

# Agricultural unmanned ground vehicles: A review from the stability point of view

Veículos agrícolas terrestres não tripulados: uma revisão sob o ponto de vista da estabilidade

Hugo Rafacho Fernandes<sup>1\*</sup>, Edna Carolina Moriones Polania<sup>1</sup>, Angel Pontin Garcia<sup>1</sup>, Oscar Barrero Mendonza<sup>2</sup> and Daniel Albiero<sup>1</sup>

**ABSTRACT** - Agricultural ground vehicles often have to traverse unstructured terrain, i.e., terrain whose conditions cannot be precisely predicted during its displacement. Such characteristics restrict the use of robots in the agricultural field because their stability could be compromised by their interaction with the terrain. As it does not have a human operator capable of observing, predicting, and controlling the interaction of the vehicle with the terrain. Therefore, a robot must deal with the unpredictability caused by this interaction, a task that was previously performed by the human operator. Given the relevance of the topic, this study investigates the literature on agricultural unmanned ground vehicles from the stability point of view, and also presents relevant criteria for dealing with the stability of agricultural robots in terms of their design and selection.

**Key words:** Agricultural robots. Stability. UGV. Control. Review.

**RESUMO** - Máquinas agrícolas terrestres transitam em terrenos não estruturados, ou seja, um terreno cujas condições não se pode prever com exatidão ao longo de seu deslocamento. Tal característica restringe a aplicação de robôs em campo uma vez que a estabilidade pode ser comprometida por sua interação com o terreno. Por não contar com um operador capaz de observar, prever e controlar a interação do veículo com o terreno, um robô deve ser dotado da habilidade de lidar com as imprevisibilidades provocadas pela interação com o terreno, tarefa esta que era antes executada pelo operador. Dada a relevância do tema, o presente trabalho faz uma revisão da literatura sob o ponto de vista da estabilidade, além de apresentar critérios para o projeto e seleção de robôs agrícolas no que diz respeito à estabilidade.

**Palavras-chave:** Robôs agrícolas. Estabilidade. Controle. Revisão.

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Editores do artigo: Professor Daniel Albiero - daniel.albiero@gmail.com e Professor Alek Sandro Dutra - alekdutra@ufc.br

\*Author for Correspondence

<sup>1</sup>Laboratório de Instrumentação e Controle, Departamento de Máquinas Agrícolas, Faculdade de Engenharia Agrícola, Universidade Estadual de Campinas/UNICAMP, Campinas-SP, Brasil, rafacho.hugo@gmail.com (ORCID ID 0000-0001-5909-7060), ednacarolina27@gmail.com (ORCID ID 0000-0003-3014-0197), angel.garcia@feagri.unicamp.br (ORCID ID 0000-0002-8163-6638), daniel.albiero@feagri.unicamp.br (ORCID ID 0000-0001-6877-8618)

<sup>2</sup>Department of Electronics Engineering, Universidad de Ibagué, Colombia, oscar.barrero@unibague.edu.co (ORCID ID 0000-0003-3264-4129)

## INTRODUCTION

Machines that are used for agricultural field operations have to move on an unstructured terrain, that is, terrain whose conditions cannot be precisely predicted during its displacement. This characteristic restricts the application of robots in the field because their stability can be compromised during their interaction with the terrain. As it does not have a human operator capable of observing, predicting, and controlling the interaction of the vehicle with the terrain, the robot must deal with the unpredictability caused by this interaction, a task that was previously performed by the operator.

The literature presents works with a focus on tasks, such as pruning, weed control, harvesting (BACHCHE, 2015; FOUNTAS *et al.*, 2020), and generic tasks related to agricultural operations, such as navigation and location (MOISIADIS *et al.*, 2020; MOUSAZADEH, 2013), and specific cultures (FUE *et al.*, 2020; REN *et al.*, 2020). In general, with regard to the use of robots for agricultural activities, it is observed that the approaches prioritize the task and operation, and less attention is given to the stability of the vehicle, which implies a significant restriction of its applicability in the agricultural field. There are also studies that review agricultural robots considering their main activities for field operation (BECHAR; VIGNEAULT, 2016; ROSHANIANFARD *et al.*, 2020; R SHAMSHIRI *et al.*, 2018), but also in this case stability is given less attention. However, to design an agricultural vehicle that is autonomous and capable of moving in a wide range of terrains, it is necessary to focus on the interaction between the terrain and the vehicle, in addition to guaranteeing its stability for the assigned operation.

Thus, this work reviews the agricultural robots from the stability point of view by classifying them according to their applicability in the field and their form of interaction with the terrain. Although the suspension and stability control system is not always detailed in the analysed studies, this article uses the information present in articles and other reference sources, such as patents, websites, photos, and videos, to classify them according to the criteria presented here. In addition, it is important to note that during the literature review process, only robots with wheels were considered, as there is no significant use of robots with legs in the agricultural context. An additional contribution of this study is the suggestion of criteria for the classification and analysis of agricultural robots regarding their stability and locomotion in agricultural fields, thereby providing a starting point for projects or selection of this type of vehicle.

The paper is organized as follows. In section 2, a brief description of the agricultural terrain and the characteristics that are relevant to its interaction with a

robot and robot stability is presented. Section 3 classifies the types of suspension found in the literature, and Section 4 presents some stability criteria and explains how they can be applied for control. In section 5, the agricultural robots found in the literature are presented and classified, and some considerations concerning these robots from the stability point of view are presented. Finally, in Section 6, the need for stability control is briefly discussed and Section 7 outlines the conclusions.

## AGRICULTURAL TERRAIN

The terrain is one of the primary challenges faced by mobile robots because this can cause its instability. Moreover, this interaction can jeopardize the execution of a task by the robot. Thus, the characterization of the terrain is crucial for the selection and design of mobile robots.

