Control strategy to change the locomotion mode of a reconfigurable wheel/track robot based on the soil conditions

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Abstract

The use of agricultural machinery damages the soil by compaction and distortion, where the compaction is due especially to vehicle with small contact areas like wheels, while the distortion is caused especially by tracked systems. In this work we discuss a wheel/track reconfigurable robot able to adjust the contact area based on the soil conditions, to minimize soil damage, energy consumption and adapt travers ability. After giving an overview, we propose a control strategy for switching between the locomotion modes.

Keywords: Reconfigurable robot, Tracked robot, Wheeled robot, Agricultural robot

1. Introduction

Soil degradation is one of the main issue of using agricultural machinery, [1]. During their operations in the field, the vehicles damage the soil by compaction and distortion. The first type of damage occurs in both topsoil (0-50 cm) and subsoil, and determines a soil volume reduction by compressing the pore space. The occlusion of the pores makes it difficult for the water to infiltrate and for the plants to reach the nutrients by the roots. The second type of damage occurs at the topsoil because of the shear loads and it destroys the pores by shear deformation [2]. Once the soil is damaged, the farmers have to restore the original status, and this is an expensive process.

Wheels and tracks are the most common running gears used for the locomotion in the agricultural fields. The two systems are different in terms of soil traversability and soil damage. With a smaller contact area, the wheels can easily sink on a soft soil, while the larger area provided by the track can allow a better floatation. For this reason, wheeled vehicles can cause higher compaction than a tracked system comparable in size. At the same time, it was observed experimentally [3] as the tracks cause a higher distortion, because of the higher shear forces and the peaks of pressure under the rollers. In terms of performance, in [4] a comparison based on the Bekker model was made between small tracked and wheeled vehicles moving on cohesive and frictional soils. The result was that a tracked vehicle outperforms a vehicle on cohesive soils, where increasing the area improves not only the floatation but also increases the maximum drawbar pull. On frictional soil instead, the performances were comparable, especially if the wheels' size is large enough to not sink too much and ensure a low rolling resistance.

Moreover, on loose frictional soils, the higher normal stress exerted by a wheel, because of the smaller contact area, leads to a higher soil strength and higher draught.

A last aspect to consider is that, while steering (especially in skid steering), a shorter contact area sliding at the ground (as for wheels) can determine a reduction of the torque, and then the energy required.

In order to mitigate the problem of the soil damage and adjust the performance of the vehicle based on the soil conditions, we introduce our reconfigurable vehicle Hadrian as in Fig. 1. This system can adjust the contact area as conceptualized in [5], to vary the pressure at the contact with the ground [6]. In this paper we provide an overview of this reconfigurable locomotion system. The target of the proposed vehicle is to transport the grape in the vineyards during the harvesting.

After describing the vehicle, we will conceptualize a possible strategy for making the robot change its locomotion system. Finally, we will describe the control interface created to operate the vehicle.

2. Reconfigurable vehicle overview

The system we developed consists of a mobile base able to pass from a half-track configuration to a wheeled configuration. The front axle of the vehicle consists of two tracks. The sprockets are rigidly connected to the chassis, while each idler is connected by a shock absorber to a Scott-Russell mechanism anchored at the top of the chassis. This mechanism is driven by an electro-hydraulic actuator, and it can lift the two idlers. When the idlers are lifted, only the sprockets remain in contact with the ground, as if they were wheels. The reconfigurable system is described in Fig.2 and Fig. 3. The rear axle consists of two wheels, which are supporting the chassis through a trailing-arm suspension system. The vehicle is equipped with four traction motors. The disposition of the motors is in-wheel for the rear axle, while the front axle sees the motors positioned inside the chassis and connected to the sprockets' shafts by a chain. The battery pack is positioned on the rear of the vehicle. The total weight is 210 kg, with a carrying capacity of 200 kg.

