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Tire sinkage measurement and entry angle calculation using stereo cameras

Hannah White [a,*], Corina Sandu [a], Jyotirmoy Mukherjee [a,b], Andrea L'Afflitto [b], David Gorsich [c], Michael Cole [c]

[a] Terramechanics, Multibody, and Vehicle Systems (TMVS) Laboratory, Department of Mechanical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, United States

[b] Advanced Control Systems Laboratory (ACSL), Grado Department of Industrial and Systems Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, United States

[c] U.S. Army DEVCOM Ground Vehicle Systems Center, Warren, MI 48397, United States

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ABSTRACT

In the modern world the use of autonomous vehicles is growing more and more common. There are many applications for autonomous vehicles on deformable terrain, such as in military, farming, and mining but the problem with most established autonomous vehicle models is that they do not take into account the effect the terrain has on vehicle performance. To be able to accurately include these values in the vehicle model, they need to be directly sensed or estimated. One of the most valuable of these values is the tire sinkage. Tire sinkage is very important when it comes to terrain-vehicle interaction. The slip-sinkage relationship is an important factor in tractive performance. This paper is part of a larger project that is working on autonomy in conditions with deformable terrain and this paper presents on the methods employed to measure and find important values for the terramechanics of the model. This study specifically focuses on measuring the rut depth left behind after a tire travels over the terrain using a set of two stereo cameras. The sinkage is then used to be able to find the entry angle of the tire in the terrain.

1. Introduction

The use of autonomous vehicles is increasing in both on-road and off-road scenarios. A majority of the research conducted on autonomous vehicles focuses on on-road terrain, where the focus on the vehicle's environment was on terrain topology and object avoidance rather than the condition of the terrain itself. The ability to transverse deformable terrain requires knowledge of the terrain, not just the location of the vehicle's surroundings. Without this knowledge, the vehicle will not move as expected or could even get stuck. Due to these needs, on-road models are not able to be directly adapted for off-road scenarios. There are many applications for off-road situations, such as in military, farming, and mining. To be able to use autonomy in off-road conditions the terrain parameters need to be taken into account. Therefore, these parameters would need to be obtained.

Tire sinkage is one of the most telling parameters in Terramechanics. It is used in many applications, such as the Bekker-Wong pressure sinkage relationship, which is shown in Eq. (1) (Wong, 2022).

$$p = \left(\frac{k_c}{b} + k_\phi\right) z^n. \tag{1}$$

Another way that can be used to find the sinkage is using the entry and exit angles, as were outlined in Chan and Sandu (2014). The first relationship described is the *vertical soil position* at any point on the tire's surface to be:

$$z = R(\cos\theta - \cos\theta_e), \tag{2}$$

They then more specifically define the *sinkage* of the tire as:

$$z_0 = R(1 - \cos\theta_e). \tag{3}$$

The *unloaded terrain depth* behind the tire was also defined as:

$$u = R(1 - \cos\theta_r). \tag{4}$$

In the case that the sinkage is known and the entry angle is the desired parameter, Eq. (3) can be rearranged to:

$$\theta_e = \cos^{-1}\left(1 - \frac{z}{R}\right). \tag{5}$$

* Corresponding author.
E-mail address: hnwhite@vt.edu (H. White).

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Nomenclature

b	Tire width [m]
c	Soil cohesion [kPa]
k_c	Pressure-sinkage parameter (cohesive modulus of terrain deformation) [kN/m^{n+1}]
k_φ	Pressure-sinkage parameter (frictional modulus of terrain deformation) [kN/m^{n+2}]
n	Sinkage exponent []
p	Pressure [kPa]
R	Tire radius [m]
R_e	Effective rolling radius [in]
s	Tire slip ratio [%]
u	Unloaded terrain height [m]
V	Linear velocity [m/s]
z	Vertical tire position [m]
z_f	Distance from camera to terrain in front of tire [m]
z_0	Tire sinkage [m]
z_r	Distance from camera to terrain behind the tire [m]
α_c	Slip angle at center of tire [rad]
γ_t	Angle between the direction of travel and the direction normal to the surface of the tire
Θ	Angle of soil particle [°]
Θ_a	Point of transition, when stress switches from sticking to sliding [°]
Θ_e	Tire entry angle [°]
Θ_r	Tire exit angle [°]
λ	Distance from tire entry point to front of tire [m]
μ_x	Friction Coefficient
μ_y	Friction Coefficient
σ_n	Radial stress [kPa]
σ_p	Lateral bulldozing pressure [kPa]
τ_x	Longitudinal shear stress [kPa]
τ_{ycp}	Lateral shear stress [kPa]
ω	Angular tire velocity [deg/s]
ω_0	Angular tire velocity at zero slip [deg/s]

In this paper the soil is assumed to be relatively inelastic to save computational time so the data can be gathered in real-time. Thus, the depth to the rut left behind by the tire is equal to the tire sinkage and the exit angle is zero.

