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Research Paper

Design and control of an active suspension system for unmanned agricultural vehicles for field operations

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In the design of both autonomously and remotely controlled unmanned agricultural vehicles it is important to use an efficient suspension system that enables free transit over uneven terrain. Most mobile robotic systems use either a direct or inverse kinematic structural model in order to accurately determine the position of the end effectors or joints. However, this increases the complexity of the system and requires greater computational effort. In this context, the objective of this work was to investigate a new strategy that integrates the concepts of zero moment point and fuzzy logic into the control system of a wheel-legged vehicle used in agricultural field operations. The control system was able to maintain the stability and working height of the vehicle within the established standards without the need for a kinematic model, thus offering a simpler solution to the problem.

1. Introduction

Most agricultural operations occur in unstructured environments characterised by rapid time and space variations, similar to military, underwater, and space environments (Bechar & Vigneault, 2016). The stability of vehicles in transit is critical maintain transit in the field and ensure smooth operations.

In unmanned vehicles, stability becomes even more relevant, since in case of disturbances reliance on external agents to make corrections is not an option. Therefore, successful transit must be ensured by maintaining vehicle stability. This means that there must be at least three points of contact with the ground and the resulting force that act on the centre of gravity must have a direction that intercepts the support polygon (Siegwart, Nourbakhsh, & Scaramuzza, 2011).

However, static stability on a horizontal surface may suffer under different conditions, such as on slopes or when operating moving over uneven terrain (Vidoni, Bietresato, Gasparetto, & Mazzetto, 2015). Thus, the vehicle must be able to remain dynamically stable.

One way of guaranteeing stability is to use the zero moment point (*ZMP*) concept, which was first introduced as an important criterion for the stability of a biped walking robot (Vukobratović & Stepanenko, 1972).

ZMP is defined as a point on the ground where the net moment of inertial and gravitational forces presents no component along the horizontal axis (Dasgupta & Nakamura, 1999) and thus there is only a component along the vertical

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Nomenclature

ZMP	Zero moment point
At_{1i}	Final actuation over upper actuator on each leg
At_{2i}	Final actuation over lower actuator on each leg
$A1_1$	Upper actuator fuzzy controller response for inputs e_{P_x} and e_{Z_c}
$A2_1$	Lower actuator fuzzy controller response for inputs e_{P_x} and e_{Z_c}
$A1_2$	Upper actuator fuzzy controller response for inputs e_{P_y} and e_{Z_c}
$A2_2$	Lower actuator fuzzy controller response for inputs e_{P_y} and e_{Z_c}
k_{1i}	Proportional multiplier
k_{2i}	Proportional multiplier
p_x	Zero moment point along *x* axis
e_{p_x}	p_x error
p_y	Zero moment point along y axis
e_{p_y}	p_y error
x	*x* coordinate of centre of mass
$\ddot{x}$	Centre of mass acceleration along *x* axis
y	*y* coordinate of centre of mass
$\ddot{y}$	Centre of mass acceleration along *y* axis
z_c	Working height
e_{z_c}	z_c error
g	Gravity acceleration
ω	sine wave angular velocity

Fuzzy Linguistic Variables

NH	Negative height
NM	Negative medium
NL	Negative low
Z	Zero
PH	Positive hight
PM	Positive medium
PL	Positive low

axis. A system is considered dynamically stable if *ZMP* falls within the support polygon.

Suzumura and Fujimoto (2012a) developed a ZMP-based system for a wheel-legged vehicle for control of the trajectory and posture of the vehicle. In their work, ZMP was controlled using the RMC (resolved momentum control) concept, introduced by Kajita et al. (2003) for bipedal robots.

Due to the irregularities of the agricultural terrain, the position of the centre of mass of the vehicle in relation to an inertial reference frame may vary nonlinearly. In this case, the controller must be able to attenuate such variations in order to maintain vehicle stability.

One possibility to address this is to use a fuzzy controller, as it is able to handle nonlinear systems, multiple inputs and multiple outputs.

Fuzzy controllers have been used successfully for position control. For instance, Lee, Leung, and Tam (1999) and Choi, Lee, and Lee (2006) developed fuzzy position control systems for wheeled vehicles and (ZMP-based) legged robots, respectively.

Mobile robotic systems such as these use either direct or inverse kinematic structural models in order to accurately determine the position of the end effector and joints. However, the use of such models increases the complexity of the system and requires greater computational effort.

In this context, the objective of this work was to investigate a new strategy that integrates the concepts of ZMP and fuzzy logic into the control system of a wheel-legged vehicle used in agricultural field operations, without the need for a kinematic model.

The paper is organised as follows: section 2 presents the vehicle concept; section 3 presents the *ZMP* model used in this work; section 4 proposes a controller that integrates the concepts of *ZMP* and fuzzy logic; and section 5 discusses the simulation and experimental results. Finally, concluding remarks are presented in section 6.

2. Vehicle's geometry

In agricultural operations, transit conditions are difficult to predict, adding complexity to even the simplest autonomous navigation system and requiring the development of a vehicle control system. A stability control system for vehicles operating in agricultural terrain is proposed, performing tasks such as monitoring crops, collecting data and soil samples, as well as low energy demand tasks such as localised spraying or weed control.

The proposed vehicle has four legs with pivoting wheels at the ends as shown in Fig. 1. Each leg is composed of two four-bar mechanisms coupled in series, allowing for variations in platform height and wheel position. This configuration allows for greater independence of the position of the chassis relative to the position of the wheels, permitting them to follow the profile of the terrain without changing the position of the chassis.

Figure 1 also shows the maximum and minimum footprints of the support polygon (hatched areas) used to ensure the stability of the vehicle during transit. The legs of the vehicle can be moved horizontally to increase the support area and hence increase the stability margin.

Each leg segment is independently actuated by a diagonally positioned linear actuator (At_{1i} and At_{2i}), as shown in Fig. 2. Thus, each leg has two independent actuation points. By

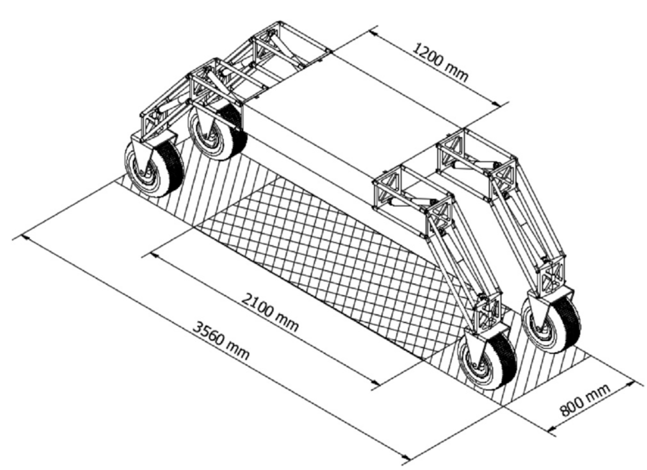

Fig. 1 – Vehicle's geometry.