Tyre tread estimation from 3D contact patch measurements on the inside of a deformed tyre

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Highlights

- A novel measurement method to aid development of soft soil tyre -terrain interaction models
- Method to determine outside tyre geometry based on inside geometry
- Large lug tyre geometry
- Tyre tread pattern superposition

Tread contact area estimation based on tyre inside geometry

Abstract

This study investigates the feasibility of using measurements of the geometry on the inner surface of a tyre to predict the geometry of the tread on the outside. The proposed method offsets the deformed inner surface along its normal directions by the tread thickness.

Initially, a simple 2D cross-section model proved the feasibility of this method. This led to the development of a full 3D tyre model that can estimate the tread of a deformed tyre. Photogrammetry was used to capture a complete 3D geometry model of an unloaded and uninflated tyre, from which the inner and outer surfaces are used to calculate a displacement map for the model. Results indicate that the model can estimate the tread of both a SUV tyre and a large lug agricultural tyre to within about 2.5mm of measurements of the deformed tread. This tyre is approximately 750mm in diameter. The remaining error is likely due to the accuracy of the inner and outer surface measurements. The findings pave the way to predict soil volume displacement and contact area, providing crucial insights for vehicle control and mitigating environmental impacts in offroad scenarios. The system is expected to provide extremely useful data for future tyre-terrain interaction research.

1. Introduction

1.1 Background

The area where all non-aerodynamic forces are applied to a vehicle is the contact patch between the tyres and the terrain. However, since the tyre interfaces with the terrain, it is not possible to measure the contact patch directly. When dealing with deformable terrain, the contact patch region becomes very important, but more complex to model since the terrain deforms under the tyre. This presents a challenge in assessing soil characteristics and tyre-terrain interactions.

In many tyre-terrain interactions studies, the tyre is assumed to be rigid and cylindrical, often due to lack of the ability to either measure or calculate the true 3-dimensional contact between the tyre surface and the terrain. For tyres operating at low pressures in soft terrain, the cylinder assumption can result in large errors.

Various studies have suggested solutions to the measurement of the displacement of the tyre contact patch such as ultrasonic sensors (Longoria et al., 2019) or digital image correlation with cameras (Guthrie et al., 2017a). The use of non-contact 3D measurement in the field of Terramechanics has become popular in recent years (Farhadi et al., 2018, Farhadi et al., 2019, Phakdee and Suvanjumrat, 2023, Kenarsari et al., 2017, Medeiros Jr et al., 2023). Most studies focus on static measurements with either a handheld laser scanner or a camera and photogrammetry. Botha et al. (2019) used stereo cameras to measure the rut profile in real time. However, so far only Guthrie et al. (2017b) attempted to estimate elastic deformation of the soil for the entire contact patch region.

One way to get around this problem is to measure the deformation on the inside of the tyre and then model what happens on the outside. This, combined with geometry for undeformed terrain in front of the tyre and deformed terrain behind the tyre (rut), could then be used to determine elastic and plastic deformation of the soil under a moving vehicle. This, in turn, is expected to give insight into soil parameters. Soil parameters are useful for vehicle control and evaluating the environmental impact of vehicles.

1.2 T2Cam

The Vehicle Dynamics Group (VDG) at the University of Pretoria has developed a measurement system that can capture the deformation of the inside of a rolling tyre in the region of the contact patch. The Tyre-Terrain Camera System (called T2Cam) uses two mechanically stabilized cameras inside of a tyre that are pointed at the contact patch (shown in Figure 1). With Digital Image Correlation (DIC) techniques, point clouds representing the deformation of the inner surface of the tyre can be calculated. Guthrie et al. (2017a) developed the initial system and illustrated the feasibility of using digital image correlation (DIC) techniques for measuring tyre deformation.

Guthrie et al. (2017b) attempted offsetting the inner surface by an even amount to obtain an estimate of the outer surface of the tyre. However, the varying tread thickness with the tread blocks was not accounted for, thus the elastic deformation of the soil resulted in artificially high values.

This paper investigates a novel method for estimating the deformed outer surface of a tyre, based on the inside geometry, accounting for the varying tread thickness.