Fig. 1. Reconfigurable track/wheel robot Hadrian

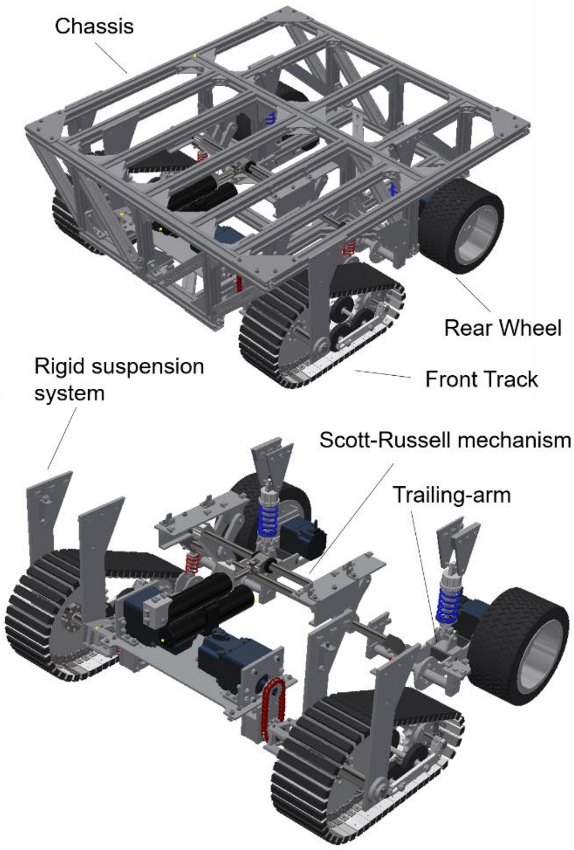

Fig. 2. Overview of Hadrian

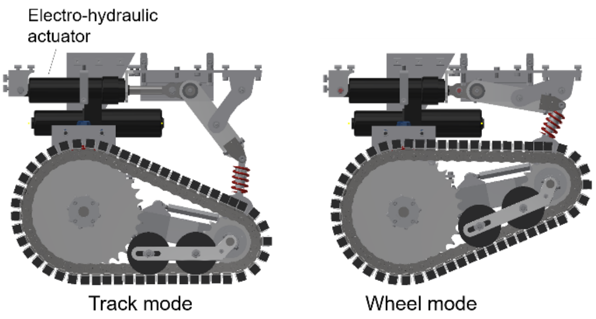

Fig. 3: Track mode (left) and wheel mode (right)

3. Soil damage and measurements for the experiments

The choice of the locomotion system by the vehicle is a difficult task, as various aspects must be taken into account, such as the state of the terrain, the payload of the vehicle, the damage caused and the performance in terms of rolling resistance (energy consumption) and traction.

The first approach to the problem is to test the vehicle on agricultural soil in several conditions, and compare the results to obtain the first thresholds to be used as a reference for the switching between the two locomotion modes.

The decrease in volume following the passage of a vehicle, and the consequent compaction can be measured by means of a device known as the Cone Penetrometer, [7]. This consists of a cone at the end of a rod, which is in turn connected to a load cell. By driving the cone into the ground, the load cell measures the pressure value on the cone and provides the so called Cone Index [MPa]. This is a measure of the state of soil compaction, where higher values indicate a greater state of soil compaction.

During our experiments, we will measure the state of soil compactness by using the Cone penetrometer.

Soil distortion is expressed as the horizontal displacement that particles of soil undergo due to the shear forces applied by the running gear. For a tracked vehicle, the shear displacement is expressed as in Eq. (1)

$$J = ix \tag{1}$$

where i is the slip and x is the position of the soil particle along the contact length (CL) in the moving direction. x can vary from 0 to the maximum length. The slip can be calculated as in Eq. (2)

$$i = \frac{\omega r - V}{\omega r} \tag{2}$$

where V is velocity of robot. ω is angular velocity of running gear or motor. For a wheeled system, the shear displacement can be calculated as Eq. (3)

$$J = r[(\theta_0 - \theta) - (1 - i)(\sin\theta_0 - \sin\theta)] \tag{3}$$

where angle θ is the rim angle where the wheel contact with terrain and angle θ_0 is the entry angle that defines the angle where a point on the wheel contact with the terrain as shown in Fig 4.

In our experiments, we will evaluate the shear displacement by using markers on the soil and measuring the markers displacement after the vehicle pass. As for the slip, we can measure it by knowing the vehicle velocity and running gear rotational velocity.

Finally, we will measure the energy consumption by monitoring the current used.

We are going to evaluate soil damage (compaction and distortion), energy consumption, rolling resistance and traction force under several soil conditions. We will consider firm and soft soil with different levels of soil moisture and compactness. The soil moisture will be monitored by using several soil moisture sensors in wireless communication with the robot.

