Autonomous Driving System for Reversing an Articulated Rover for Precision Agriculture

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Andrea Botta[0000−0002−7272−7132], Eleonora Moreno, Lorenzo Baglieri, Giovanni Colucci[0000−0002−2996−9013], Luigi Tagliavini[0000−0001−8925−0417], and Giuseppe Quaglia[0000−0003−4951−9228]

Politecnico di Torino, 10129 Torino, Italy
{andrea.botta, giovanni_colucci, luigi.tagliavini,giuseppe.quaglia}@polito.it
{eleonora.moreno, lorenzo.baglieri}@studenti.polito.it

Abstract. This paper focuses on a unique articulated robot architecture for precision agriculture to develop an autonomous driving system for its reverse motion. This driving system employs a path planner based on Dubins path to generate an optimal trajectory which has to be tracked by a path following routine based on the pure pursuit algorithm while a controller ensures the stability of the vehicle. This control system has been successfully tested and assessed using kinematic and dynamic models of the rover.

Keywords: Autonomous reversing · Articulated vehicle · Path following · Agriculture robot.

1 Introduction

Within the growing trend of autonomous driving, a large portion of the spotlight has been focused on articulated vehicles. This is mostly related to their significance in logistics, which is considered a key part of the economy [10]. There are two primary reasons for choosing articulated vehicles over non-articulated ones: 1) articulated vehicles can perform significantly sharper turns than rigid vehicles of similar size [11], and 2) they improve the wheels contact with the ground on uneven terrain [9]. However, articulated vehicles suffer from the jackknife effect, which causes the vehicle to fold into a position from which it cannot recover. While in reverse motion, the pushed module of the articulated vehicle (i.e., a trailer) naturally tends to jackknife since it is in an unstable equilibrium while the folded condition is the stable equilibrium of the vehicle [14].

This represents a safety hazard also in the agricultural field where several autonomous articulated robots could be employed in the precision agriculture framework. In particular, it is of great interest the autonomous navigation in orchards or vineyards, environments that feature tight spaces that could benefit from the improved manoeuvrability of articulated vehicles moving also in reverse.

Several studies have discussed various implementations of autonomous navigation in reverse for articulated vehicles [13]. Moreover, recent studies have proposed some alternatives to be employed in agriculture on conventional articulated rover architectures [1].

This work focuses on developing an autonomous driving system for reversing a specific articulated rover that consists of a path planner, a trajectory tracker, and a hitch angle controller to avoid the jackknife effect. The proposed solution was tested and evaluated through kinematic and dynamic models of the robot.

2 Articulated rover modelling

Agri.Q is a mobile robot developed for precision agriculture applications [12, 15, 8, 7, 2]. The prototype is shown in Fig. 1. The robot is made up of two modules that are linked together by several joints, resulting in an articulated vehicle. Each module is outfitted with two drive units, each with two wheels. As a result, each module is an independent skid-steered part. Yet, a freewheel mechanism constraint the rear module to contribute only to the forward motion. Finally, two PV panels that can be positioned using two joints are put on the robot to serve as a landing platform for drones as well as a method to extend the robot autonomy in a sustainable manner.

2.1 Kinematic model

Fig. 1. Agri.Q in a vineyard

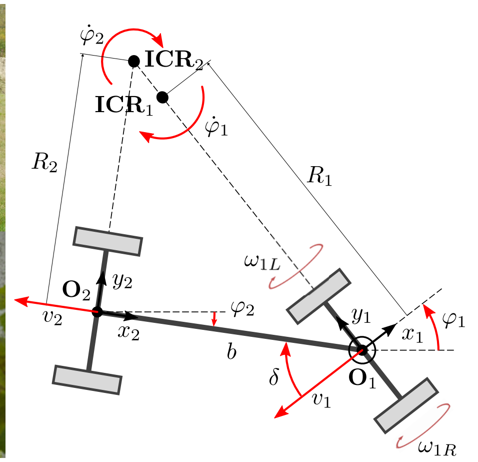

Fig. 2. Agri.Q simplyfied kinematic model

The kinematic model is based on the following hypothesis:

- the model considers only planar motion on a flat surface, out-of-plane motions are neglected;

– the locomotion units are simplified considering a single equivalent wheel per side with the axis passing through the centre of mass of the module.