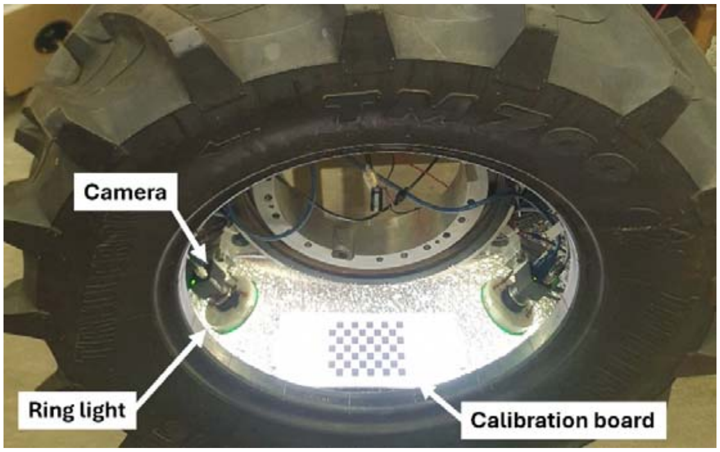

Figure 1. The stereo-camera system T2Cam inside of a tyre

1.3 Proposed method

This paper proposes tracking the location of the inner surface and offsetting the inner surface along its normal directions by the correct tread thickness to obtain an estimate of the outer surface of the tyre.

The method assumes that the rubber and carcass of the tyre is incompressible and as such the volume should remain constant. Considering the fact that the Poisson's ratio of tyre rubber is close to 0.5, this is a reasonable assumption. This assumption is also expected to result in the largest errors on rigid obstacles and high tyre inflation pressures as the contact pressure distribution is highly localised, as used in this study. As the tyre pressure is decreased, or the terrain deformation increases, a larger area of the tyre comes into contact with the soil, therefore reducing the contact pressure and therefore reducing the magnitude of the forces trying to compress the tyre rubber. The implementation of the proposed method goes one step further and assumes that the total area of the inner surface remains constant. This is not strictly true since the neutral bending plane of the tyre is closer to the centre of the tread which may result in a small change in size of the inner surface area. However, it is expected that the error introduced by this assumption is small compared to the possible available measurement accuracy. It is further assumed that the tyre condition remains constant (i.e., no wear).

The advantage with the proposed method is that simple displacement maps can be used to offset the inner surface. Compared to using Finite Element Methods (FEM) to calculate the outer surface this is computationally inexpensive and could pave the way for real-time deformation measurements.

The proposed solution consists of the following steps. First a displacement map of the tread thickness needs to be baked. In the context of 3D computer graphics, the term "baking" refers to the process of calculating a displacement or texture map, whilst "rendering" typically uses these texture or displacement maps, projects them onto simplified geometry and then calculates an image of the scene.

For the baking process, a 3D reference model of the tyre is needed. The inner surface is mapped into UV coordinates, reducing the three dimensions to a 2-dimensional map. The UV-coordinate system is defined so that the U-direction is longitudinally along the circumference of the tyre and the V-direction laterally from bead-to-bead. This described in more detail in paragraph 3.2.1. and Figure 8. Also, the normal direction on the inner surface is calculated. The distance along this normal from the inner surface to the outer surface is determined and baked into a displacement map with the UV-coordinate system. Specific markers are mapped into UV-coordinates to track the tyre position. To predict the outside deformation of a deformed tyre, the deformation on the inner surface needs to be measured. The markers are detected and then the UV-coordinate system fit through the point cloud. Now each point in the point cloud can be offset along its normal direction by its corresponding value in the displacement map. This provides a point cloud of an estimate of the outside surface geometry of the tyre.

2. Proof of Concept (2D)

A 2D proof of concept was developed to explore the feasibility of the proposed method and to explore the impact of the assumptions on the prediction accuracy. This simplifies the measurement side of the problem significantly and allows a better understanding of any challenges with the approach.

A flatbed scanner was used to record the cross section of a Michelin LTX AT2 tyre. The edge of the tyre was painted white for better contrast. The points were then manually sampled on the images. Figure 2 shows an example of the scan with sampled points for both an undeformed and a deformed state. A reference dot was placed at the centre of the contact patch to function as a reference point from which the surface can be resampled later.