For autonomous vehicles models it is important know the value of the forces acting on the tire. In Chan and Sandu (2014) the importance of entry and exit angles can be seen in the longitudinal and lateral tire force equations:

$$F_x = R_u b\left(\left(\int_{\theta_a}^{\theta_e}\tau_x(\theta)\cos\theta d\theta + \frac{\mu_x^2 s}{\sqrt{\left(\mu_y\tan\alpha_c\right)^2+(\mu_x s)^2}}\int_{-\theta_r}^{\theta_a}\tau_{max}(\theta)\cos\theta d\theta\right)\right) - \int_{-\theta_r}^{\theta_e} R_u\sigma_n(\theta)\sin\theta d\theta \tag{6}$$

$$F_y = \left(-R_u b\left(\left(\int_{\theta_a}^{\theta_e}\tau_{ycp}(\theta)d\theta + \frac{\mu_y^2\tan\alpha_c}{\sqrt{\left(\mu_y\tan\alpha_c\right)^2+\left(\mu_y s\right)^2}}\int_{-\theta_r}^{\theta_a}\tau_{max}(\theta)d\theta\right)\right) - \left(\int_0^{2\sin\theta_e}\sigma_p d\lambda\right)\tan\alpha_c\right)\cos\gamma_t + F_z\sin\gamma_t \tag{7}$$

One of the biggest issues when trying to adapt autonomy to off-road vehicles is adding sensors that are easy to access and adjust that also do not affect the integrity of the vehicle or tires. Stereo cameras are relatively inexpensive, easily attainable, and are small enough that they will not affect the vehicle and its performance. Stereo cameras are cameras that consist of two different lenses that are a known distance apart. The disparity between the images captured by both lenses can be used to find the distance from the camera to any object in the image. This provides a depth value for each pixel in the images.

This paper uses a set of stereo cameras to measure the rut depth in real-time. The relationship in Eq.5 is then used to further find the entry angle using the depth measured by the two stereo cameras.

1.1. Literature review

The typical use of stereo cameras in on-road autonomy is sensing the environment around the vehicle for use in navigation. This has been implemented in a many works such as in Cao et al. (2015) where stereo cameras are used to build a disparity mapping, object detection, and path planning, and Zaarane et al. (2020) where stereo cameras were used to measure the distance to other vehicles.

In off-road autonomy tire sinkage needs to be sensed as it is one of the most important parameters of vehicle-terrain interaction, but there has not been little work in directly sensing it in real-time. In 2019 Botha et al. (2019) did work on measuring the 3D rut profiles with stereo cameras in real-time. They created the 3D profiles using digital image correlation, which is when the disparity is used to get the distance.

Photogrammetry has been used previously to measure the rut depth, but it is impractical for real-time applications. The 3D profile is found by capturing images of the same area from different vantages. The overlap between the images is used to determine the profile. In 2017 Kenarsari et al. (2017) measured the profiles of a static tire print and the rut left behind by a tire. Pierzchała et al. (2016) used photogrammetry at a logging site, measuring the rut left by tracked vehicles.

Salmivaara et al. (2018) used lidar to measure the rut depth left behind by trucks. The sensor was mounted to the rear of the vehicle to gather data. This was not in real-time, as the ruts were found by post-processing the data.

Guthrie et al. (2017b) implemented a system of stereo cameras on the Terramechanics Rig at Virginia Tech to get the measurement of the tire sinkage, using cameras inside the wheel, pointed at the terrain in front of the tire as well as behind the tire, and one pointed at the side that collected data on the tire's deflection and slip.