Fig. 2 represents the kinematic model, where (x_n, y_n, φ_n) is pose of the n^{th} module ($n = 1$ for the front module, $n = 2$ for the back), δ is the relative yaw rotation between the modules, $i = 0.845\,\mathrm{m}$ is the wheel track of the module, $b = 1.3\,\mathrm{m}$ is the distances between the central joint and the rear module. v_n and $\dot{\varphi}_n$ are the longitudinal and the angular speeds respectively of the n^{th} module in its reference frame. A characteristic of Agri.q is that the reference point of the front module $\mathbf{O}_1$ coincides with the relative yaw join; this feature makes reversing behaviour particularly unstable.

The kinematic model[4] of is defined as

$$\dot{\mathbf{q}} = \begin{bmatrix} \dot{x}_1 \\ \dot{y}_1 \\ \dot{\varphi}_1 \\ \dot{\delta} \end{bmatrix} = \begin{bmatrix} \cos\varphi_1 & 0 \\ \sin\varphi_1 & 0 \\ 0 & 1 \\ -\frac{1}{b}\sin\delta & 1 \end{bmatrix} \begin{bmatrix} v_1 \\ \dot{\varphi}_1 \end{bmatrix} \tag{1}$$

then, considering that each module behaves as a skid steering robot, it is possible to introduce the two following relations

$$v_1 = \frac{r}{2}\left(\omega_{1R} + \omega_{1L}\right) \quad \text{and} \quad \dot{\varphi}_1 = \frac{r}{i}\left(\omega_{1R} - \omega_{1L}\right) \tag{2}$$

By solving the equation

$$\dot{\delta} = \dot{\varphi}_1 - \frac{v_1}{b}\sin\delta_{eq} = 0 \tag{3}$$

it is possible to define the equilibrium hitch angle δ_{eq}. The equation has two solutions, representing the stable and unstable equilibrium points. While going in reverse it is possible to demonstrate that the equilibrium hitch angle of a given trajectory is an unstable equilibrium point of the system.

2.2 Dynamic model

The hypothesis behind the kinematic model does not take into account the different characteristics of the real robot. The most important aspects, neglected in the kinematic model are: 1) wheel longitudinal and lateral slippage, 2) tyre-ground contact behaviour, and 3) the capabilities of the robot actuators. For this reason some dynamic models were developed by the authors in [3, 6]. In this study, an Agri.Q multibody model was done with ADAMS to be able to improve the control simulation results.

3 Autonomous reverse control system

Fig. 3 illustrates a block diagram of the proposed autonomous reverse control system with its main functional blocks. It starts with an off-line path planner that generates a suitable trajectory to minimise the jackknife occurrence. The generated path is then followed employing a pure pursuit algorithm that drives the robot motors together with a PD hitch angle controller to avoid jackknifing the robot. These main blocks are described in the following sections.

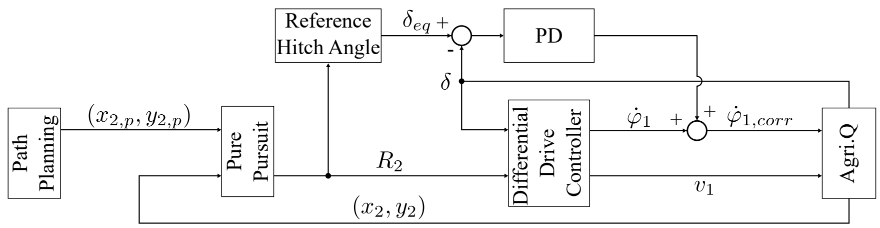

Fig. 3. Autonomous reverse control system block diagram

3.1 Path planning

An off-line path planner based on Dubins path (i.e., a path composed only of straight segments and circular arcs) has been adopted to generate a suitable trajectory. As the typical Dubins algorithm, it is possible to achieve the minimum number of elemental paths without any obstacle, but the same approach can be adapted to an environment with obstacles. The first case is reported here. Since the path has to be done in reverse, the planning is done with respect to the rear module (i.e., the trailer), but through the kinematic model, it is possible to relate the required quantities to the front module as well.

Fig. 4 depicts the working principle of the proposed planner. The algorithm receives as input the initial pose of the robot $\mathbf{P}_O$, the final pose $\mathbf{P}_R$ and the radius of the circular arcs is set to the minimum value possible, $R_{2,min}$. A typical Dubins path between the poses is then generated. Later, the first path element (always an arc) is simulated kinematically to predict the hitch angle δ_I at the end of the first path. If the magnitude of δ is above the threshold value δ_{max}, jackknifing may occur, hence the curvature radius is increased and the whole path is generated again. When the first path is verified, the second (it can be an arc or a segment) and the third (an arc) ones are checked similarly. However, if one of the following paths violates the hitch angle threshold, the previous verified path is kept and used as a starting point. This approach improves the path computation time and avoids increasing δ when not required.The planning ends when the final pose is reached.