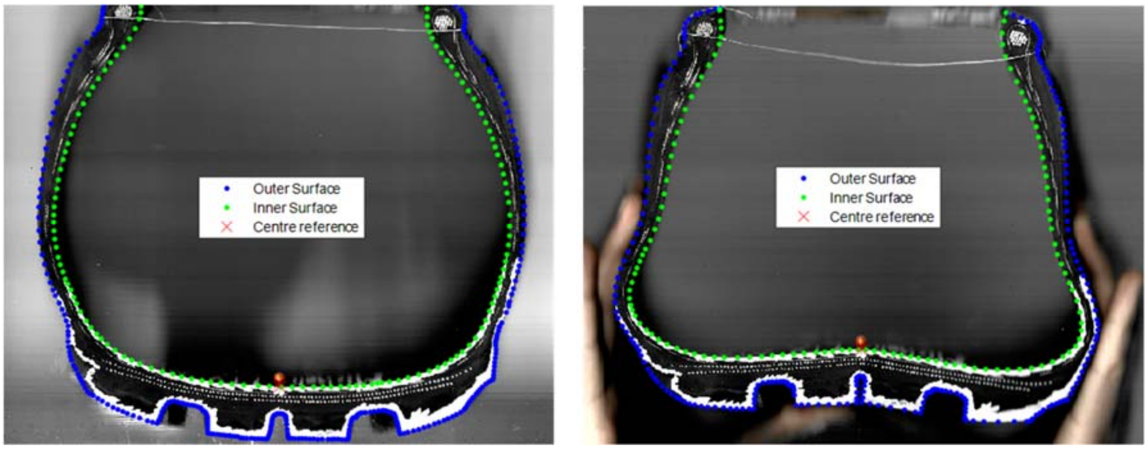

Figure 2. Flatbed scanner tyre cross-sections

2.1 Baking displacement maps

A parametric cubic spline was fitted through the sampled inner surface. The surface was then resampled to a predefined even arc-length spacing. The points were resampled from the reference centre point on the contact patch. The node spacing can also be modified so that the regions of interest (i.e., the tread) have denser spaced nodes than the side walls. It was assumed that the area of the inner surface would remain constant. In the various tests the length of the inner surface of the deformed states remained within 0.1% of the reference state, confirming that the assumption is acceptable.

The vector between two consecutive points gives the tangential vector. Consecutive tangential vectors are averaged to provide the nodal vector. The cross product of this vector with a unit vector in the z direction gives the normal vector.

The unit normal vector can then be used to calculate the tread thickness. The intersection of each normal with the points of the outer surface is calculated by translating the outer surface points so that the current node is at the origin and then rotated so that the current normal is aligned with the x-axis. The x-intercept of the line between the two points that are nearest above and below the x-axis is the tread thickness. Figure 3 illustrates this process and shows the resulting tread displacement map.

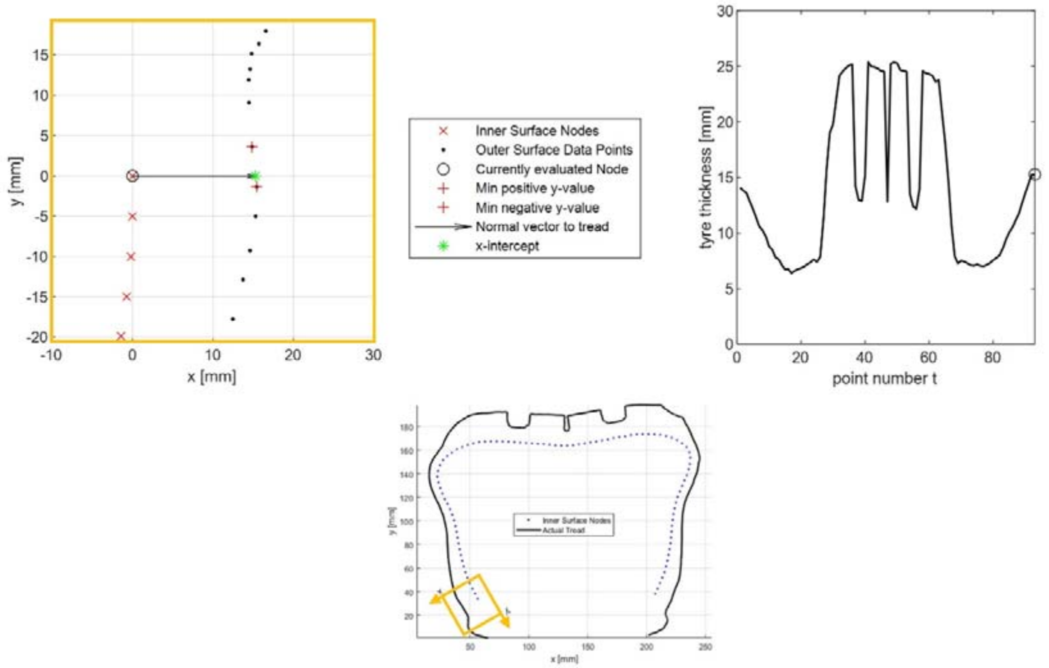

Figure 3. Left - Tread thickness calculation, Right - Tread displacement map, Bottom – Overview of cross-section

2.2 Applying displacement maps

The inner surface of the deformed tyre is sampled with the same spacing as the reference, and the resulting normal directions for the nodes are calculated. The displacement map, obtained from the undeformed tyre, provides the information on how far each node needs to be displaced along its normal to represent the outer surface of the tyre.