The terrain used for agricultural applications presents a wide variety of characteristics that make it difficult to build robots capable of simultaneously dealing with them. However, we can list some relevant factors that can contribute to the selection of characteristics and design of an agricultural robot. In particular, when considering the stability of a robot, one may can classify the agricultural terrain according to three main aspects: regularity of terrain, soil cohesion, and slope.

## TERRAIN REGULARITY

The regularity of terrain concerns variations in its profile that directly impact vehicle locomotion and alter the force of contact between the wheels and the ground. Irregular terrains are those that present variations in their profiles, holes, stones, and large obstacles. In general, greenhouses, grain, or vegetable fields generally have a high regularity, whereas forestry or coffee fields may have a low regularity.

Traditionally, agricultural terrain is mechanically regularized to enable sowing. However, when this terrain is used by an autonomous system, any type of irregularity in the terrain profile can play a relevant role in causing robot instability, and may even lead to its rollover.

## SOIL COHESION

Soil cohesion is the parameter related to its shear capacity by applying a load, such as the weight of the vehicle when traveling. Soils that are not very cohesive present a large deformation, which can cause the wheels

to sink. The ASAE D497.7 standard (ASAE, 2011) refers to four types of soil surface conditions related to its cohesion. According to the standard, the soil can be hard, firm, tilled, or soft.

Due to the agricultural needs and the mechanical soil destructuring inherent to agricultural operations, agricultural soil usually presents low cohesion and can also be clayey, sandy, or have high humidity. Such parameters influence the traction capacity of the wheels and can cause skidding, lateral displacement, or even sinkage. Methods to mitigate the influence of low soil cohesion on the stability and locomotion of the robot in agricultural terrain include the adoption of features that reduce soil pressure and increase traction, such as wider wheels, tracks, or reduction of vehicle mass.

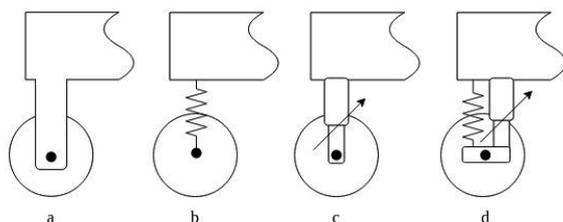
## SLOPE

The slope of the terrain influences the distribution of the forces between the wheels and the position of the centre of mass of the robot in relation to its supporting polygon. The variation in the position of the centre of mass of the vehicle allied to the forces inherent to the interaction with the ground can cause overturning if these characteristics are not observed and controlled. Therefore, an agricultural robot must be able to deal with the slope of the terrain on which it moves. Low slopes require a structure, either mechanical or control, that is simpler than that required for higher slopes.

## SUSPENSION TYPES

The robot suspension system can be defined as the set of mechanical and non-mechanical elements that allow the interaction of the chassis with the ground. For the purpose of this study, we classify the type of suspension in four distinct ways: rigid, passive or partially passive, active, and hybrid.

**Figure 1** - Presents the diagram of each suspension type, all of which are briefly explained in the following sections



Description: (a) rigid (b) passive or partially passive (c) active (d) hybrid. Authors' own elaboration

## RIGID SUSPENSION

Robots with rigid suspension have wheels that are rigidly connected to the chassis, so there is no possibility of movement between them (except the rotation of the wheel itself). Because there is no degree of freedom between the chassis and the wheels, these robots do not deal with ground irregularities in an optimal way, and any variations in the contact of the wheel with the ground reverberate to the chassis. Thus, robots with this type of suspension are more suitable for locomotion on regular and cohesive terrain, with low slopes, and at low speeds.

An example of this type of robot is the AgTracker, which uses a system composed of four wheels rigidly connected to the chassis for navigation between corn rows (XUE; ZHANG; GRIFT, 2012). Another example is the TERRA-MEEP, a platform used in the phenotyping of sorghum, which is inspired by rescue vehicles with a tracked locomotion system and has been tested on saturated soil after strong events of precipitation (YOUNG; KAYACAN; PESCHEL, 2019).

## PASSIVE OR PARTIALLY PASSIVE SUSPENSION

This category includes robots that employ passive elements in their suspension system, such as springs, shock absorbers, or simply an articulated system. There may be variations in which a control system acts on the passive element, such as the shock absorbers with a variable damping coefficient. In this case, the suspension is considered partially passive despite the presence of a control system because it is performed on the passive element and not on the suspension.

This category includes a weed removal robot, an intelligent autonomous weeder (IAW), developed by the University of Wageningen in 2009, with articulated support on the front of the chassis to ensure the contact of the wheels with the soil (BAKKER *et al.*, 2010). Another example is TerraSentia, a robot that can navigate on a variety of field conditions and has been tested in corn, soybean, and wheat sorghum fields (ZHANG *et al.*, 2020).

## ACTIVE SUSPENSION

Robots with active suspension have wheels and chassis that are connected by electric, hydraulic, or pneumatic actuators, and use some type of control system.

In order to use a control system, it is also necessary that a stability criterion is established and measured through sensors so that the controller sends the command signal to the actuators.

In general, this type of suspension presents great mechanical rigidity, as any compliance can significantly affect the stability of the robot. For this reason, such robots move at low speeds and on partially structured terrains. In this category, the robot by Fernandes and Garcia (2018) uses a double-actuated wheeled leg to move in rough terrains.

## HYBRID SUSPENSION

When the suspension system of a robot contains both passive elements, such as springs and shock absorbers, and active elements, such as actuators, and their stability is controlled, one can say that such a robot has a hybrid suspension system because it contains both elements. Robots in this category exhibit greater mobility because they combine the advantages of both

previous categories and are able to transit through unstructured terrain at higher speeds. However, they require a more elaborate control system that is capable of dealing with the ground reaction forces during motion.

An example of a robot with hybrid suspension is the Agri.q (QUAGLIA *et al.*, 2020), which has eight wheels connected two by two by a rocker arm and a platform actively controlled by electric actuators.

