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Design, implementation and validation of a stability model for articulated autonomous robotic systems

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HIGHLIGHTS

- The articulated 4-wheeled system can be suitable in hilly and mountain terrains.
- A kinematic and (quasi-)static model for the articulated robotic platform is presented.
- The predicted phase I and II instabilities have been experimentally validated.
- A cheap mechatronic anti-overturning prototype is designed.

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ABSTRACT

The use of robots in agriculture and forestry is rapidly growing thanks to the progress in sensors, controllers and mechatronics devices. Especially in hilly and mountainous terrains, the development of (semi-)autonomous systems that could travel safely on uneven terrain and perform many operations is an open field of investigation. One of the most promising mobile robot architectures is the articulated 4-wheeled system that shows an optimal steering capacity, and the possibility to adapt to uneven terrains thanks to a central passive degree of freedom. In this paper, the kinematic and (quasi-)static model for evaluating the phase I instability presented in Baker and Guzzomi(2013) has been firstly extended to allow to threat a generic articulated robotic system and to forecast the instability conditions. Then, the model and the stability conditions have been implemented in a Matlab™ simulator and validated by means of an experimental emulator. Finally, a first prototype for a mechatronic anti-overturning device is discussed.

1. Introduction

Robotics and (semi-)autonomous systems for agricultural activities, e.g. planting, weeding, crop and environmental monitoring and crop harvesting have been testing since eighties [1]. Recent advances in sensors and control systems and their availability at reasonable prices, allow for new, smart and more efficient mechatronic applications that, together with special robotic systems, can help not only to solve different problems of operational sustainability related to the management of field processes [2] but also to increase the safety and risk assessment related to the use of machines on slopes [3,4].

In that regard, the optimal configuration of a mobile robot is strongly related to the working environment [1]. Wheeled systems are surely a good solution on flat surfaces [5] but, when rough and uneven terrain has to be travelled, the performance of classical wheeled systems drops significantly [6]. Indeed, the overall stability of the vehicle is highly affected by the terrain and slope [7–10] and, until now, the lack of a sufficient technological level for creating safe and self-stabilizing systems has been one of the main limitations for their development and exploitation. Small mobile platforms, either human-driven or (semi-)autonomous, able to move effectively between rows of vines on hills, for example, are still an exception.

As pointed out in [11], a versatile robotic platform able to move and turn easily on different slopes and between rows, e.g. vineyards, is still a challenge, and one of the most promising robotic architecture is the articulated-frame configuration, where a central active joint controls the steering angle. Indeed, this kind of system shows a high versatility, i.e. they have smaller external turning radii than vehicles with a conventional configuration [11]. Their central joint usually has two (yaw and roll) degrees of freedom (DoFs), one actuated (yaw) to let the vehicle steer and

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the other passive (roll), to allow the system to comply with the terrain. As demonstrated by effective prototypes and commercial machines [12,13], these systems could be an effective solution both for agricultural activities and for inspecting, monitoring and exploring outdoor uneven areas without requiring the kinematic and control complexity of effective but expensive legged systems such as the Big-Dog from Boston-Dynamics [14]. However, even if machines with this kind of articulated kinematics are already available on the market, they have not been deeply studied from the stability point of view.

1.1. Previous works on the stability

Looking at the mobile robotic literature, with the purpose of monitoring the stability of the robot at each instant through the use of a stability criterion while walking, moving or manipulating objects, the stability of multi-legged and multi-wheeled robots, usually with a rigid chassis, has been widely investigated since the sixties, e.g. [15]. Several stability criteria have been developed and validated and they can be mainly classified into (quasi-)static and dynamics-based criteria, the latter clearly more complex with respect to the former. According to many authors, e.g. [16], they can be further divided in five categories depending on the measurement mode: *distance-based* [15,17], *angle-based* [18] to which belongs the well-known Force Angel Stability Margin (FASM), *energy-based* [19], *moment-based* [20] of which the Dynamic Stability Margin (DSM) and the Zero Moment Point (ZMP) are the most known, and *force-based* criteria with, as an example, the Foot Force Stability Margin (FFSM) [16].