Because the evaluation of the thresholds requires many experiments, we need a way to easily control the robot remotely. For this reason, we develop a user friendly interface for controlling the robot and switching locomotion mode, while also monitoring the torque, the velocity and the current used by the motors. This control interface is described in Section 5

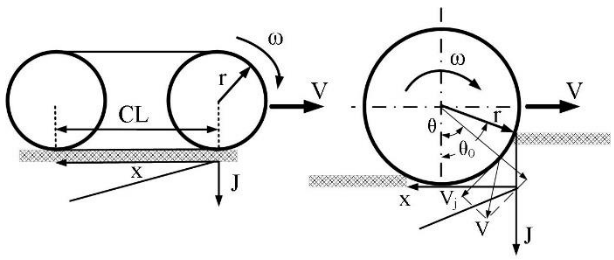

Fig. 4. Development of shear displacement of track and wheel

4. Control Strategy

In this section we propose a preliminary control strategy for switching locomotion mode based on the soil conditions. Decision making process is used to analyze and classify soil conditions. Fuzzy logic [8] and neural network [9] are the most popular decision making process to classify soil and terrain. We can classify the soil based on compactness and moisture level. For that reason, we consider four classes of: firm soil (usual condition), soft soil and soft dry soil (after plowing it), and wet saturated soil (after some heavy rain). For the firm and soft soil, we consider different level of moisture contents, since the moisture affects the soil strength. A soft soil and a soft dry soil have different moisture. A soft soil is more humid, while a soft dry soil being under the sun for long becomes dry. Four features are defined as soil moisture, energy, slip and velocity. Concept of control strategy is shown in Fig. 5. The goal and the expected output of control strategy is described as below.

1) To minimize soil damage. If the robot is sinking too much, robot is damaging too much the soil and causing compaction or distortion. It doesn't matter with a track or a wheel. However, if wheel cannot move, track can help robot to move when wheel stuck. If the robot is not sinking too much, the robot uses wheeled mode, because the track causes higher distortion. Cone penetration test, shear displacement of track as Eq. (1) and wheel as Eq. (3) are used to evaluate soil damages.

2) To minimize energy consumption. The rolling resistance is relative with energy. If robot sink too much, the robot has higher rolling resistance and use higher energy. Track doesn't sink too much if compared with wheel because longer contact area. For this reason, track use lower energy consumption if compared with wheel. However, track use higher energy consumption when robot turn left or right using skid-steering because of longer contact area.

If robot is sinking too much, it will use tracked mode. If robot is not sinking too much, it will use wheeled mode because track cause higher soil distortion. We will test robot on agricultural soil in several conditions and collect data of torque of motor and measure sinkage after robot pass. After we do many times, we can calculate sinkage using torque of motor. The robot uses wheeled mode when it turns left or right because wheel can reduce energy consumption

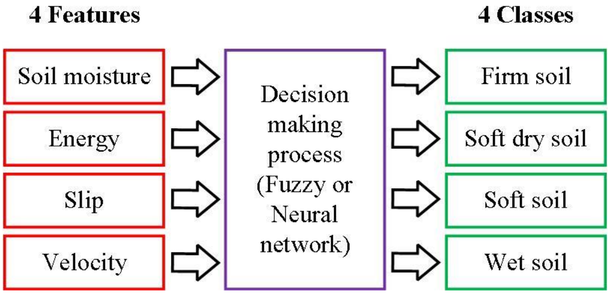

Fig. 5. Classification strategy

5. Control hardware actuator and sensor

After we proposed the control strategy in section 4, we need to consider about sensor, microcontroller and actuator for switching locomotion mode based on the soil conditions. The microcontrollers used in this research are ESP32. ESP 32 is microcontroller that can be transmitter and receiver with wireless. Control diagram of ESP32 Transmitter is shown in Fig. 6. Soil moisture sensor is connected to ESP32 transmitter for measuring the moisture in each soil condition, and send moisture data to ESP32 receiver. Control diagram of ESP32 receiver is shown in Fig. 7. Two Brushless DC Motors for tracks are BLV620K100S (24 VDC, 40 RPM, torque 36.5N.m) and two Brushless DC Motors for wheels are BLV510K100S (24 VDC, 30 RPM, torque 27.4 N.m). Four motors can send data of torque and angular velocity to calculate energy consumption. One electro-hydraulic actuator (EHA) is installed inside robot to switch between tracked and wheeled mode. Relay is used to control direction of EHA. One JRT laser distance sensor (B series) is used to measure distance and calculate velocity of robot. We are planning some simplified experiments and the use of the wall and distance sensor is only a way to easily localize the robot in the field, when this is moving on a prescribed rectilinear path. We can calculate slip using angular velocity from motor and velocity from laser distance sensor as Eq. (2). The robot user interface is developed and tested using Microsoft Visual Basic 2022 as in Fig. 8. The robot user interface allows the user to control the robot for effective operation and get feedback data from the robot. The robot user interface offers users many advantages. Users can easily and quickly operate the robot. Even farmers with little technical knowledge can control the robot with the robot user interface. For the experiment, the robot can be remotely operated, but it is not autonomous path planning. We discuss how to use the robot user interface as below

1) Manual control can be operated independently by pushing arrows ↑forward,↓backward, ←left , →right.