## STABILITY CRITERIA

The interaction of an agricultural robot with the environment can be affected by a series of agents that can make it unstable in situations that were previously stable. The higher the locomotion speed, the greater the contribution of the dynamic effects of the reaction of the soil to the instability of the vehicle. Furthermore, the presence of external forces, such as those caused by seeding or ploughing tools that interact with the robot can also make it unstable.

**Figure 2** - Displays some examples of robots with rigid suspension



Description: (a) BoniRob (FLECKENSTEIN; DORNHEGE; BURGARD, 2017), (b) AgTracker (XUE; ZHANG; GRIFT, 2012), (c) Asterix (UTSTUMO *et al.*, 2018) (d) Grape project (ROURE *et al.*, 2018) (e) TERRA-MEEP (YOUNG; KAYACAN; PESCHEL, 2019) (f) Xaver (FENDT, 2020). Authors' own elaboration

**Figure 3** - Presents some examples of robots with passive suspension



Description: (a) Agbot II (BAWDEN; KULK *et al.*, 2017) (b) IAW (BAKKER; ASSELT *et al.*, 2010), (c) Kiwi Harvester (JONES *et al.*, 2019); (d) Vinbot (LOPES *et al.*, 2016), (e) Thorvald II (GRIMSTAD; FROM, 2017) (f) Agribot (TABILE *et al.*, 2013). Authors' own elaboration

Therefore, the simple determination and control of the static stability of the robot may not be sufficient to guarantee the success of the operation. It is necessary to evaluate the operating conditions, such as speed, possibility of shock with external agents, and interaction with agents that apply some external force to the robot in order to guarantee its stability.

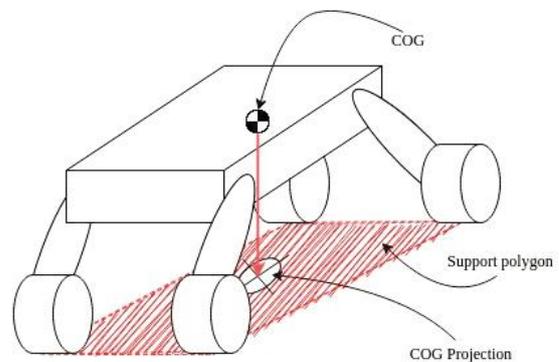
The stability of a vehicle can be classified in two distinct ways: statically or dynamically. The first disregards the action of external forces and the acceleration of the vehicle, whereas the second uses this information to measure stability.

### STATIC STABILITY

The concept of static stability was first defined by McGhee and Frank (1968) for quadrupeds and is based on the projection of the centre of gravity (COG) of a robot over its supporting polygon (projection of the robot's support points in the horizontal plane), as illustrated in Figure 4. If the COG is inside the supporting polygon, the robot is statically stable. Therefore, to measure the degree

of instability, it is possible to calculate the shortest distance from the projection point of the COG to the border of the nearest supporting polygon ( $S_{SM}$ ). The shorter this distance, the greater the instability of the vehicle (SANTOS; GARCIA; ESTREMER, 2007).

**Figure 4** - Robot scheme with the projection of the centre of gravity inside the support polygon



Source: Authors' own elaboration

In addition, the supporting polygon must be formed by considering at least three points of contact with the soil (SIEGWART; NOURBAKHS; SCARAMUZZA, 2011). However, the static stability on a horizontal surface may become unstable in the presence of other conditions, such as slopes, manoeuvre, and advancement on uneven terrain or steps (VIDONI; BIETRESATO *et al.*, 2015).

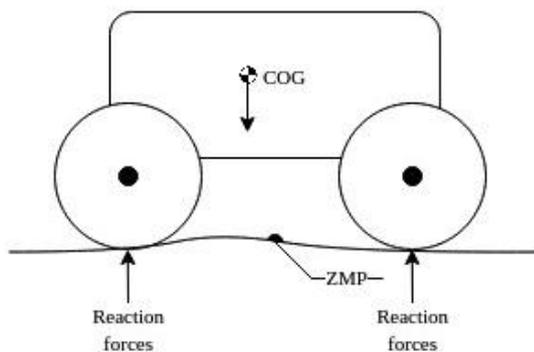
Some studies have defined the stability of agricultural machinery (PREVIATI; GOBBI; MASTINU, 2014; VIDONI *et al.*, 2015). However, these definitions are based on the static stability criterion, which does not account for the inertial characteristics of the robot and, hence, may be insufficient when the vehicle moves at higher speeds (above  $1\text{ms}^{-1}$ ). In these cases, it is necessary to establish a criterion that allows the vehicle to remain dynamically stable.

## DYNAMIC STABILITY

When the dynamic effects present in the system are considerable, it is necessary to apply a stability criterion capable of dealing with such effects. Therefore, several stability criteria have been developed to consider the dynamics of the robot and the acceleration involved in the system. The first stability criterion based on the moment was developed by Orin (1976) and Vukobratovic and Stepanenko (1972). The concept of dynamic stability margin ( $S_{ZMP}$ ) was defined based on the projection of the pressure centre (COP) on the supporting polygon, as depicted in (Figure 5).

In addition to the moment-based stability criterion, some authors have proposed an energy-based stability concept. We can highlight the model presented by Ghasemipoor and Sepehri (1998), and later extended by

**Figure 5** - Zero moment point concept



Source: Authors' own elaboration

Garcia and Santos (2005), as they consider the dynamics of the vehicle. Such concepts are more significant for application in the agricultural environment because they allow the evaluation of the dynamic stability of vehicles in unstructured terrain and in the presence of external forces, such as the forces caused by the use of tools attached to the robot.

## AGRICULTURAL GROUND ROBOTS

Based on the parameters presented in Sections 2, 3, and 4, we classified the robots found in the literature and qualitatively evaluated their stability and capacity to deal with the irregular terrain.