Optical sensors were implemented by Naranjo et al. (2014). The sensors were attached to the rim inside the tire which measured the deflection of the tire, the vertical displacement of the wheel was measured by a string potentiometer, and the distance to the undisturbed soil in front of the tire was measured with an ultrasonic sensor. These measurements were combined in order to find the tire sinkage. This would be impractical to implement in real-time, or on a real vehicle since the sensors would need to be mounted inside the tire which would make it hard to mount the tire to the rim and access the sensors for maintenance.

One of the most common methods for measuring the rut depth is simply using a ruler. An example of this method is used in He et al. (2019). This study set out a grid of points where the depth was measured in different points of the rut. This method is very inexpensive compared to other methods, but unfortunately cannot be used in real time.

Stereo cameras specifically have also previously been used in terramechanics for other applications. Cameras mounted inside of the tire have also been used to find many tire-terrain interaction parameters. Botha and Els (2015b) used digital image correlation and a pair of cameras combined into a stereo camera to collect 3D terrain profiles. Botha and Els (2015a) used a stereo camera setup that was mounted to the rear of a vehicle and digital image correlation to measure the vehicle side-slip angle. Johnson et al. (2019) adapted this method so it was able to be done in real-time. Guthrie et al. (2017a) used stereo cameras mounted inside of a tire to get the 3D profile of the contact patch. Feldesi et al. (2020) and Pegram et al. (2021) found the strain on the inside of a tire by using stereo cameras mounted inside the tire.

Other types of cameras have also been used in terramechanics to get information about the soil properties themselves. Ajadadi *et al.* (2016) determined the quality of tillage in soil by using a camera and an artificial neural network. Shivanna et al. (2017) used a RGB camera to collect data such as color, and texture from images of terrain to be able to classify between two different soil types. Wellhausen et al. (2019) used a camera and supervised semantic segmentation to classify between several types of terrain: asphalt, grass, dirt, sand, and soil. Ewing et al. (2020) used a hyperspectral camera to determine soil gradation.

The scope of this paper is to use stereo cameras to measure the rut depth of a tire in real-time for eventual use in an off-road autonomous vehicle. To meet the needs of the autonomous model, the entry angle of the tire is calculated using the rut depth.

2. Experiment

2.1. Theory

Two stereo cameras are used in this experiment. One is placed in front of the tire to measure the distance to the undeformed terrain, and one is placed behind the tire to measure the distance to the rut. The assumption is made that the soil is relatively inelastic, so the rut depth is equal to the tire sinkage.

The rut left behind in the dry sand was triangular in shape due to the shape of the tire and the non-cohesive nature of the sand. Due to this, data from about the middle eighth of the rut was used to find the depth of the rut. This was done the sinkage used be from the area of maximum depth. The data provided from this area was averaged to get the final depth at each time step.

2.2. Terramechanics Test rig

The Terramechanics rig at the Terramechanics, Multibody, and Vehicle Systems Laboratory (TMVS) at Virginia Tech was used to collect the data experimentally. This rig can be set to several camber, toe, slip, and normal load values (Sandu, et al., 2008). The soil used in the experiment was fine, dry sand. An AT 171 by Balkrishna Industries was mounted on the Terramechanics rig for testing. This tire had a pressure of 140 kPa for the entire length of testing. Before each test, the soil was prepared. The first step of preparation used a shovel to eliminate any compaction and stresses in the sand. The sand was then leveled using a leveling blade that is attached to the carriage of the terramechanics rig. This experiment varied the slip ratio of the tests, running two tests at each desired slip value. Tests were measured at two different normal loads, 2000 Newtons and 4000 Newtons. The slip values used for 2000 Newtons normal load were 0 %, 5 %, 30 %, 40 %, 50 %, 60 %, −5%, −15 %, −25 %, −40 %, and −60 %. The slip values used during the 4000 Newton normal load were: −10 %, −15 %, −25 %, −40 %, 35 %, 40 %, and 60 %.

The tests were validated using 3D profiles of the ruts left behind using an Einstar Shining 3D scanner that were analyzed by Sonalkar et al. (2023). The scanner collected point cloud information, which was then saved as a.stl file. These scans only included the data from once the tire reaches the steady-state conditions. The value that was used to validate the cameras was the maximum sinkage value from the entire run. This value was found using CAD software by placing a reference frame at the same height as the undeformed terrain and measuring the distance from the reference plane to the rut.

