of the predefined path that needs to be tracked.

The remainder of this paper is organized as follows. The problem formulation is discussed in Section 2. The system dynamics is described in Section 3. The formulated problem is solved in Section 4 by a discussion of underlying methodologies. Section 5 discusses the achieved results with a simulation example. At last, Section 6 provides conclusions and directions for future work.

2. PROBLEM FORMULATION

The purpose of this paper is to develop a model-based control strategy such that an AGV with an arbitrary number of wheels follows a given path accurately. We assume that there exists a supervisory system that is responsible for offline planning of the desired path and determining the vehicle state reference trajectory under the motion constraints. With the prior knowledge concerning the vehicle state reference trajectory, the tracking control problem in this research amounts to finding the optimal actuation signal for each driving and steering actuator.

In order to solve the state trajectory tracking problem, a general class of AGVs is considered with the possibility of incorporating an arbitrary number of wheel-tire modules. In particular, this study includes but is not limited to the configuration in which each wheel admits independent in-wheel actuators. This allows the possibility of independent control over each wheel-tire motion and at the same time is equally applicable for a standard steering architecture. A multi-body model can describe the dynamics of such an AGV where the chassis is separated from each wheel-tire module. For the purpose of path tracking this leads, in principle, to an over-actuated system (Gerard and Verhaegen, 2009). Specifically, we show that it is possible to seperate the control tasks over the dynamics of chassis and wheel-tire module separately. Inspired by Wang and Longoria (2006), a cascade-like control structure is extended for an AGV with an arbitrary number of wheels and the control design of chassis dynamics is separated from wheel-tire dynamics. In this work, we illustrate the proposed architecture for an AGV with N wheels ($N \in \mathbb{Z}^+$) as shown in Fig. 1. The problem of reference trajectory tracking of the multi-body configuration of an AGV is divided into the following sub-problems:

(1) The *chassis control problem* amounts to determining the optimal longitudinal, lateral body force and also the yaw moment to be applied to the center of mass of the chassis in order to follow a predefined state trajectory based on dynamic state measurements.
(2) The *force distribution problem* amounts to distributing the desired forces and moment from the chassis controller over N controllable wheels, while respecting physical constraints of its dynamical behaviour.

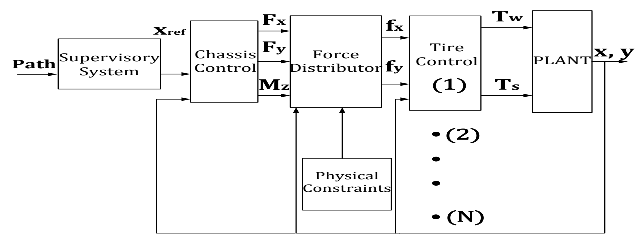

Fig. 1. Cascade control structure for trajectory tracking of an AGV with N wheel-tire modules.

(3) The *tire control problem* amounts to following the desired forces at each wheel-tire module by determining the control input for each in-wheel actuator.

The above sub-problems will be discussed in Section 4.

3. SYSTEM DYNAMICS

In this section, we describe the rigid-body dynamics of the chassis and each wheel-tire module separately. In the remainder of this section, we refer to Fig. 2 which describes a top view schematics of an N-wheeled AGV indicating respective tire forces and steering angles in the chassis reference frame.

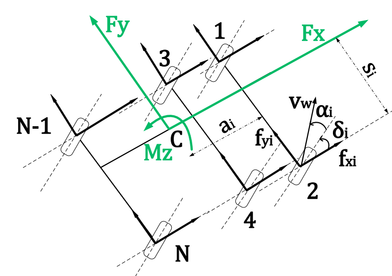

Fig. 2. Top view force configuration of AGV.

3.1 Chassis Dynamics

The dynamics describing longitudinal, lateral, yaw and roll motion of the center of mass of the chassis (point C in Fig. 2) is written in the state-space form as

$$\dot{x}_b = f_b(x_b, u_b). \tag{1}$$

Here, the state vector $x_b := \begin{bmatrix} u & v & r & \phi & \dot{\phi} \end{bmatrix}^T$ consists of the longitudinal velocity (u), lateral velocity (v), yaw rate (r), roll angle (ϕ) and roll rate ($\dot{\phi}$). Since this study does not concern sudden braking, the pitch motion of the vehicle is neglected. The effect of all the tire forces are collectively represented as a resultant longitudinal force (F_x), lateral force (F_y) and a yaw moment (M_z) applied to the center of mass of the chassis. Therefore, the input is defined as $u_b := [F_x \ F_y \ M_z]^T$. Specifically, in (1) $f_b(x_b, u_b) = \left(M^H\right)^{-1} F^H$. Where M^H and F^H are functions of x_b and u_b as

$$M^H = \begin{bmatrix} M & 0 & -Mh\,\phi & 0 & 0 \\ 0 & M & 0 & 0 & Mh \\ -Mh\,\phi & 0 & J_{zz} & 0 & J_{zz} - J_{xz} \\ 0 & 0 & 0 & 1 & 0 \\ 0 & Mh & J_{zz} - J_{xz} & 0 & J_{xx} + Mh^2 \end{bmatrix}, \tag{2}$$