We analysed 52 papers published since 2010. Among the robots mentioned in these, 31 have a rigid suspension (Table 1), 18 have a passive or semi-passive suspension system (Table 2), one uses active suspension (Table 3), and two robots have a hybrid suspension (Table 3).

It is observed that most of the analysed robots contain a rigid suspension and, therefore, they do not have any kind of stability control. Such robots have good performance in regular terrain, with high cohesion and low slopes. However, they are not suitable for working conditions that require their locomotion in different conditions, at higher speeds, or even when the operation requires chassis alignment, such as in spraying or cargo transport.

In addition, all the robots presented in Table 1 travel on regular terrain, which has a high cohesion and low slope, except for the TERRA-MEPP (YOUNG; KAYACAN; PESCHEL, 2019) and ByeLab (VIDONI *et al.*, 2017), which have a system of tracks and can therefore travel on terrains with low cohesion. The limitation of locomotion while traversing this type of terrain is due to the fact that vehicles with rigid suspension are unable to control their stability because they cannot vary the position of the centre of mass in relation to the wheels and are unable to ensure the contact of the wheels with the ground. Some robots use commercial Husky platforms, such as Levin Robot (LEVIN; DEGANI, 2016) and Grape-Project (ROURE *et al.*, 2018), which allows greater agility in the development of algorithms but is restricted to the concept of suspension offered by a commercial platform.

In this type of suspension, the tire plays a pivotal role because it can be considered as the first level of damping, providing the robots a minimum adaptability to the terrain. Therefore, most of the observed robots have wheels with a tire.

When one wants to travel on slightly less cohesive and steeper terrain, it is necessary to use a passive suspension system, such as the robots presented in (Table 2).

Owing to the suspension system, such robots can travel on less cohesive terrain and even with higher slopes. However, most of the analysed robots travel on regular terrains with little variation in their profile. The only exceptions among the analysed vehicles are the Vinbot (LOPES *et al.*, 2016), which presents a

more robust suspension system because it is based on the commercial platform SUMMIT XL (ROBOTNIK, 2020), and Swagbot (WALLACE *et al.*, 2019), which uses a rocker type suspension, similar to that used by space exploration robots. It is important to note that, although they can travel in considerably uneven terrain, no vehicle in this category has a system capable of ensuring that the chassis is able to perform an agricultural operation, and the suspension system is used to maintain contact between the wheels and the ground.

**Table 1 - Rigid Suspension Robots**

Name	Suspension Type	Terrain characteristics			Cited work
		Regularity	Cohesion	Slope	
BoniRob (V2)	Rigid	Regular	Firm	Low	(BIBER <i>et al.</i> , 2012; FLECKENSTEIN; DORNHEGE; BURGARD, 2017)
TERRA-MEPP	Rigid	Regular	Soft	Low	(YOUNG; KAYACAN; PESCHEL, 2019)
Lady Bird	Rigid	Regular	Firm	Low	(UNDERWOOD <i>et al.</i> , 2015)
RIPPA	Rigid	Regular	Firm	Low	(SALAH SUKKARIEH, 2016)
ecoRobotix	Rigid	Regular	Firm	Low	(ECOROBOTIX, 2017)
ARA	Rigid	Regular	Firm	Low	(ECOROBOTIX, 2019)
Xaver	Rigid	Regular	Firm	Low	(FENDT, 2020)
MARS	Rigid	Regular	Firm	Low	(BLENDER <i>et al.</i> , 2016)
Asterix	Rigid	Regular	Firm	Low	(UTSTUMO <i>et al.</i> , 2018)
AgTracker	Rigid	Regular	Firm	Low	(XUE; ZHANG, L.; GRIFT, 2012)
Octopus	Rigid	Regular	Firm	Low	(REN <i>et al.</i> , 2020)
Vegebot	Rigid	Regular	Firm	Low	(BIRRELL <i>et al.</i> , 2020)
Levin Robot	Rigid	Regular	Firm	Low	(LEVIN; DEGANI, 2016)
TED	Rigid	Regular	Firm	Low	(NAÏO TECHNOLOGIES, 2017b)
OZ	Rigid	Regular	Firm	Low	(NAÏO TECHNOLOGIES, 2019)
Grape-Project	Rigid	Regular	Firm	Low	(ROURE <i>et al.</i> , 2018)
Shrimp	Rigid	Regular	Firm	Low	(GUTIÉRREZ; WENDEL; UNDERWOOD, J., 2019)
Phenomobile	Rigid	Regular	Firm	Low	(DEERY <i>et al.</i> , 2014)
Bakken Robot	Rigid	regular	Firm	Low	(BAKKEN; MOORE; FROM, 2019)
UGV Platform	Rigid	Regular	Firm	Low	(BARRERO; TILAGUY; NOVA, 2018)
mBase-MR7 robot	Rigid	Regular	Firm	Low	(BENGOCHEA-GUEVARA <i>et al.</i> , 2016)
RobHortic	Rigid	Regular	Firm	Low	(CUBERO <i>et al.</i> , 2020)
Vitrover	Rigid	Regular	Firm	Low	(DIAGO <i>et al.</i> , 2015; KERESZTES <i>et al.</i> , 2014)
MARIO	Rigid	Regular	Firm	Low	(SHARIFI <i>et al.</i> , 2018)
Cotton Harvesting Robot	Rigid	Regular	Firm	Low	(FUE, K. <i>et al.</i> , 2020)
MARIA	Rigid	Regular	Firm	Low	(IQBAL <i>et al.</i> , 2020)
AgROS	Rigid	Regular	Firm	Low	(TSOLAKIS; BECHTSIS; BOCHTIS, 2019)
Hiremath Robot	Rigid	Regular	Firm	Low	(HIREMATH <i>et al.</i> , 2014)
ByeLab	Rigid	Regular	Soft	Low	(VIDONI; GALLO <i>et al.</i> , 2017)
Xf-Rovim	Rigid	Regular	Firm	Low	(REY <i>et al.</i> , 2019)
Barbosa Robot	Rigid	Regular	Firm	Low	(BARBOSA <i>et al.</i> , 2019)