Figure 4 shows the predicted tread against one of the measured treads. The prediction looks excellent with some small errors. The maximum error is about 2mm, and the mean error between 0.25mm and 0.40mm. This is excellent for such a simple approach. Smaller step sizes decrease the error. However, the improvement in error decreases with the decreasing step size. Thus, there is a compromise between accuracy and computational cost due to number of node evaluations. The choice of step size should be related to the specific application. Els and Scholtz (2017) investigated the effect of road profile resolution on ride simulations using an FTire model and concluded that there is little improving using road profile resolutions of smaller than 15x15 mm. In this case a smaller step size may not contribute to improved results. If sharp definition of the grooves in the tread is important, then a small step size will improve accuracy on the sharp transitions and vertical portions of the tread. For many terramechanics applications, where pressure distributions are integrated over the contact area, a large step size may be good enough to accurately represent the contact area.

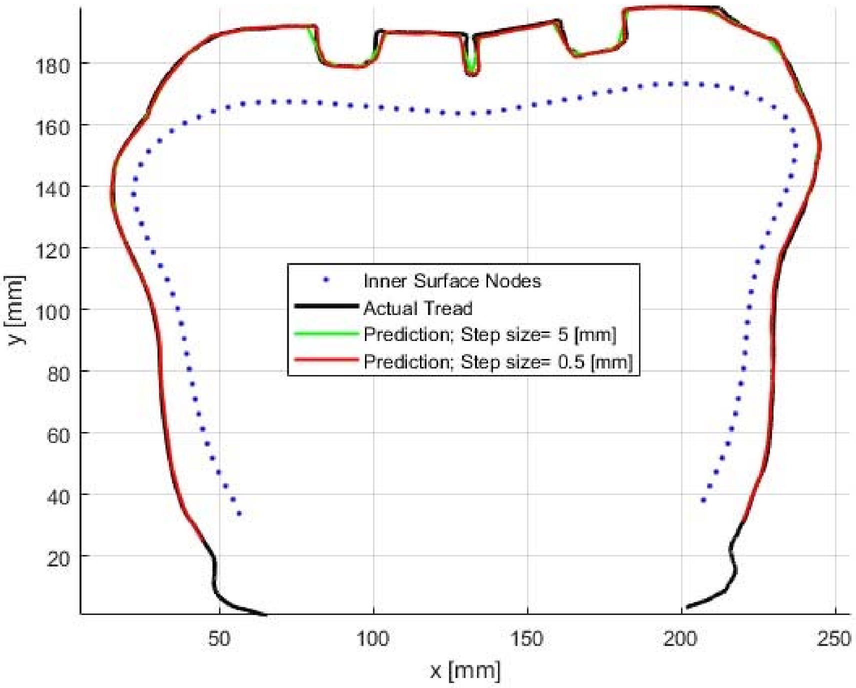

Figure 4. Tread prediction and measured tread for two different node spacings

The manual sampling of the surfaces was only accurate to within 0.7mm. However, to calculate the error, a total of four different surfaces need to be measured (the inside and outside of the reference and the deformed states). Thus, in the worst case, the measurement-induced error could be up to 2.8mm large. The maximum error in the present 2D example is about 2mm; thus, any error introduced by the model's assumptions cannot be isolated with the available measurement accuracy.

Overall, the model performed excellent and was able to estimate the outer surface geometry of a deformed tyre within the measurement accuracy. It proved that a simple offset in the normal direction should be sufficient to accurately predict the tread geometry.

3. Proof of Concept (3D)

3.1 Reference tyre geometry

For the proposed method to work in three dimensions, a full tyre geometry is needed. The challenge here is that both the inside and the outside of the tyre need to be captured in relation to each other, as this is what defines the displacement map.

Different approaches can be used to determine this reference geometry, including CAD, laser scanning and photogrammetry. It is important to determine the reference geometry for the specific tyre that is used in the study, and not use a generic CAD model as production tolerances result in radial runout, conicity and other effects that are well-known on large tyres since many of these are hand-made to a large extent.

Two different brands of hand-held 3D laser scanners were initially used for the tyre scanning, however this resulted in numerous issues. Only a small region can be scanned at a time, resulting in drifting geometry. Both these scanners did not have an external tracking system, which would solve many of the issues. However, these type scanners with external tracking are very expensive. The typical IMU driven 3D scanners are very good for smaller objects, but performed poor for scanning the entire tyre, inside and outside. Using these scanners only for a section of the outside, can perform very well.