Before testing, an experiment was conducted to find the effective rolling radius (R_e). The force in the longitudinal direction was measured at several angular velocities, while the linear velocity was held constant. It was then assumed that the zero slip occurred at the angular velocity that had the smallest longitudinal force. This smallest measured longitudinal force was 0.45 Newtons. This angular velocity was then used to find the effective rolling radius using this equation 8:

$$R_e = \frac{V}{\omega_0}. \tag{8}$$

The effective rolling radius was found to be 0.3556 m for the 2000 Newton normal load and 0.3645 for the 4000 Newton load. The angular velocities that corresponded with the desired slip values for the experiment were then found by using the equation for calculating slip (Fig. 1):

$$s = \frac{R_e\omega - V}{V} * 100. \tag{9}$$

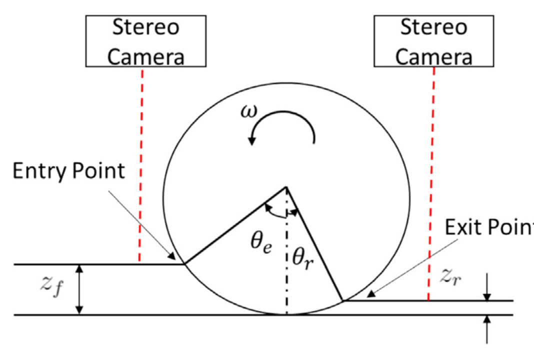

Fig. 1. Schematic of camera placement.

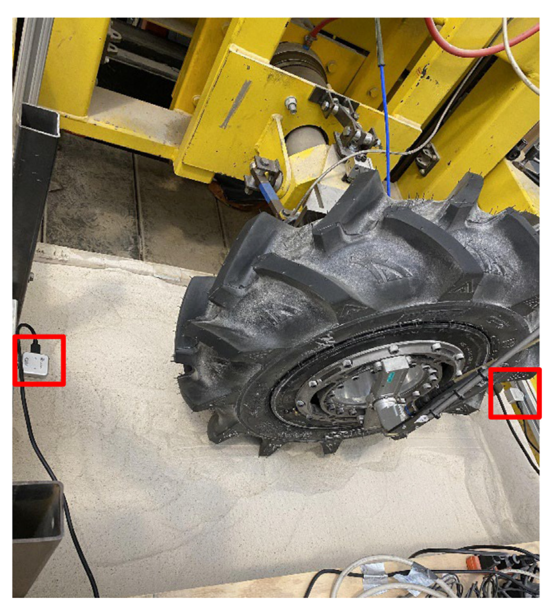

Fig. 2. Location of the stereo cameras on the Terramechanics Rig.

2.3. Cameras

The two cameras used in this experiment to measure the rut depth were Intel® RealSense™ D405 stereo cameras (Intel® RealSenseTM Depth Camera D405, 2023). The cameras were mounted onto the carriage of the Terramechanics rig. One was placed in front of the tire to capture the distance to the undeformed terrain, and one was mounted behind the tire to measure the distance to the rut. The cameras were placed at the same lateral position and were each leveled. This setup of the cameras on the Terramechanics rig can be seen in Fig. 2.

The data collection code was implemented in C++. The images were collected at 30 frames per second. Each frame had a depth value at each pixel. Fig. 3 shows a frame with the colored depth values on the left and the RGB image of the tire track captured at the same moment.

3. Results

The experimental data was implemented in MATLAB for post-processing and plotting.

3.1. Sinkage

The sinkage for the 2000 Newton load can be seen in Figs. 4 and 5 and for the 4000 Newton can be seen in Fig. 6. The values of the stereo camera match the values of the 3D scanner. While the scanner is a little higher in most places, it makes sense due to the fact that while the scanner is looking at the maximum value, the stereo cameras take the average of the middle of the rut, which would obviously be less than the maximum value. It can be observed in the 2000 Newton load section that in most of the slips the pattern of the lugs can be seen in the pattern of the sinkage values. This is

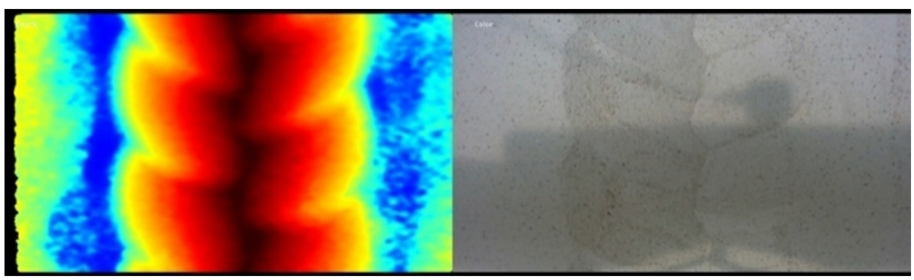

Fig. 3. Images of a tire track, both in colored depth values (Left) and normal RGB (Right).