Source: Authors' own elaboration

**Table 2** - Passive Suspension Robots

Name	Suspension Type	Terrain characteristics			Cited work
		Regularity	Cohesion	Slope	
AgBot II	Passive	Regular	Tilled	Low	(BAWDEN; BALL. <i>et al.</i> , 2014; BAWDEN; KULK. <i>et al.</i> , 2017)
Autonomous Weeding robot	Passive	Regular	Tilled	low	(BAKKER; ASSELT. <i>et al.</i> , 2010)
Thorvald II	Passive	Regular	Tilled	Half	(GRIMSTAD; FROM, 2017)
AgriBot	Passive	Regular	Tilled	Low	(TABILE. <i>et al.</i> , 2013)
TerraSentia	Passive	Regular	Tilled	Low	(KAYACAN; ZHANG, Z.; CHOWDHARY, 2018; ZHANG, Z. <i>et al.</i> , 2020)
IAW	Passive	Regular	Tilled	low	(BAKKER; VAN ASSELT. <i>et al.</i> , 2010)
AVO	Passive	Regular	Tilled	Low	(ECOROBOTIX, 2020)
Kiwi Harvester	Passive	Regular	Firm	Low	(JONES. <i>et al.</i> , 2019)
Ball Robot	Passive	Regular	Firm	Low	(BALL, 2015)
Strawberry harvesting robot	Passive	Regular	Tilled	Half	(XIONG. <i>et al.</i> , 2020)
DINO	Passive	Regular	Tilled	Low	(NAÏO TECHNOLOGIES, 2017)
Vinbot	Passive	Irregular	Tilled	High	(LOPES. <i>et al.</i> , 2016)
VineRobot	Passive	Regular	Tilled	Low	(ROVIRA-MÁS; MILLOT; SÁIZ-RUBIO, 2015)
Autonomous Tractor	Passive	Regular	Tilled	Low	(KAYACAN, Erkan; KAYACAN. <i>et al.</i> , 2015)
Multi-sensor Robotic Plataforma	Passive	Regular	Firm	Low	(MILELLA; REINA; NIELSEN, 2019)
CERES	Passive	Regular	Tilled	Half	(SOLAQUE; GUILLERMO SANCHEZ; ADRIANA RIVEROS, 2019)
Bergerman Robot	Passive	Regular	Firm	Low	(BERGERMAN. <i>et al.</i> , 2015)
Swagbot	Passive	Irregular	Soft	High	(WALLACE. <i>et al.</i> , 2019)

Source: Authors' own elaboration

Such robots have good performance in medium cohesion and operate on higher slopes owing to the better contact of the wheels with the ground, but they do not properly handle abrupt transitions in the terrain profile.

Table 3 presents the remaining analysed robots and classifies their suspension systems as active or hybrid.

The only instance of a robot with exclusively active suspension for agricultural applications was the one proposed by (FERNANDES; GARCIA, 2018),

which allows the vehicle to travel on uneven terrain while keeping the chassis stable. However, this work does not include a practical experiment capable of evaluating the simulated control system in a real environment. Few agricultural robots with hybrid suspension systems have been found in the literature. Some of them have a purely passive suspension system and platform position control, such as the Wang Robot (WANG *et al.*, 2019) and Agri.q (QUAGLIA *et al.*, 2020). However, both present a passive suspension system together with an active platform positioning system.

**Table 3** - Active and Hybrid Suspension Robots

Name	Suspension Type	Terrain characteristics			Cited work
		Regularity	Cohesion	Slope	
Fernandes Robot	Active	Irregular	Tilled	High	(FERNANDES; GARCIA, 2018)
Wang Robot	Hybrid	Irregular	Soft	High	(WANG. <i>et al.</i> , 2019)
Agri.q	Hybrid	Irregular	Soft	High	(QUAGLIA. <i>et al.</i> , 2020)

Source: Authors' own elaboration

Although there have been few reports of robots with active or hybrid suspension in the agricultural context, one can observe the use of these types of robots for locomotion in other contexts, where they traverse challenging terrains, such as (BOUTON; BENAMAR; GRAND, 2017), and (GRAND *et al.*, 2004). Such robots can be considered for agricultural applications.

## SUSPENSION SYSTEM CONTROL

The use of a more complex suspension, such as partially passive, active, or hybrid, has a drawback concerning the complexity of its control system. In such cases, the control system required to respond rapidly, analyse the stability criterion, and act on the active element during its movement.

In addition, to determine the stability criterion, a set of sensors is required that is capable of determining the position of the center of gravity of the robot and its supporting polygon, such as an inertial measurement unit (IMU) and ground contact sensors. In some cases, it is necessary to measure the contact force of each wheel with the ground.

Based on the measured data and the robot model, it is possible to calculate the appropriate stability index for the application. When the robot travels at lower speeds and does not suffer from the action of external agents, the simple correction of the Euler angles is sufficient to keep it stable. However, in the absence of these conditions, it is necessary to use a more robust stability concept, such as those based on moment (ORIN, 1976; VUKOBRATOVIC; STEPANENKO, 1972) or energy (GHASEMPOOR; SEPEHRI, 1998; GARCIA; SANTOS, 2005).

The mechanical complexity, the use of sensors and actuators, and the need to establish a stability criterion can explain the low adherence of robots of this type in the literature. However, this limits the applicability of such robots to more regular terrain with high cohesion and low declivity. These challenges must be addressed in the project or selection of robots destined for field agricultural operations in order to make them successful in the operation for which they are designed.