To the authors' knowledge, almost all the recent stability studies and evaluations that refer to articulated architectures are referred to the agricultural machine and tractors field where the joint is on the front axle [21–24]; these theoretical works, unfortunately validated only by numerical simulations, have shown that the articulated platforms, given the passive DoF, often cannot be treated with classical methods and stability metrics of rigid-chassis mobile robots. By applying an approach that falls in the *distance-based* category, they demonstrated that two kind of instabilities/possible overturning [21–23] can occur. Indeed, in addition to the classical stability condition (type II instability) related to the quadrilateral polygon made of the four wheel contacts, the passive roll DoF creates a second critical stability condition that results in the triangle which is made by considering the position of two wheels of a vehicle half and the joint (type I instability). This effect has been highlighted and modelled for tractors with a front axle pivot by Guzzomi [22] by means of a quasi-static model given the low operating working speed. Recently, Li et al. [24] extended the Guzzomi's model by taking into account the tyre stiffness and the main inertial terms. However, the model has been neither experimentally validated nor generalized for a generic articulated platform. Indeed, in order to implement an anti-overturning mechatronic system able to forecast and prevent critical configurations in a mobile robot with a central articulated joint, a simplified and light model has to be developed; this to allow to implement it into a micro-controller for a real-time control system. Thus, experimental validation becomes important both to demonstrate the effectiveness of the model and to know the possible model prediction error range for the future implementation in a real-time safety device.

1.2. Aims and outline

In this work, in order to future define and develop an effective stability metric, the kinematic and (quasi-)static model presented in [22] is extended to allow to threat a generic articulated robotic system (Section 2). Then, in Section 3, the equations of motion and stability conditions are obtained. Since the future robotic prototype will be surely driven at low speed, the quasi-static assumption adopted by [21] is maintained for the stability model development and validation. The developed model is implemented and experimentally validated by means of a platform emulator in Section 4 and, finally, in Section 5, a first cheap mechatronic prototype for predicting the overturning conditions based on the developed model is described and discussed.

2. Model of the articulated robot

2.1. Model assumptions

Starting from and recalling the basic hypothesis of [21], the model is based on the following assumptions:

- the roll DoF of the articulated joint is considered frictionless;
- since the robot speed is going to be slow in practical activities, the dynamic effects have been neglected;
- the robot does not slide down the slope, due to a non-limiting coefficient of friction between surface and tyres;
- tyres are considered stiff, so the contact surfaces result in discrete points/lines (not areas).[1]
- the joint mass is much more lighter with respect to the other parts, so it does not heavily affect the dynamic behaviour and it is neglected.

These, even if these hypotheses can be strong and unrealistic in some non-standard outdoor working conditions, they can be accepted if the articulated robotic platform has to travel with a slow speed on a compacted soil such as the one on a orchard, eventually sloped, row.

2.2. Kinematic model

An articulated robot, which model is presented in Fig. 1, is basically composed of a front "f" and a rear "r" part connected by a 2 Degree of Freedom (DoF) joint: the first DoF, i.e. the β angle, is actuated and allows a rotation around the yaw axis to let the robot turn; the second DoF is passive and allows a rotation around the roll axis, i.e. the α angle; thanks to this passive DoF, the articulated chassis can adapt itself to the ground surface allowing to have the four wheels in contact even if in the case of uneven substrates.

In Table 1 the geometric parameters of the model shown in Fig. 1 are explained (see Fig. 2).

For evaluating the robot stability, different surface configurations, i.e. slope and surface conformation, and different robot postures are to be considered. In order to do so, the articulated system is supposed to move on a circle on a sloped surface, as shown in Fig. 2(a) where ϑ is the sloped surface, φ defines the position of the robot related to the maximum slope direction, β sets the trajectory followed by the robot and α describes the surface conformation ($\alpha = 0$ implies a plane surface).

In our model, three main coordinate systems are considered: a global coordinate system ($x_0\, y_0\, z_0$) and two local ones ($x_1\, y_1\, z_1$) and ($x_2\, y_2\, z_2$), rigidly attached on the rear and front robot parts respectively. With reference to Fig. 2(a), the matrix $\boldsymbol{R}_1^0$ that describes the rotation from the global system to the rear local one

[1] In reality, the contact occurs on a surface but it is possible to define an equivalent force acting on an equivalent contact point. Generally the width of a wheel is not large compared with the track width, so the error due to the possible contact point relocation can be considered acceptable.