In recent years, the photogrammetry approach to scan objects as an alternative to laser scanning has gained popularity. Photogrammetry can easily result in acceptable accuracy with an affordable setup. We opted to use photogrammetry. Photogrammetry just requires any type of camera and is therefore cost effective. Even with a cell phone camera, very decent results can be obtained.

We opted to use photogrammetry to digitally capture the full tyre geometry. The object is photographed from different sides with a normal DSLR camera. The photos are taken in sequence moving around the object with 60-80% forward and sideways overlap. Some typical algorithms for 3D image reconstruction using structure-from-motion are described in Toldo et al. (2015). Features are detected in each image, matching features between images found, the 3D position of the camera for each image estimated and then the features are aligned in 3D space to give the structure.

The key challenge to getting good models is the quality of the image. Clear high-resolution images are desirable that show all the detail. Unsharp images and inconsistent lighting cause issues in the model quality. This is because the features in overlapping areas of the images will be different. Overlapping regions need to look as consistent as possible between images.

Scanning a full tyre poses several difficulties. An uninflated tyre without a rim is used, since the entire inside and outside of the tyre needs to be visually accessible for the scan at once. Normally objects can be scanned in sections and then merged afterwards. However, due to flexible nature of the tyre, repositioning the tyre between scans to observe different sections will deform the tyre differently. Thus, different sections will not necessarily line up correctly for merging.

It is ideal to scan the entire tyre all at once. For this, lighting becomes a challenge on the underside and the inside of the tyre. These regions are too dark for the camera to capture enough detail when the outside is exposed correctly. Shining external lights at the tyre can be difficult without proper studio lighting equipment. Using a normal camera flash is also inconvenient as each image will have the bright spot of the flash on some other part of the tyre, thus resulting in different features between images.

It was found that the best way to capture the entire tyre at once was to use a digital single-lens reflex (DSLR) camera with a wide-angle lens and a ring flashlight, with both lens and flashlight having a polarizing filter. Shining only polarized light at the object and then filtering this again with a polarizing filter on the camera lens removes virtually all the bright reflections and gives a neutrally lit picture (See Figure 5). Thus, pictures of different parts of the tyre all result in similarly lit images where the detected features stay constant. The evenly lit image of the aligned filters is desirable since this helps immensely with the digital reconstruction of the object from the images in photogrammetry software.

Figure 5. Effect of polarizing filters on reflections (Left - misaligned filters; Right - aligned filters) illustrating the evenly lit image resulting from the aligned polarizing filters.

The images were processed with the commercial software RealityCapture (Epic Games, 2024). Since April 2024, this software has become free to use. Compared to other available free software, such as Meshroom (Griwodz et al., 2021), RealityCapture 1.4 uses proprietary algorithms that makes it capable to process the same images much faster and tends to result in a more accurate mesh. Figure 6 shows an example of the photogrammetry scan of a tyre, where the inside and outside have already been separated for further processing.

Figure 6. Photogrammetry scan of tyre (Left – Outside, Bottom – Right)

The photogrammetry approach proved to be successful in scanning the full tyre. The approach was able to capture the inside and outside of a tyre in one take. It only had minor issues with poor quality images, but other than that it performed well. The accuracy proved to be within measurement accuracy of the validation. This proves that this can be used as an affordable way of obtaining full 3D models of tyres.

3.2 Model and method

A 3-dimensional geometrical model was developed that can predict the tread deformation of a tyre over the full contact patch region. This model uses the same approach as the 2D model discussed in Section 2 but expands on this by rotating the cross sections along the length of the measured contact patch. The tyre's digital model obtained with photogrammetry is used to bake the displacement map. T2Cam is then used to measure the geometry of the inside the deformed tyre. With the use of the displacement map, the measured inner surface is virtually displaced to provide the estimate of the deformed tread of the tyre.

3.2.1 Baking displacement map

The full reference tyre model is needed to bake the displacement map. Mapping tyre geometry is a challenge because the patterns on both the inside and outside of the tyre are highly repetitive. Finding the absolute position of an image in the tyre is slow and cumbersome. For this reason, a row of 36h11 April tags (Olson, 2011) (shown in Figure 7) is positioned at the centre line of the tyre as shown in Figure 6. The location of each of these tags is marked in the model. The tags are later used to track the position of the tyre when captured with T2Cam and map the correct part of the tread onto the surface. The UV-coordinate system is defined so that the U-direction is longitudinally along the circumference of the tyre and the V-direction laterally from bead-to-bead (see Figure 8).