## CONCLUSION

1. This study analysed and classified agricultural robots from the stability point of view. In general, it was observed that the literature has devoted insufficient attention to the subject up to now, focusing on other

activities necessary for the viability of robots in the field, such as navigation, weed control, and crop treatments. However, these approaches restrict the applicability of agricultural robots to more regular, cohesive terrain with lower slopes. This work contributed to the literature by analysing a fundamental dimension that is still under-explored in the agricultural context;

2. In general, most works do not consider a stability criterion, with the exception of those reported by (FERNANDES; GARCIA, 2018), which uses the  $S_{ZMP}$ , and Wang Robot (WANG *et al.*, 2019) and Agri.q (QUAGLIA *et al.*, 2020), which control the stability of a platform on the chassis with passive suspension;
3. To implement agricultural robotics in areas with challenging terrain, it is necessary to use more complex suspension systems and a control system that accounts for the platform stability criteria. In particular, hybrid suspension systems are more suitable because they present the advantages of both passive and active systems; however, they have a more complex control system;
4. Finally, the criteria for the classification of agricultural robots outlined in this study can be used as a starting point for the selection or design of an agricultural robot to suit the conditions in any terrain.

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## REFERENCES

- ASAE, S. ASAE D497. 7. **Agricultural Machinery Management Data**. ASAE, St. Joseph, MI, USA, 2011.
- BACHCHE, S. Deliberation on design strategies of automatic harvesting systems: A survey. **Robotics, Multidisciplinary Digital Publishing Institute**, v. 4, n. 2, p. 194-222, 2015.
- BAKKEN, M; MOORE, R; FROM, P. End-to-end Learning for Autonomous Navigation for Agricultural Robots. **Northern Lights Deep Learning Workshop**, 2019.
- BAKKER, T. *et al.* Systematic design of an autonomous platform for robotic weeding. **Journal of Terramechanics**, v. 47, n. 2, p. 63-73, 2010.
- BAKKER, T. *et al.* Robotic weeding of a maize field based on navigation data of the tractor that performed the seeding. **IFAC Proceedings Volumes (IFAC PapersOnline)**, IFAC, v. 3, p.1, 2010.

- BALL, D. *et al.* Robotics for Sustainable Broad-Acre Agriculture. In: MEJIAS L., Corke P., Roberts J. (eds) Field and Service Robotics. **Springer Tracts in Advanced Robotics**. [S.l.]: Springer, Cham, v. 105. p. 439-453, 2015.
- BARBOSA, W S *et al.* Design and Development of an Autonomous Mobile Robot for Inspection of Soy and Cotton Crops. In: IEEE. 2019 12th International Conference on Developments in eSystems Engineering (DeSE). [S.l.: s.n.], 2019. p. 557-562.
- BARRERO, O; TILAGUY, S; NOVA, Y. Outdoors Trajectory Tracking Control for a Four Wheel Skid-Steering Vehicle. **2018 IEEE 2nd Colombian Conference on Robotics and Automation, CCRA 2018**, IEEE, p. 1-6, 2018.
- BAWDEN, O. *et al.* A lightweight, modular robotic vehicle for the sustainable intensification of agriculture. **Australasian Conference on Robotics and Automation, ACRA**, 02-04-December-2014, 2014.
- BAWDEN, O. *et al.* Robot for weed species plant-specific management. **Journal of Field Robotics**, v. 34, n. 6, p. 1179-1199, 2017.
- BECHAR, A; VIGNEAULT, C. Agricultural robots for field operations: Concepts and components. **Biosystems Engineering**, v. 149, p. 94-111, 2016.
- BENGOCHEA-GUEVARA, J. *et al.* Merge fuzzy visual servoing and GPS-based planning to obtain a proper navigation behavior for a small crop-inspection robot. **Sensors**, v. 16, n. 3, 2016.
- BERGERMAN, M. *et al.* Robot farmers: Autonomous orchard vehicles help tree fruit production. **IEEE Robotics and Automation Magazine**, v. 22, n. 1, p. 54-63, 2015.
- BIBER, P. *et al.* Navigation System of the Autonomous Agricultural Robot "BoniRob. **Workshop on Agricultural Robotics: Enabling Safe, Efficient, and Affordable Robots for Food Production**, p. 1-7, 2012.
- BIRRELL, S. *et al.* A field-tested robotic harvesting system for iceberg lettuce. **Journal of Field Robotics**, v. 37, n. 2, p. 225-245, 2020.
- BLENDER, T. *et al.* Managing a Mobile Agricultural Robot Swarm for a seeding task. **IECON Proceedings (Industrial Electronics Conference)**, p. 6879-6886, 2016.
- BOUTON, A; BENAMAR, F; GRAND, C. Design of a compliant wheel-legged robot. In: ADVANCES in Cooperative Robotics. [S.l.]: **World Scientific**, p. 498-505, 2017.
- CUBERO, S. *et al.* RobHortic: A Field Robot to Detect Pests and Diseases in Horticultural Crops by Proximal Sensing. **Agriculture**, v. 10, n. 7, p. 276, 2020.
- DE SANTOS, P; GARCIA, E; ESTREMER, J. **Quadrupedal locomotion: an introduction to the control of four-legged robots**. [S.l.]: Springer Science & Business Media, 2007.
- DEERY, D. *et al.* **Proximal remote sensing buggies and potential applications for field based phenotyping**, v. 4, p. 349-379, 2014.
- DIAGO, M. *et al.* Vinerobot: On-the-go vineyard monitoring with non-invasive sensors. **Progres Agricole et Viticole**, p. 1-4, 2015.
- ECOROBOTIX. **ARA - Phenomobile Scouting Robot**. [S.l.: s.n.], 2019. Disponível em: <<https://www.ecorobotix.com/en/autonomous-scouting-robot/>>. (Accessed: 10.08.2020).
- ECOROBOTIX. **AVO - Switch to Weeding Robot**. [S.l.: s.n.], 2020. Disponível em: <<https://www.ecorobotix.com/en/avo-autonomous-robot-weeder/>>. (Accessed: 10.08.2020).
- ECOROBOTIX. **The autonomous robot weeder from Ecorobotix**. [S.l.: s.n.], 2017. p. 1-4. Disponível em: <<https://www.ecorobotix.com/en/autonomous-robot-weeder/>>. (Accessed: 10.08.2020).
- FENDT. **Project Xaver: Research in the field of agricultural robotics**. [S.l.: s.n.], 2020.
- Disponível em: <<https://www.fendt.com/int/xaver/>>. (Accessed: 10.08.2020)
- FERNANDES, H. R. **Desenvolvimento, otimização e controle de um sistema de suspensão ativa para um veículo agrícola não tripulado**. Fev. 2017. Dissertação. (Mestrado) - Faculdade de Engenharia Agrícola, Unicamp, Campinas, SP.
- FLECKENSTEIN, F; DORNHEGE, C; BURGARD, W. Efficient path planning for mobile robots with adjustable wheel positions. **Proceedings - IEEE International Conference on Robotics and Automation**, p. 2454-2460, 2017.
- FOUNTAS, S. *et al.* Agricultural robotics for field operations. **Sensors**, v. 20, n. 9, p. 1-27, 2020.
- FUE, K. *et al.* An Extensive Review of Mobile Agricultural Robotics for Field Operations: Focus on Cotton Harvesting. **AgriEngineering, Multidisciplinary Digital Publishing Institute**, v. 2, n. 1, p. 150-174, 2020.
- FUE, K. *et al.* Center-Articulated Hydrostatic Cotton Harvesting State Machine. **Electronics**, v. 9, p. 1223, 2020.
- GARCIA, E; SANTOS, P. An improved energy stability margin for walking machines subject to dynamic effects. **Robotica**, v. 23, n. 1, p. 13-20, 2005.
- GHASEMPOOR, A; SEPEHRI, N. A measure of stability for mobile manipulators with application to heavy-duty hydraulic machines. **Journal of Dynamic Systems, Measurement, and Control**, v. 120, n. 3, p. 360-370, 1998.
- GRAND, C. *et al.* Stability and traction optimization of a reconfigurable wheel-legged robot. **The International Journal of Robotics Research**, v. 23, n. 10-11, p. 1041-1058, 2004.
- GRIMSTAD, L; FROM, P. Thorvald II - a Modular and Reconfigurable Agricultural Robot. **IFAC-PapersOnLine**, v. 50, n. 1, p. 4588-4593, 2017.
- GUTIÉRREZ, S; WENDEL, A; UNDERWOOD, J. Ground based hyperspectral imaging for extensive mango yield estimation. **Computers and Electronics in Agriculture**, v. 157, p. 126-135, 2019.