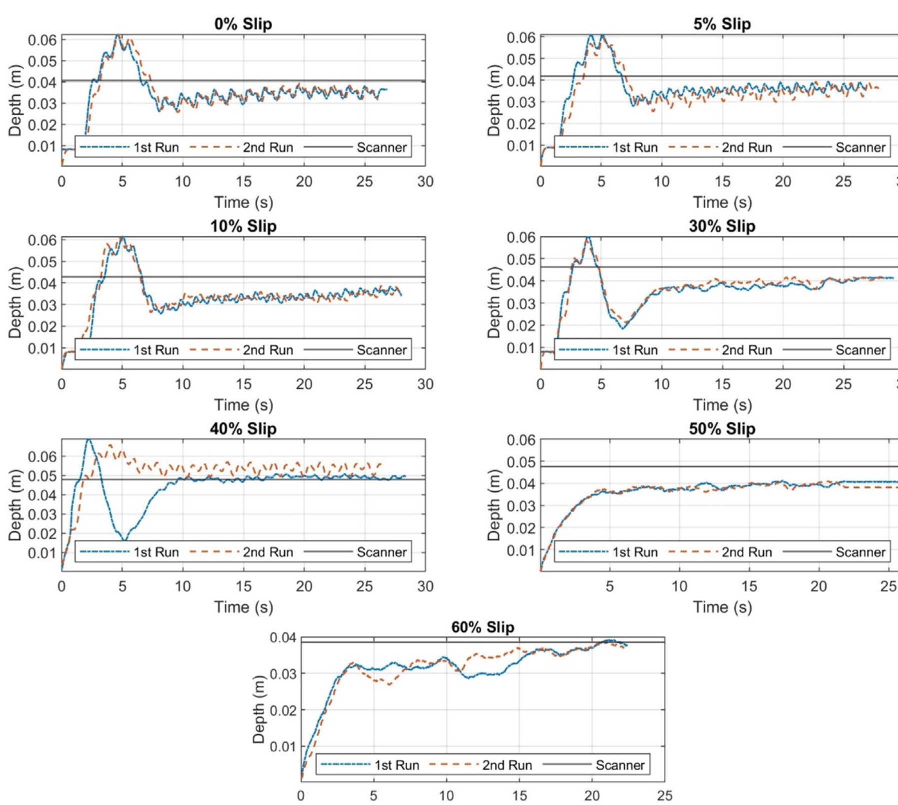

Fig. 4. Tire sinkage at positive slips for 2000 N normal load.