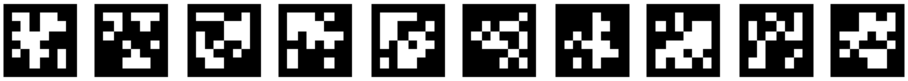

Figure 7. The first 10 April tags of 36h11

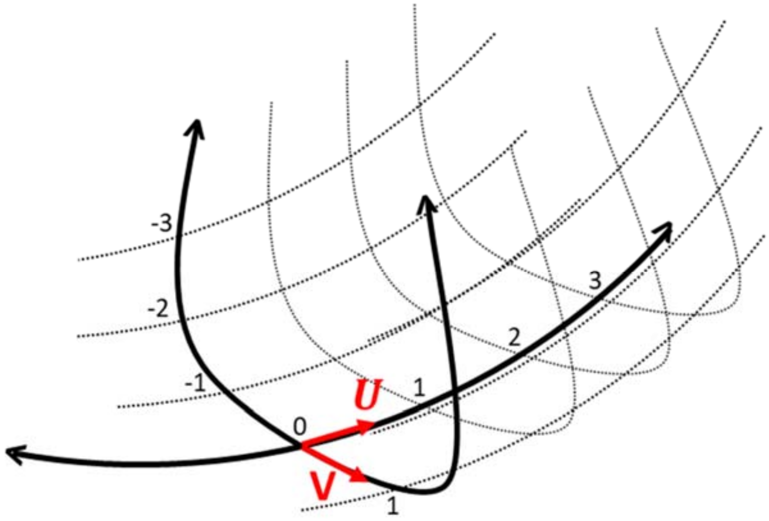

Figure 8. The UV-coordinate system on the inner tyre surface used for the displacement map

The reference tyre is divided into evenly spaced cross-sections along U. First a curve is fit through the tags to create the U-axis. The curve is resampled to have a constant spacing between the sections. For each U coordinate, a slice of the tyre point cloud is isolated, as shown in Figure 9. The points of each section are sorted with a nearest neighbour sorting algorithm from one side to the other. This is needed since the point cloud is not ordered, and to fit a line through the points, some parameter is needed for the order. After ordering the points, the data is smoothed, and a parametric cubic spline is fit through. The zero V coordinate is used as the reference point and passed along with the fit of the surface to a modified version of the 2D model. The model then determines the tread displacement for each cross-section. Doing this for the entire tyre results in a tread displacement map as shown in Figure 10. This map stores the distance from the inner surface to the outer surface of the tyre for each UV-coordinate. The map can then be used to displace any deformed inner surface of this tyre given the location of the tags. Careful inspection of Figure 10 shows some artifacts in the tread displacement map, caused by the method of sampling sections of the point cloud and the resulting point density. More sophisticated code could be developed to account for the missing sections or rather perform interpolations in 3-dimensions before simplifying it into 2-dimensions. Also, the displacement map can be cleaned up and fixed after the fact. In the given example, the map edges could potentially be repaired with interpolation schemes, but this requires further investigation. In spite of these artifacts, the results obtained by the study is still very good.

