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Research Paper

Terrain assessment for precision agriculture using vehicle dynamic modelling

Giulio Reina [a,*], Annalisa Milella [b], Rocco Galati [a]

[a] Department of Engineering for Innovation, University of Salento, Via Arnesano, 73100 Lecce, Italy

[b] Institute of Intelligent Systems for Automation, CNR-ISSIA, Via Amendola 122 D/O, 70126 Bari, Italy

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Advances in precision agriculture greatly rely on innovative control and sensing technologies that allow service units to increase their level of driving automation while ensuring at the same time high safety standards. This paper deals with automatic terrain estimation and classification that is performed simultaneously by an agricultural vehicle during normal operations. Vehicle mobility and safety, and the successful implementation of important agricultural tasks including seeding, ploughing, fertilising and controlled traffic depend or can be improved by a correct identification of the terrain that is traversed. The novelty of this research lies in that terrain estimation is performed by using not only traditional appearance-based features, that is colour and geometric properties, but also contact-based features, that is measuring physics-based dynamic effects that govern the vehicle–terrain interaction and that greatly affect its mobility. Experimental results obtained from an all-terrain vehicle operating on different surfaces are presented to validate the system in the field. It was shown that a terrain classifier trained with contact features was able to achieve a correct prediction rate of 85.1%, which is comparable or better than that obtained with approaches using traditional feature sets. To further improve the classification performance, all feature sets were merged in an augmented feature space, reaching, for these tests, 89.1% of correct predictions.

1. Introduction

Latest research efforts in robotic mobility are devoted to the development of novel perception systems that allow vehicles to travel long distances with limited or no human supervision in difficult scenarios, including planetary exploration, mining, all-terrain self-driving cars, and agricultural vehicles. One of the challenges in agricultural robotics is the ability to perceive and analyse the traversed ground. The knowledge of the type of terrain can be beneficial for a vehicle to deal with its environment more efficiently and to better support precision farming tasks. It is known that on natural terrain, wheel–terrain interaction has a critical influence on vehicle mobility that can be very different on ploughed terrain rather than on dirt road or compacted soil. Therefore, locomotion performance can be optimised in terms of traction or power consumption (e.g., fuel or battery life) by adapting control and planning strategy to site-specific environments.

* Corresponding author.
E-mail address: giulio.reina@unisalento.it (G. Reina).

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Nomenclature

Δz	Height range, m
$\widehat{n}_p$	Normal unit vector of a terrain patch
$\widehat{z}$	Z-axis unit vector
λ	Irregularity wavelength, m
λ_i	Minimum singular value of points' covariance matrix
ω	Tyre angular velocity, rads^{-1}
ω_e	Excitation frequency, Hz
σ_i^2	Variance of pixel intensity value
σ_z^2	Height variance, m^2
τ	Motor gearhead ratio
θ, ϕ, ψ	Vehicle pitch, roll, and yaw angle, rad
θ_p	Average slope of a terrain patch, rad
B, L	Vehicle width and length, m
$c_1c_2c_3$	The $c_1c_2c_3$ colour space
C_p	Points' covariance matrix
c_w	Vertical wheel damping coefficient, Nsm^{-1}
E_i	Mean pixel intensity value
F	Goodness of fit
F^W, F^V	Vehicle weight force in the world and vehicle reference frame, N
f_r	Coefficient of motion resistance
$F_{z,i}$	Vertical force on wheel i, N
h	Height of the centre of gravity above the ground, m
H_a	Magnitude of transfer function for acceleration, s^{-2}
I	Electrical current, A
k_t	Motor torque constant, NmA^{-1}
k_w	Vertical wheel stiffness coefficient, Nm^{-1}
m_b	Sprung mass, kg
N	Total number of points in a terrain patch
r	Wheel radius, m
R_V^W	Rotation matrix from vehicle to world reference frame
S	Slip
s_z	Normal stress, Nm^{-2}
SK_i, Ku_i	Skewness and Kurtosis of pixel intensity value
T_r	Driving torque, Nm
V	Actual forward vehicle speed, ms^{-1}
W	Vehicle weight, N
W_v	Tyre vertical load, N
x_n	Pixel intensity value
z_b	Sprung mass vertical displacement, m
z_d	Vertical displacement of terrain profile, m
z_{max}, z_{min}	Maximum and minimum point coordinate value along Z-axis, m
4WD	Four wheel drive
IMU	Inertial measurement unit
QV	Quarter-vehicle model
r_p, g_p, b_p	Red, Green, and Blue channel
RGB	Red Green Blue colour space
RGB-D	Red Green Blue-Depth
RPY	Roll, Pitch and Yaw angle convention
SVD	Singular value decomposition
SVM	Support Vector Machine
VO	Visual Odometry
WRF, VRF	World and Vehicle Reference Frame

Terrain estimation would also contribute to increase the safety of agricultural vehicles during operations near ditches or on hillsides and cross slopes and on hazardous highly-deformable terrain. Another important aspect that is raising interest in precision agriculture is related with the prediction of the risk of soil compaction by farm machinery that can be drawn from monitoring terrain parameters related with the ability to support vehicular motion (Stettler et al., 2014).

This paper addresses the problem of terrain assessment for highly-automated vehicles. This issue can be divided into two sub-problems: terrain characterisation and classification. Terrain characterisation deals with the determination of distinctive traits or features that well describe and identify a certain class of terrain. Based on these features, terrain can be classified by association with one of the predefined, commonly known, categories, such as ploughed terrain, dirt road, etc.

In this research, it is shown that terrain identification can be performed based on geometric and visual appearance of the terrain, that is using common exteroceptive features, as well as based on measures pertaining to vehicle–terrain interaction, that is resorting to proprioceptive or contact features. Overall, three sets are considered, namely colour, geometric and contact features. The colour set accounts for the normalised Red Green Blue (RGB) content of a given terrain. The geometric block refers to statistics obtained from 3D point coordinates associated with terrain patches. Finally, the contact block describes the vehicle dynamic response to a given terrain in terms of wheel slip, rolling resistance and body vibration.

Using a supervised classifier, the association of a given terrain under inspection with a few predefined agricultural surfaces is investigated. The colour, geometric and contact feature sets are used first singularly and, then, in combination, showing their advantages and disadvantages for terrain classification.

Experimental results are included to validate the proposed approach using an all-terrain vehicle operating in agricultural settings.

The research is presented in the paper as follows. Section 2 surveys related research in the literature, pointing out the differences and novel contributions of this work. Section 3 provides an overview of the framework proposed for terrain estimation and classification, whereas a description of the test bed used for the testing and development of the system is presented in Section 4. Terrain estimation through feature selection is thoroughly discussed in Section 5, along with practical examples. In Section 6, extensive experimental results obtained from field tests are included to support and evaluate quantitatively the proposed terrain classier. Final remarks are drawn in Section 7.