The same planner can be adopted with some variations also when there are some obstacles. The two main differences are that a probabilistic roadmap planner is employed to estimate a simple path between the two robot poses and that the previously introduced planner is used considering that more than three elemental Dubins paths may be required and that such paths may differ from the typical Dubins optimal combinations.

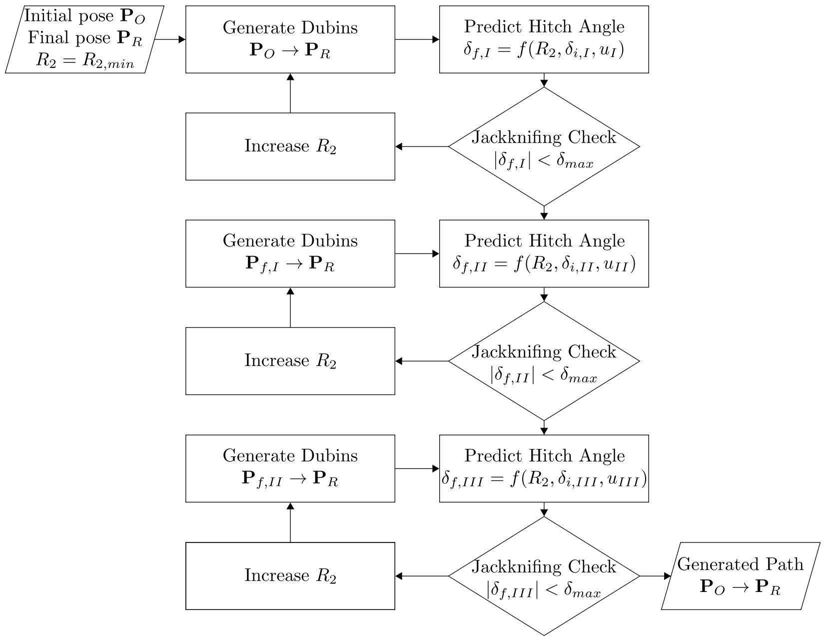

Fig. 4. Path planning flowchart

3.2 Path tracking

Pure pursuit [5] was chosen among various existing tracking algorithms because it is simple and reliable. To bring the vehicle back and keep it on its trajectory (Fig. 5), the algorithm geometrically evaluates the circular arc that enables the vehicle to move from its current position towards a target point $\mathbf{G}$, which is located at a look-ahead distance $\mathbf{L}$ from the current projection of the vehicle on the path. The resulting curvature is then used to calculate the linear and angular velocity commands of the front module.

The planned path can be defined as a succession of waypoints ($\mathbf{P}_O$, $\mathbf{P}_1$, ..., $\mathbf{P}_R$) connected by segments $\mathbf{S}_n = \overrightarrow{\mathbf{P}_n\mathbf{P}_{n+1}}$. The algorithm locates the closest segment to the robot, but to speed up the process the heuristic assumption of checking only a part of the whole path is done. Then the objective point $\mathbf{G}$ is defined and the circular tracking trajectory between $\mathbf{O}_2$ and $\mathbf{G}$ is computed.

Differently from the traditional implementation of pure pursuit, the required robot longitudinal speed v_1 is not constant, instead it is defined to be a function of the tracking path curvature and the maximum yaw rate. By doing so, the pursuit algorithm adapts v_1 to the path, automatically slowing down before tight corners and speeding up on straight segments.