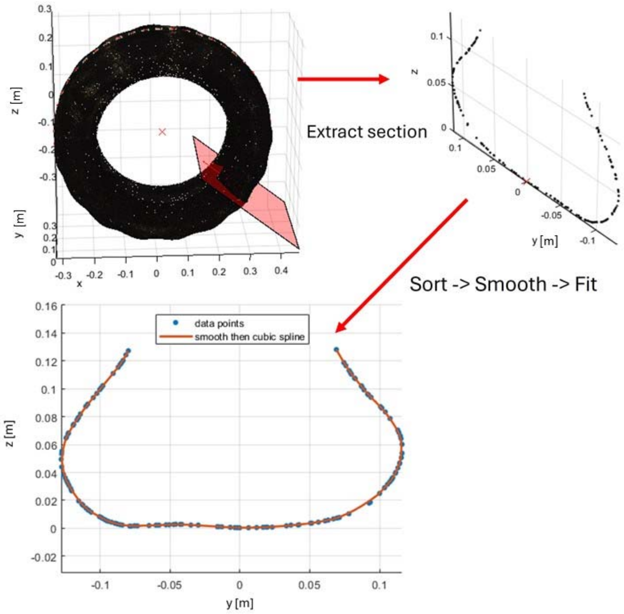

Figure 9. Cross sections extracted from the full model

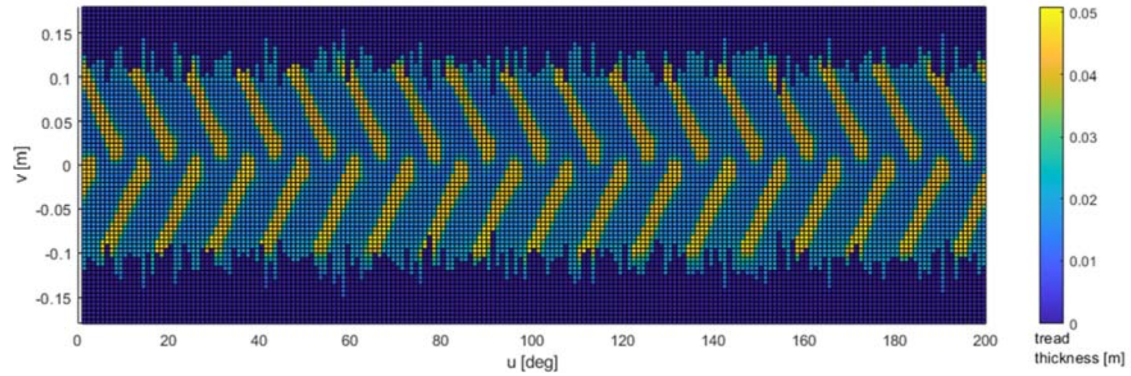

Figure 10. UV Tread displacement map

3.2.2 Applying displacement map

To estimate the tread geometry of a deformed tyre, the inner surface geometry first needs to be measured. T2Cam was used to record images of the inner surface of the tyre. These images were then later used in Reality Capture (Epic Games, 2024) to compute the point cloud of the inner surface. This software uses a structure-from-motion approach, requiring multiple images in a sequence of the object. Thus, for the following tests, only static measurements were possible. The reconstructed inner surface of the contact patch of the tyre along with the April tag locations is shown in Figure 11.

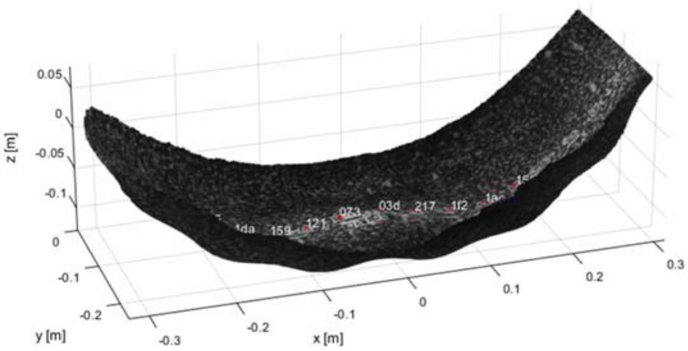

Figure 11. A processed deformed contact patch that shows the deformation and the April tag locations

The same UV coordinate system is fit through the tags and the point cloud. The UV coordinate system is aligned with the tag locations. The fitting is done in a way that ensures that the same nodes on the inner surface are obtained that were used to bake the displacement map. The tag identifiers are used to locate the relevant section of the displacement map. Now, each node is displaced along its normal direction by the distance that is stored in the tread map. This results in an estimate of the tread geometry as shown in Figure 12.