2) Automatic control can be operated by pushing blue button in the top center of screen. The robot will move forward, and use our control strategy to switch between tracked mode and wheeled mode autonomously.

3) Direction of EHA can be shortened and extended by pushing the pull and the push button.

4) Direction of four motors control can be controlled by pushing clockwise and counterclockwise button.

5) Data of angular velocity and load torque of four motors are shown as graphs in the center of screen. Distance, velocity and soil moisture are shown as numerical value on bottom right of screen.

The robot user interface is developed to control and obtain the feedback data easily for control strategy as described in section 4. For the future application, farmers who have little technical knowledge can control the robot remotely and operate the autonomous path planning of robot during the harvesting period with our robot user interface.

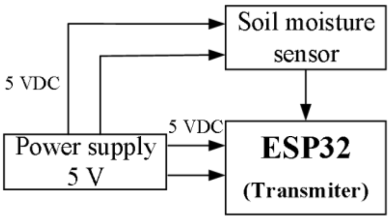

Fig. 6. Control diagram of ESP32 Transmitter

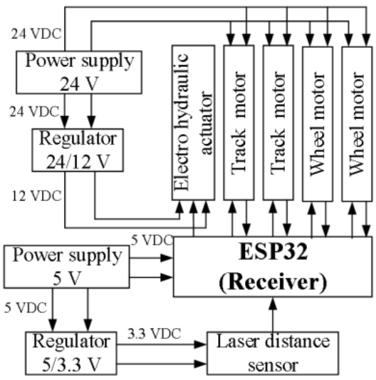

Fig. 7. Control diagram of ESP32 Receiver

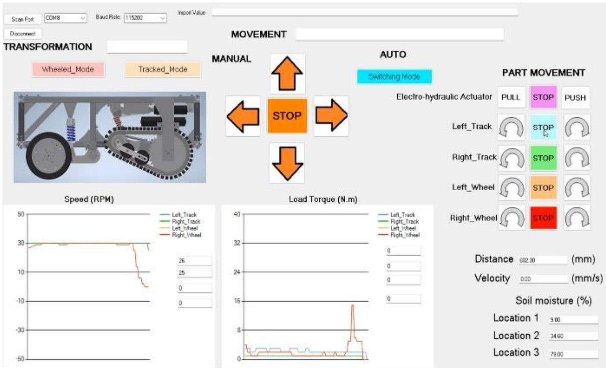

Fig. 8. Robot user interface

The robot can switch between tracked and wheeled mode using electro hydraulic actuator (EHA). EHA extends to push track to the ground in tracked mode. Video of switching from wheeled to tracked mode is shown in Fig. 9. EHA shortens to pull and lift the partial track off the ground in wheeled mode. Video of switching mode from tracked to wheeled mode is shown in Fig. 10. After we complete software, we will get data of four features to classify soil conditions for autonomous switching modes. In future work, we will test the robot on various soil conditions as shown in. Fig. 11 experiment setup. Soil moisture sensors and ESP32 transmitters are putted on each soil conditions to measure moisture and send data to ESP32 receiver inside robot. The laser distance sensor is installed on the front of robot to detect wall for estimation position and calculation velocity. GPS navigation will be used to estimate the position in next work. For experiment, the robot will move forward in tracked or wheeled mode on soil condition 1, then change to another mode on soil condition 2 autonomously using our control strategy that is described in section 4.

6. Conclusion and future work

A reconfigurable wheel/track robot is built to minimize soil damage and energy consumption using the advantages of both track and wheel running gear. The electrical system, robot user interface and control strategy to change the locomotion mode based on the soil conditions are presented in this research. In future plan, we will collect data of four features and use fuzzy logic or neural network to classify the four soil conditions for

Fig. 9. Switching from wheeled to tracked mode

Fig. 10. Switching from tracked to wheeled mode

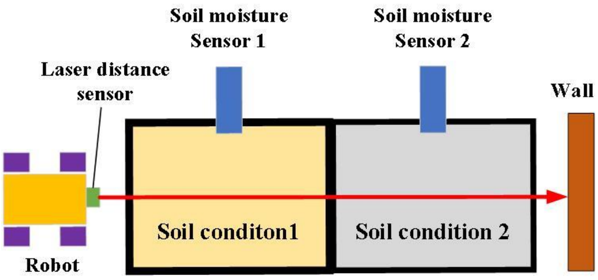

Fig. 11. Experiment setup

autonomous switching modes to minimize soil damage and energy consumption

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