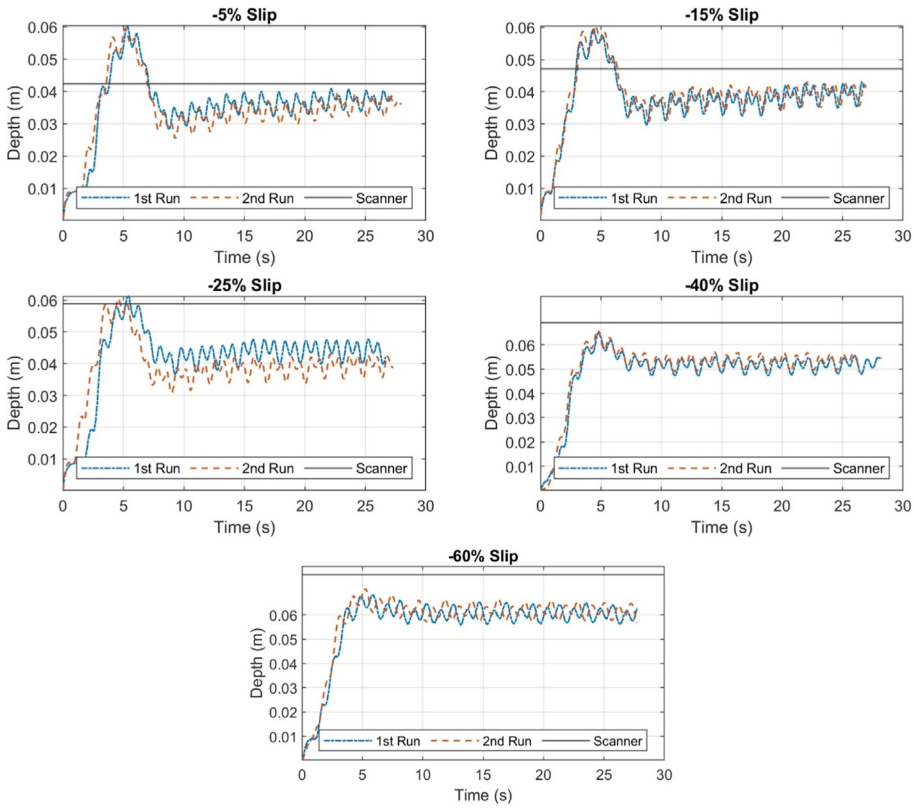

Fig. 5. Tire sinkage at negative slips for 2000 N normal load.

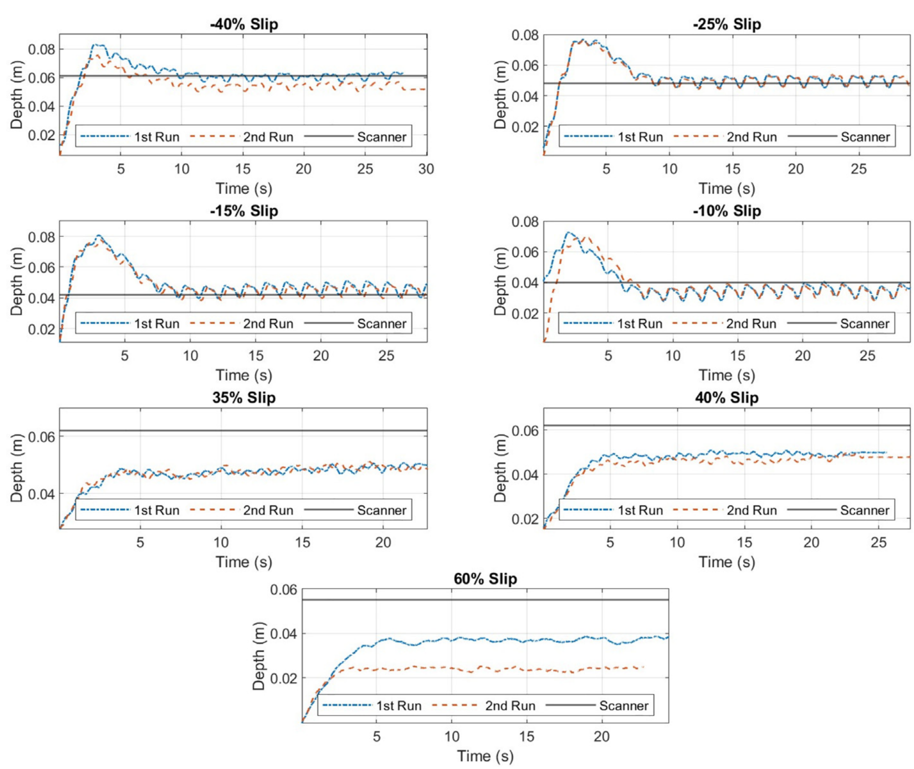

Fig. 6. Tire sinkage at 4000 N normal load.