- HIREMATH, S. *et al.* Laser range finder model for autonomous navigation of a robot in a maize field using a particle filter. **Computers and Electronics in Agriculture**, v. 100, p. 41-50, 2014.
- IQBAL, J. *et al.* Development of a Multi-Purpose Autonomous Differential Drive Mobil Robot for Plant Phenotyping and Soil Sensing. **Electronics**, v. 9, n. 9, p. 1550, 2020.
- JONES, M. H. *et al.* Design and testing of a heavy-duty platform for autonomous navigation in kiwifruit orchards. **Biosystems Engineering**, v. 187, p. 129-146, 2019.
- KAYACAN, E. *et al.* Towards agrobots: Identification of the yaw dynamics and trajectory tracking of an autonomous tractor. **Computers and Electronics in Agriculture**, v. 115, p. 78-87, 2015.
- KAYACAN, E; ZHANG, Z.; CHOWDHARY, G. Embedded High Precision Control and Corn Stand Counting Algorithms for an Ultra-Compact 3D Printed Field Robot. In: PROCEEDINGS of the Robotics: **Science and Systems**. Pittsburgh, USA: 20-30 June, 2018.
- KERESZTES, B. *et al.* Vineyard Vigilant & INNovative Ecological Rover (VINNER): an autonomous robot for automated scoring of vineyards. **International Conference of Agricultural Engineering**, p. 6-10, 2014.
- LEVIN, M; DEGANI, A. Design of a Task-Based Modular Re-Configurable Agricultural Robot. **IFAC-PapersOnLine**, v. 49, n. 16, p. 184-189, 2016.
- LOPES, C. M. *et al.* Vineyard Yield Estimation By Vinbot Robot - Preliminary Results With the White Variety Viosinho. July, 2016.
- MCGHEE, R B; FRANK, A. On the stability properties of quadruped creeping gaits. **Mathematical Biosciences**, v. 3, p. 331-351, 1968.
- MILELLA, A; REINA, G; NIELSEN, M. A multi-sensor robotic platform for ground mapping and estimation beyond the visible spectrum. **Precision Agriculture**, v. 20, n. 2, p. 423-444, 2019.
- MOISIADIS, V. *et al.* Mobile Robotics in Agricultural Operations: A Narrative Review on Planning Aspects. **Applied Sciences, Multidisciplinary Digital Publishing Institute**, v. 10, n. 10, p. 3453, 2020.
- MOUSAZADEH, H. A technical review on navigation systems of agricultural autonomous off-road vehicles. **Journal of Terramechanics**, v. 50, n. 3, p. 211-232, 2013.
- NAÏO TECHNOLOGIES. **Dino Large-Scale Vegetables Weeding Robot**. [S.l.: s.n.], 2017. Disponível em: <<https://www.naio-technologies.com/en/agricultural-equipment/large-scale-vegetable-weeding-robot/>>. (Accessed: 20.10.2020).
- NAÏO TECHNOLOGIES. **Oz Weeding Robot**. [S.l.: s.n.], 2019. Disponível em: <<https://www.naio-technologies.com/en/agricultural-equipment/weeding-robot-oz/>>. (Accessed: 20.10.2020).
- NAÏO TECHNOLOGIES. **Vineyard Weeding Robot TED**. [S.l.: s.n.], 2017. Disponível em: <<https://www.naio-technologies.com/en/agricultural-equipment/vineyard-weeding-robot-ted/>>. (Accessed: 20.10.2020).
- ORIN, D. **Interactive control of a six-legged vehicle with optimization of both stability and energy**. 1976. Tese (Doutorado) - The Ohio State University.
- PREVIATI, G; GOBBI, M.; MASTINU, G. Mathematical models for farm tractor rollover prediction. **International Journal of Vehicle Design**, v. 64, n. 2-4, p. 280-303, 2014.
- QUAGLIA, G. *et al.* Design of a UGV Powered by Solar Energy for Precision Agriculture. **Robotics, Multidisciplinary Digital Publishing Institute**, v. 9, n. 1, p. 13, 2020.
- R SHAMSHIRI, R. *et al.* Research and development in agricultural robotics: A perspective of digital farming. **International Journal of Agricultural and Biological Engineering**, v. 11, 2018.
- REN, G. *et al.* Agricultural robotics research applicable to poultry production: A review. **Computers and Electronics in Agriculture**, v. 169, p. 105216, 2020.
- REY, B. *et al.* XF-ROVIM. A field robot to detect olive trees infected by *Xylella fastidiosa* using proximal sensing. **Remote Sensing, Multidisciplinary Digital Publishing Institute**, v. 11, n. 3, p. 221, 2019.
- ROBOTNIK. Summit XL Robot. Out. 2020. Disponível em: <<https://robotnik.eu/products/mobile-robots/summit-xl-en/>>. (Accessed: 20.10.2020).
- ROSHANIANFARD, A. *et al.* A review of autonomous agricultural vehicles (The experience of Hokkaido University). **Journal of Terramechanics**, v. 91, p. 155-183, 2020.
- ROURE, F. *et al.* GRAPE: Ground Robot for vineyard Monitoring and Protection. **Conference: Iberian Robotics Conference**, p. 249-260, 2018.
- ROVIRA-MÁS, F; MILLOT, C; SÁIZ-RUBIO, V. Navigation strategies for a vineyard robot. **American Society of Agricultural and Biological Engineers Annual International Meeting 2015**, v. 5, p. 3936-3944, 2015.
- SHARIFI, M. *et al.* Modelling and simulation of a non-holonomic omnidirectional mobile robot for offline programming and system performance analysis. **Simulation Modelling Practice and Theory**, v. 87, p. 155-169, 2018.
- SIEGWART, R; NOURBAKHS, I. R; SCARAMUZZA, D. **Introduction to autonomous mobile robots**. [S.l.]: MIT press, 2011.
- SOLAQUE, L; SANCHEZ, G.; RIVEROS, A. Design and test of a path tracking controller to a high capability agricultural vehicle. **ACM International Conference Proceeding Series, Part F1476**, p. 60-64, 2019.
- SUKKARIEH, S. **An Intelligent Farm Robot for the Vegetable Industry**. Sydney, 2016. p. 52.
- TABILE, R. A. *et al.* Application of systematic methods in the electromechanical design of an agricultural mobile robot. **IFAC**

