Robotics and Computer Integrated Manufacturing 53 (2018) 93–107

Contents lists available at ScienceDirect

Robotics and Computer Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim

Coordinated path tracking of two vision-guided tractors for heavy-duty robotic vehicles

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ARTICLE INFO

Keywords:
Mobile robot
Path tracking
Coordinated control
Vision guidance
Trajectory conversion

ABSTRACT

Heavy-duty robotic vehicles are increasingly required to transport and position large-quantity and large-scale objects in the manufacturing process. The load-carrying capacity of vehicles can be enhanced by configuring multiple automated guided tractors and coordinating their motions. A vision-guided tractor is developed by using an on-board camera in order to improve the guidance accuracy. Each tractor can recognize the guide paths, measure its path deviations and control the speeds of driving motors independently. A coordinated path tracking technique is proposed for two vision-guided tractors of a robotic vehicle, in order to make them move along a guide path accurately and smoothly. The finite area of the vision field, the actuation capacity of driving motors and the motion conflict of two tractors are considered as control constraints of path tracking. Six path deviation states and their relevant approaching trajectories are classified based on deviation properties and control constraints. The general law of mutual conversion of six approaching trajectories is analyzed. Other approaching trajectories should be converted into the tangent-arc trajectory that can eliminate two path deviations synchronously. Expected tracking distance is a coupled parameter that influences control efficiency, safety margin of trajectory conversion and coordination degree of two tractors. A fuzzy logic regulator is used in the leader-follower control strategy to adjust this parameter, by taking two path deviations and the difference of attitude angles of two tractors into account. Numerical simulation and prototype experiment show that two vision-guided tractors can move along the straight and curvilinear guide paths with high tracking accuracy, control efficiency and motion coordination, which enhanced the load-carrying capacity of robotic vehicles significantly.

1. Introduction

Automated guided vehicles (AGVs) are commonly used to carry out repeating transportation tasks in inside and outside environments, such as manufacturing plants, distribution, transshipment and (external) transportation areas [1]. Heavy-duty vehicles are preferred in some applications to transport large-quantity and large-scale objects. For example, the load-carrying capacity of a self-lifting AGV should at least be equal to 40 tons in order to transport a container in ports [2]. Besides, some heavy and bulky workpieces, tooling and fixtures are present in the manufacturing process of heavy-duty plants, e.g., the fixture base on board the AGV for aircraft structures [3], which also need to be moved and positioned automatically.

The load-carrying capacity of vehicles can be enhanced by resorting to several approaches. Articulated heavy vehicles (AHV) and over-actuated vehicles with four-wheel steering/driving (4WS/4WD) make one class of heavy-duty transport vehicles on the road [4–8]. AHV is a new class of vehicle for mass transit, combining the advantages of commuter buses and railroad vehicles. The capacity of AHV can be increased by connecting one trailer to one another at articulated points by mechanical couplings, which can be regarded as the advantage of the towing mechanism of a tractor and its trailer. However, it is difficult to control the pose of trailers accurately and quickly, resulting in problems of swept-path, off-tracking, tail-swing, rearward amplification and tire scrubbing [6].

One class of heavy-duty AGV is developed based on conventional chassis of manned vehicles with pneumatic tires, e.g. AutoStrad [9]. AutoStrad is an autonomous straddle carrier with two legs enabling it to drive over and pick up a shipping container in a port environment. The vehicle is capable of traveling at speeds of up to 10 km/h, and of achieving docking accuracy of 5 cm approximately, sufficient for twin load containers.

However, this accuracy is not sufficient for in-plant precision motion of heavy loads, especially when moving and positioning components or sections for further assembly. It is difficult to make pneumatic tires move precisely due to their deformation and the nonholonomic

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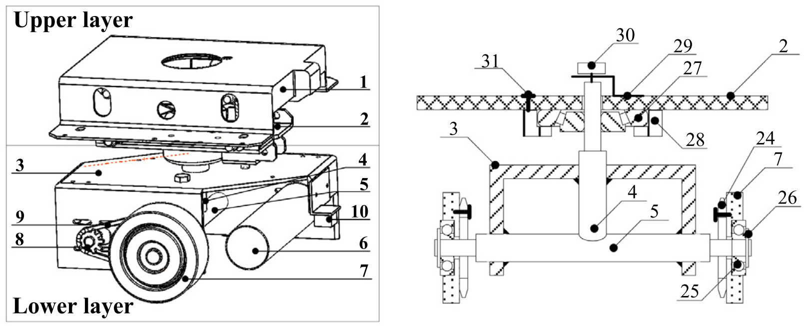
https://doi.org/10.1016/j.rcim.2018.03.012
Received 4 May 2017; Received in revised form 18 March 2018; Accepted 18 March 2018



(a) perspective view (b) section view

Fig. 1. Structure of the vision-guided tractor.

constraints. Mecanum wheels are among the most common holonomic wheels with three degrees of freedom (3-dof) planar mobility, but the low energy utilization, sensitivity to irregularities of ground surfaces, roller wear and vibration restrains their application to heavy-duty vehicles, and the random slippage of rollers that cannot be controlled by wheel frame even at low speeds decreases its motion accuracy [10,11]. Some prototype vehicles [11,12] claiming to be heavy-duty Mecanum-wheeled robots, have a nominal load-carrying capacity of lower than 300 kg, still waiting for further experimental validation.