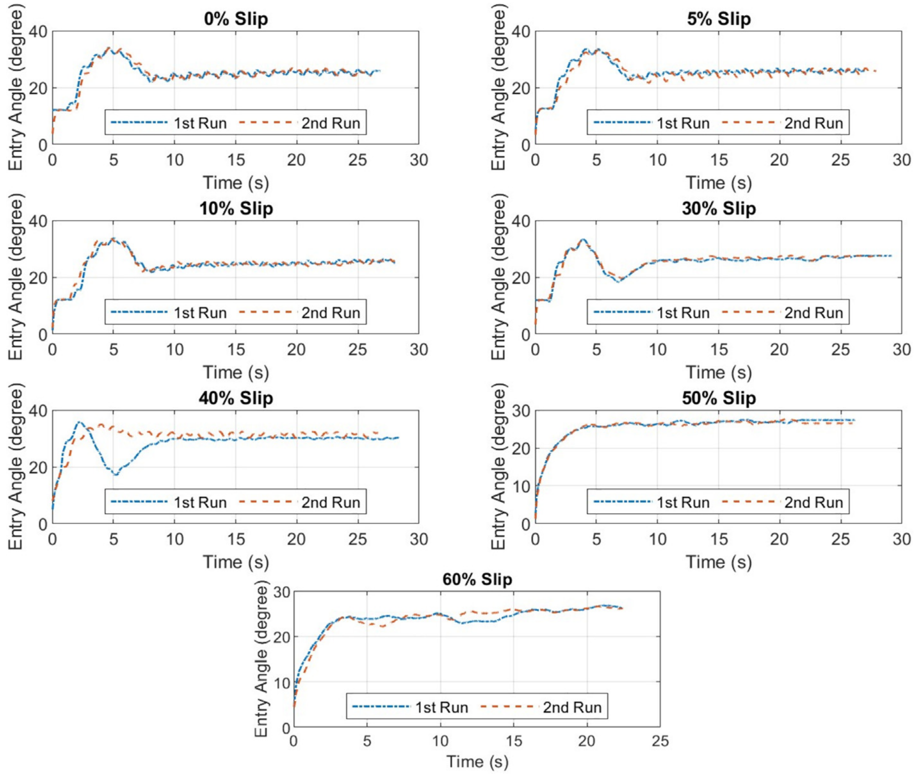

Fig. 7. The calculated entry angles at runs with positive slip for 2000 N normal load.

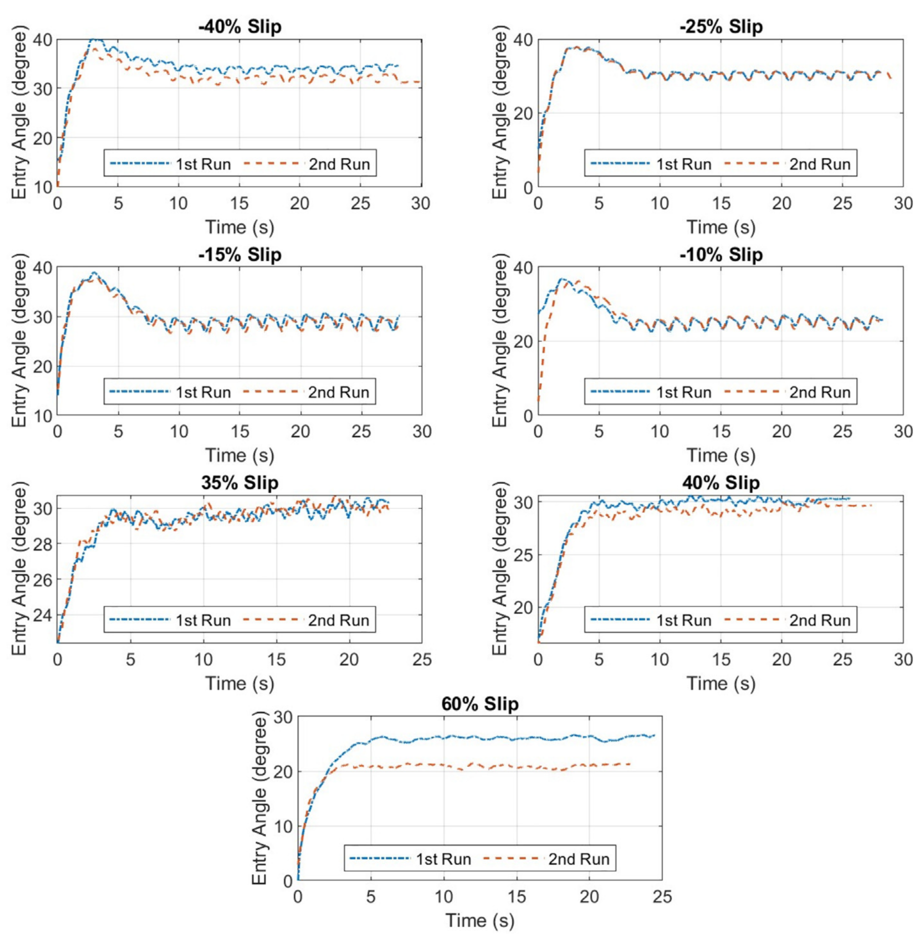

Fig. 8. The calculated entry angles for 4000 N normal load..

