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Research Paper

Evaluation and stability comparison of different vehicle configurations for robotic agricultural operations on side-slopes

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Progress in sensors, controllers and mechatronics devices and the development of (semi-) autonomous systems that can travel safely on uneven terrain and perform many operations has encouraged research interest in the use of robotics for agriculture and forestry in hilly and mountainous terrains. Here, the main mobile configurations that are likely to be used for robotic platforms as implement-carriers (3-wheeled, conventional/articulated 4-wheeled, tracked) were reviewed and discussed in terms of their suitability for agricultural operations and their stability. A numerical index accounting for the lateral stability of a vehicle, the roll stability index, was used to indicate the in-field working capacity of these platforms during side-slope operations. Assuming the same overall dimensions for all the configurations, the 3-wheel configuration, although very simple and agile, was seen as being the least stable, while a tracked vehicle was the most stable, although it had some important drawbacks when used in an agricultural context. This drawbacks included increased soil erosion and landslides caused by its tracks especially in the areas involving turning manoeuvres. The articulated system was found to be the most suitable for uneven and side-slope terrains because of its optimal steering capacity, agility and good stability. It was found to reach a critical stability angle close to the 4-wheel vehicle.

1. Introduction

The use of robots, i.e. smart autonomous machines, in agriculture and forestry is not a new topic. In the past, most approaches to this topic (Billingsley, Visala, & Dunn, 2008; Ting, Ling, & Giacomelli, 1996) were adapted from an industrial point of view, i.e. the need to create working areas in the environment where almost all is known and where machines and robots can operate in predefined ways in a

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Nomenclature

Symbols

α slope angle of the plane on which a vehicle is travelling (rad; °)

γ steering angle in a single-line model of a vehicle, i.e. angle formed by the plane of its directional wheel and the longitudinal axis of the vehicle (rad)

γ_{est} steering angle of the outside directional wheel of a vehicle, i.e. angle formed by the plane of this directional wheel and the longitudinal axis of the vehicle (rad)

γ_{int} steering angle of the inside directional wheel of a vehicle, i.e. angle formed by the plane of this directional wheel and the longitudinal axis of the vehicle (rad)

$\Delta R_{2w,conv}$ misalignment between the front and the rear wheels trajectories in the bicycle (or single-line) model of a conventional vehicle (m)

$\Delta R_{4w,art}$ misalignment between the trajectories of the external and internal wheels of the four-wheel model of an articulated vehicle (m)

$\Delta R_{4w,conv}$ misalignment between the trajectories of the front external and rear internal wheels of the four-wheel model of a conventional vehicle (m)

$\overrightarrow{\Delta v}$ vector difference between two (vector) velocities (its modulus is in m s^{-1})

ϕ angular position of the reference point for the steering kinematics for a vehicle along a circumferential trajectory, computed with respect to the horizontal axis of a Cartesian system centred on O (centre of curvature of the trajectory); if the trajectory is observed from above and looking uphill, it is 0 when the centroid G of a vehicle is in the extreme left point of the travelled circumference and increases clockwise (rad; °)

ϕ_0 angular position of the reference point for the steering kinematics for a vehicle along a circumferential trajectory, computed with respect to the horizontal axis of a Cartesian system centred on O (centre of curvature of the trajectory) when the travel direction of the vehicle is perfectly parallel to the maximum slope direction; if the trajectory is observed from above and looking uphill, it is 0 when the centroid G of a vehicle is on the horizontal axis of a Cartesian system centred on O and increases clockwise (rad; °)

$\overrightarrow{\omega}$ angular speed (its modulus is in rad s^{-1})

d distance of the projection of the centre of gravity on the travelling plane (CoG*) from the point S along the line “s” (m)

d_l limit value of the distance of the projection of the centre of gravity on the travelling plane (CoG*) from the point S along the line “s” (i.e. it corresponds to the condition in which the centre of gravity projection is on a lateral border of the support polygon; in m); also indicated as “critical stability distance”

$\overrightarrow{Fp}$ weight of a vehicle (modulus in N)

ℓ wheelbase length for wheeled vehicles, tracks length for tracked vehicles (m)

max_θ maximum steering angle (rad)

p_f front tread width (m)

p_r rear tread width (m)

P_n generic (n-th) point in a figure, identified by its coordinates x, y, z (m)

r line passing through the centroid G of the supporting polygon of a vehicle, perpendicular to the radius vector from the centre of curvature of the trajectory and the centroid G and hence tangential to the vehicle trajectory

$\overrightarrow{R}(P_n)$ vector distance between the coordinate centre and the point P_n (its modulus is in m)

$R_{ext,f,art}$ radius of the trajectory followed by the external front wheel of an articulated vehicle in a turning manoeuvre (m)

$R_{ext,f,conv}$ radius of the trajectory followed by the external front wheel of a conventional vehicle in a turning manoeuvre (m)

$R_{int,r,art}$ radius of the trajectory followed by the internal rear wheel of an articulated vehicle in a turning manoeuvre (m)

$R_{int,r,conv}$ radius of the trajectory followed by the internal rear wheel of a conventional vehicle in a turning manoeuvre (m)

R_n n-th (scalar) distance between two points (m)

RSI roll stability index of a vehicle, defined as in equation (1) (%)

s line passing through the projection of a vehicle's CoG on the supporting plane (CoG*) and perpendicular to nearest lateral border of the supporting polygon of that vehicle (–)

$\overrightarrow{V}(P_n)$ vector velocity in the point P_n (its modulus is in m s^{-1})

wb wheelbase width (m); this symbol can be accompanied by a number if more than one vehicle is compared

wb_f front wheelbase width (m)

wb_f_d distance articulation joint-front wheelbase in an articulated vehicle (m)

wb_r rear wheelbase width (m)

wb_r_d distance articulation joint-rear wheelbase in an articulated vehicle (m)

Abbreviations

CoG, CoG_f, CoG_r centre of gravity of a generic vehicle, of the front half of an articulated vehicle, of the rear half of an articulated vehicle respectively

CoG^0, CoG_f^0, CoG_r^0 projection of the centre of gravity (of a generic vehicle, of the front half of an articulated vehicle, of the rear half of an articulated vehicle