In order to improve the controllability of wheel mechanisms, to avoid nonholonomic constraints or to decrease the energy consumption, some novel rolling mechanisms using conventional wheels are proposed for mobile robots [13–16]. An active dual-wheel caster is developed by setting a passive steering axis with offset in the front of two conventional independent driving wheels [13]. Another dual-wheel mechanism comprises two identical epicyclic gear trains, lying at two different levels and coupled by a common planet carrier [14,15].

By taking the towing mechanism of a tractor and its trailer, and the structure of the active dual- wheel caster as a reference, we designed a novel dual-layer two-wheel differential-driving steering assembly with a guiding sensor, termed automated guided tractor, which was used for accurately guiding and maneuvering a heavy-duty robotic vehicle on a designated path [17]. Mechatronics synthesis techniques are introduced to overcome the disadvantages of low-power motors and short-range sensors, e.g. a rotational degree of freedom between the tractor and the vehicle allowed the tractor to follow the guide paths rapidly, in order to keep it within its vision field, while the vehicle might deviate significantly from the guide paths. The objective of [17] is to enhance the load-carrying capacity of AGVs by means of designing an automated guided tractor, which can utilize the towing mechanism and the differential-driving steering mechanism to actuate a heavier vehicle, extend the detectable range of the guide sensor, and tolerate the more path deviations of the vehicle.

Based on the previous research work, coordinated control of two automated guided tractors is investigated for heavy-duty robotic vehicles in this paper, in order to improve the load-carrying capacity of AGVs in the further step. An on-board camera is adopted as the guiding sensor instead of the magnetic sensor in order to improve the guidance accuracy. Although many existing free-ranging AGVs use laser range-finders (LRFs) for gathering information [18,19], it is not feasible to mount the laser emitter/receiver in the front of the steering frame of the tractor because the emitting and returning lights must be occluded by the robotic vehicle. Visually recognizing artificial landmarks can help the AGV to acquire a huge amount of guide information, especially a vision-based line tracking technique [20–24]. The on-board camera can be installed in the AGV looking downwards vertically or obliquely. A marked (grey or coloured) line or tape is painted on or adhered to the floor as guide paths. Path deviations of the AGV with respect to a guide path can firstly be calculated by image processing, and then be eliminated by path tracking in order to keep the AGV move along the guide path precisely [20,23,25].

The rest of this paper is organized as follows. The structure of the vision-guided tractor, the configuration of the robotic vehicle and the formulation of coordinated control is described in Section 2. Six path deviation states and their relevant approaching trajectories are classified, and the general law of mutual conversion of these foregoing trajectories is analyzed in Section 3. How to adjust the coupled parameter of expected tracking distance according to path deviations and coordination degree of two tractors is presented in Section 4. Some simulation examples covering different initial deviation states on straight and curvilinear paths are discussed in Section 5. A prototype of heavy-duty robotic vehicle is developed and some experiments of path tracking are conducted in Section 6. Some conclusions and potential research points are given in Section 7.

2. Problem formulation

2.1. The structure of the tractor

The structure of the vision-guided tractor is illustrated in Fig. 1. The upper layer is a suspension mechanism used to distribute the payload among the tractor and other passive wheels. It comprises a set of articulated links and springs between the top plate (1) and bottom plate (2). The lower layer is a differential-driving steering mechanism integrating motors and sensors with the steering frame (3) for guidance control. The vertical shaft (4) is connected with the bottom plate (2) by using the thrust bearing (27), which allows the steering frame (3) to rotate with respect to the upper layer. Two driving wheels (7) supported on the horizontal shaft (5) are actuated by means of two motors (6) and sprocket transmission trains ((8), (9) and (24)). An on-board camera (10) is placed in the front of the steering frame (3) as the guidance sensor, and an angle sensor (30) fixed with the bottom plate (2) is used to measure the steering angle of the steering frame (denoting the tractor) with respect to the upper layer (denoting the vehicle platform).

2.2. The configuration of the vehicle

When several tractors are arranged in a tandem or parallel layout to construct a more complicated robotic vehicle, the guidance sensor can be installed either in the vehicle platform or in the tractor. A simple solution is to place the guidance sensor in the center of the platform if two tractors are connected with the vehicle symmetrically. A monocular AGV consists of one on-board camera looking downwards vertically and two tractors without guidance ability, as shown in Fig. 2. A hybrid control law combining an evaluation function method of error intelligent-transformation with an approach of exponential stability control is proposed for path tracking of it [26]. However, the control performance is inhibited by this configuration of separating the guidance sensor from the tractor. Since the path deviations measured by the on-board camera is the historical data of guide paths for tractor 1, a