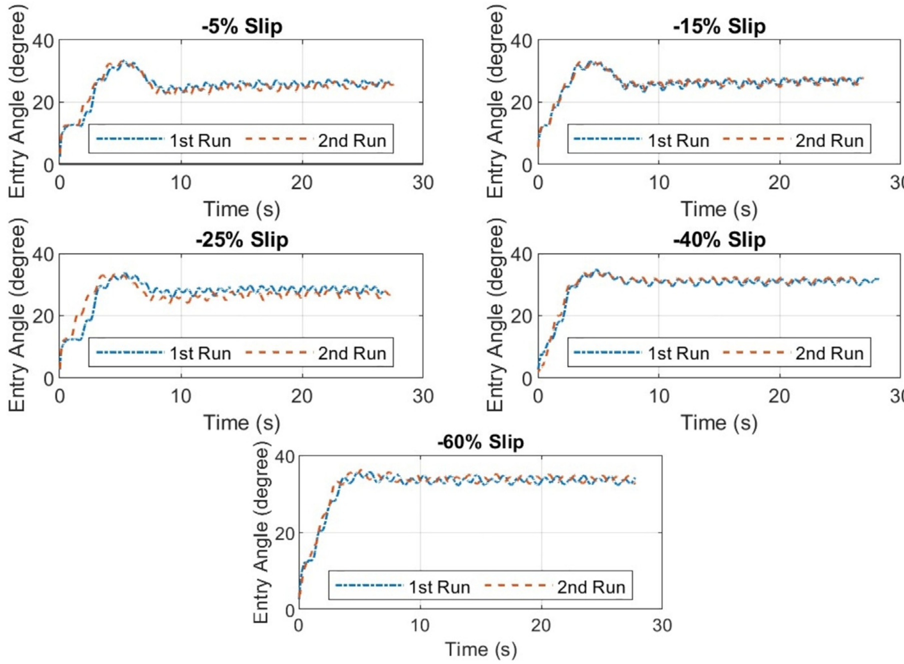

Fig. 9. The calculated entry angles at runs with negative slip for 2000 N normal load.

not true in the higher slip values. This would be due to the fact that the tire slips so much that instead of creating a distinct tire footprint in the sand, it spins. It can also be observed that by the time the slip gets up to 60 %, the sinkage gets more unpredictable. In the case of the 2000 Newton load, this is represented by sinkage that does not really reach the steady state portion of the run, they instead keep rising. In the 4000 Newton load, it is shown by the fact that do not match very well.

3.2. Entry angle

The entry angles were found using the relationship in equation 5. The entry angles for the 2000 Newton load can be observed in Figs. 7 and 8. The entry angles for the 4000 Newton load can be seen in Fig. 9. All the entry angles fall between 20° and 40°. It can be observed that the angles vary with the lug pattern present in the rut, the same as the depth does.

4. Conclusions and future work

This paper presented a novel method to measure the sinkage of a tire in real-time using a set of two Intel RealSense D405 stereo cameras and using the measured depth to calculate the entry angle of the tire. These sensors are relatively affordable and easy to implement on vehicles without interfering with performance. This was tested experimentally using an agricultural tire mounted on the Terramechanics Rig at TMVS laboratory at Virginia Tech. The depth results were compared against the maximum sinkage of the steady state portion of the run, which validated the camera data. The camera sinkage was proven to be easily repeatable and accurate.

One step to improve the model would be to implement another sensor to be able to measure the tire sinkage in the soil. This would allow the ability to find the tire's exit angle for soil that is very elastic. It also creates the ability to be able to calculate the effective rolling radius in real-time. The accuracy can also be further tested by implementing the sensors on a full vehicle. The ultimate final step for this project is to use the entry angle to be able to calculate the forces on the tire, that will in turn be implemented in a full autonomy stack.

CRediT authorship contribution statement

Hannah White: Writing – review & editing, Writing – original draft, Validation, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Corina Sandu:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Jyotirmoy Mukherjee:** Writing – review & editing, Resources, Conceptualization. **Andrea L'Afflitto:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **David Gorsich:** Resources, Project administration. **Michael Cole:** Resources, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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