**Proceedings Volumes (IFAC-PapersOnline)**, v. 4, p. 276-281, 2013.

TSOLAKIS, N; BECHTSIS, D; BOCHTIS, D. Agros: A robot operating system based emulation tool for agricultural robotics. **Agronomy**, v. 9, n. 7, 2019.

UNDERWOOD, J. P. *et al.* Real-time target detection and steerable spray for vegetable crops. **in proceedings, Workshop on Robotics in Agriculture at International Conference on Robotics and Automation (ICRA)**, 2015.

UTSTUMO, T. *et al.* Robotic in-row weed control in vegetables. **Computers and Electronics in Agriculture**, v. 154, n. 7034, p. 36-45, 2018.

VIDONI, R. *et al.* Evaluation and stability comparison of different vehicle configurations for robotic agricultural operations on side-slopes. **Biosystems Engineering**, v. 129, p. 197-211, 2015.

VIDONI, R. *et al.* ByeLab: An agricultural mobile robot prototype 496 for proximal sensing and precision farming. In: AMERICAN SOCIETY OF MECHANICAL ENGINEERS. ASME International Mechanical Engineering Congress and Exposition. [S.l.: s.n.], 2017.

VUKOBRATOVIĆ, M; STEPANENKO, J. On the stability of anthropomorphic systems. **Mathematical Biosciences**, v. 15, n. 1, p. 1-37, 1972.

WALLACE, N. *et al.* Experimental validation of structured receding horizon estimation and control for mobile ground robot slip compensation horizon estimation and control for mobile ground robot slip compensation. **Proc. of the 12th Conference on Field and Service Robotics**, August, p. 1169-1175, 2019.

WANG, Z. *et al.* Development of an agricultural vehicle levelling system based on rapid active levelling. **Biosystems Engineering**, v. 186, p. 337-348, 2019.

XIONG, Y. *et al.* An autonomous strawberry-harvesting robot: Design, development, integration, and field evaluation. **Journal of Field Robotics**, v. 37, n. 2, p. 202-224, 2020.

XUE, J; ZHANG, L; GRIFT, T. E. Variable field-of-view machine vision based row guidance of an agricultural robot. **Computers and Electronics in Agriculture**, v. 84, p. 85-91, 2012.

YOUNG, S N.; KAYACAN, E; PESCHEL, J M. Design and field evaluation of a ground robot for high-throughput phenotyping of energy sorghum. **Precision Agriculture**, v. 20, n. 4, p. 697-722, 2019.

ZHANG, Z. *et al.* High precision control and deep learning-based corn stand counting algorithms for agricultural robot. **Autonomous Robots**, 2020.



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