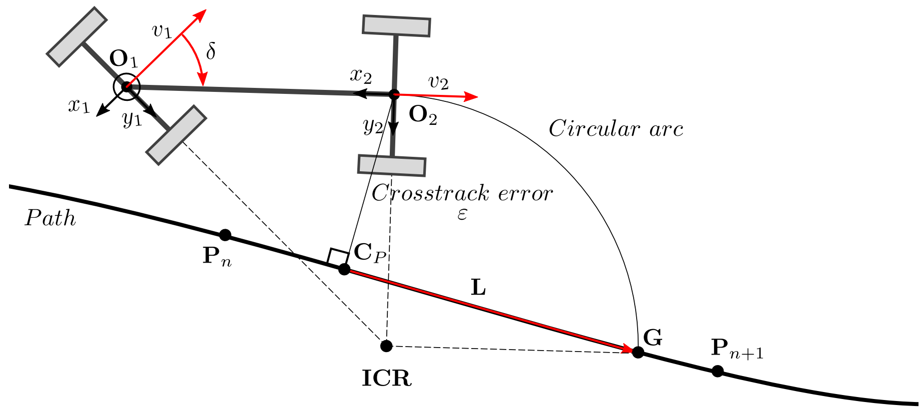

Fig. 5. Pure pursuit working principle

3.3 Hitch angle control

To avoid instability due to jackknifing, a PD controller has been implemented in parallel with the pure pursuit algorithm. The controller takes as input a reference angle δ_{eq}, that is computed from the path curvature R_2, and the measured hitch-angle δ. The controller could act both on the front module yaw rate $\dot{\varphi}_1$ and its longitudinal velocity v_1, however, a sensitivity analysis demonstrated that for Agri.Q and articulated vehicles where the hitch point is on the axle of the first module acting only on $\dot{\varphi}_1$ is more effective.

It is important to note that both the PD controller and the path tracking drive the front module yaw rate $\dot{\varphi}_1$, hence their contributions are added together to define the reference yaw rate of Agri.Q. This means that on some occasions the PD controller could slightly worsen the tracking of the planned path if it is required to compensate some deviation of δ from the reference value δ_{eq}.

4 Results

Fig. 6 shows the results of the autonomous reverse control system applied to a simple manoeuvre. Kinematic and dynamic behaviours showed very close results. In particular, it observable a slightly larger tracking error in the dynamic model compared to the kinematic one (the peak errors were 43 cm and 41 cm respectively). This result comes with no surprise since the vehicle architecture is known to have an understeering behaviour, an effect that becomes clearer with tighter turns. Fig. 6 also depicts the evolution in time of v_1 and $\dot{\varphi}_1$. Among the two, the yaw rate showed the result of a quite aggressive controller trying to stabilise δ while tracking the path during the turn (between 10 s and 28 s).

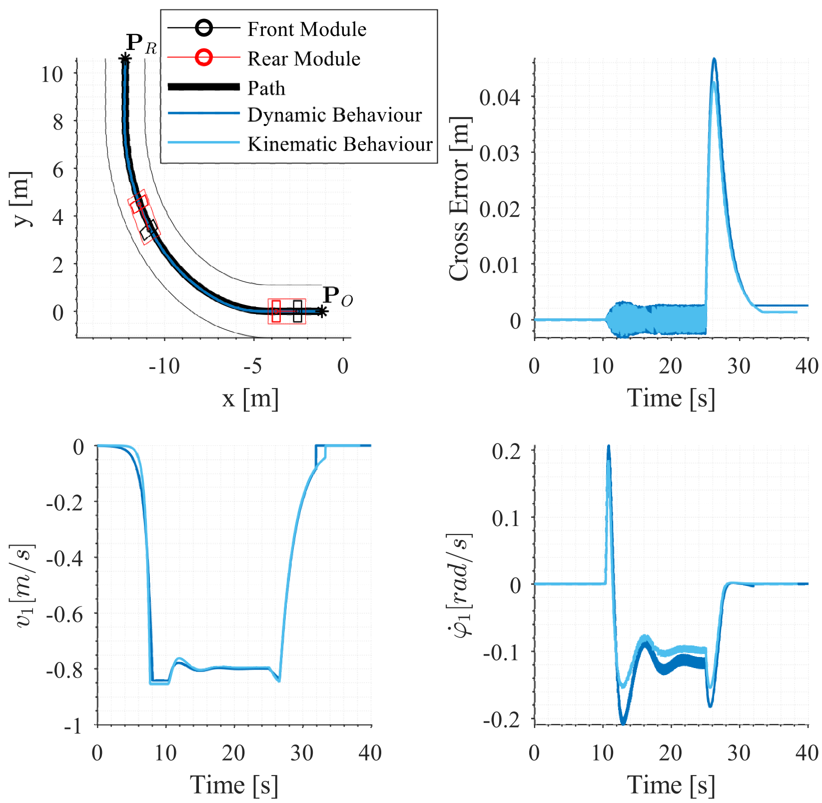

Fig. 6. Kinematic and dynamic results

5 Conclusions

In this work, an algorithm has been developed to plan, track, and control the reverse motion of the articulated mobile robot Agri.Q, with the particular goal of avoiding the occurrence of jackknifing (i.e., the folding of the articulated vehicle on itself). The autonomous driving system proved to be a robust algorithm for open field scenarios, but is easily adaptable to an environment with obstacles, through kinematic and dynamic simulation of the robot.

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