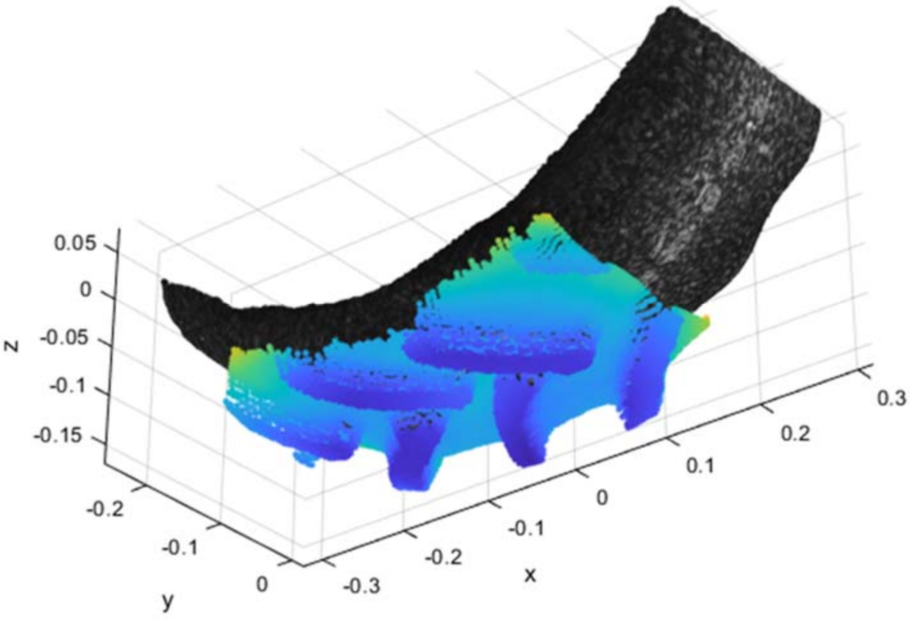

Figure 12. Estimate of the tread deformation

3.3 Experimental setup

Experimental tests were done to validate the estimate of the tread geometry. A Trelleborg TM700 280/70R16 agricultural tyre was used for the tests. This is the same tyre that has previously been used by VDG (Feldesi et al., 2020, Pegram et al., 2021). The large tyre lugs can easily be captured in 3D with photogrammetry. The large lugs are also expected to exaggerate any errors in the geometry estimation due to the steep sides of the lugs.

The tyre was mounted on a tyre testing rig. The complete setup is shown in Figure 13 (left). Different cleats were attached to apply differing loading conditions. A point load cleat, longitudinal cleat, lateral cleat, and flat plate were tested. The point load obstructed a very small region of the outside of the tyre. The unobstructed parts of the tyre tread could thus be captured with photogrammetry to be used to validate the tread geometry estimate. The wheel was pushed into the cleats at increasing displacements to emulate differing tyre load cases. The tyre was displaced in approximately 10mm increments up to about 40mm. The tyre was uninflated for the tests; thus, the measured load was not representative of typical driving conditions and was only present due to the tyre carcass stiffness. The test aimed to determine if the estimates of the tyre tread geometry were correct. The inflation pressure and representative loading is not expected to significantly influence the results as the carcass material is incompressible, or at least orders of magnitude stiffer in compression than the tyre itself.

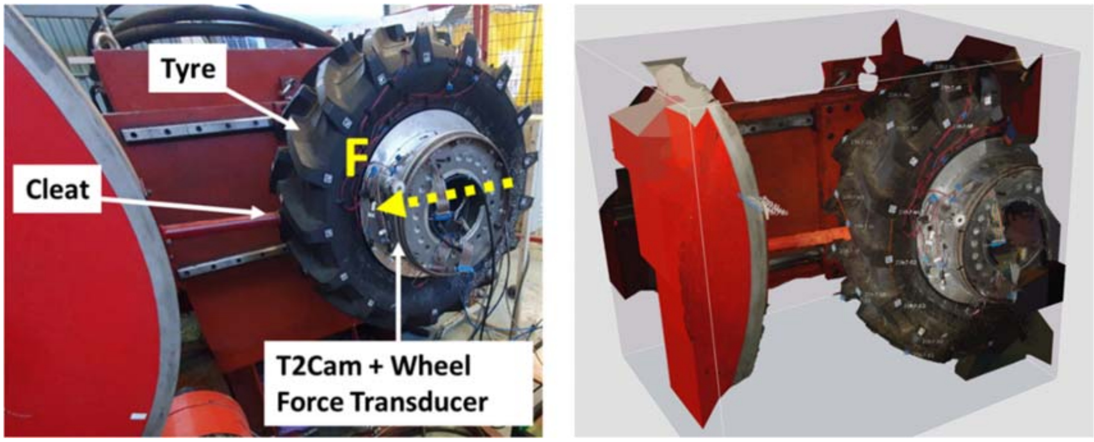

Figure 13. Test Setup to apply deformations to the tyre (left) and a 3D scan of the setup (right)

For each load increment, the inside geometry was captured with T2Cam and the outside of the tyre was scanned in with the same photogrammetry method as used before. A DSLR camera with flash and polarizing filters was used to capture the images. Reality Capture was used to process the images immediately to ensure that the entire region of interest was captured in enough detail. Figure 13 (right) shows a digital scan of the deformed tyre and test setup. These models were cleaned up to only have the relevant section of the tyre to compare with the tread geometry estimate.

3.4 Results and discussion

3.4.1 Cleats

The inner measurements were used with the 3D model to estimate the deformed tread geometry. This estimate was roughly aligned with the use of the April tags to the measurement from the outside. The estimate and measured tread were then finely aligned in CloudCompare (2024), and the signed cloud to mesh distance between the two calculated. The following results show this difference between the estimates and the tread measurements.

The left of Figure 14 shows the simple case where no load is applied to the tyre. The estimate performed well. Almost all the points are within 2.5mm of the measured surface. The flat regions are estimated very well. Most of the tread block edges are also estimated well with only some deviations.

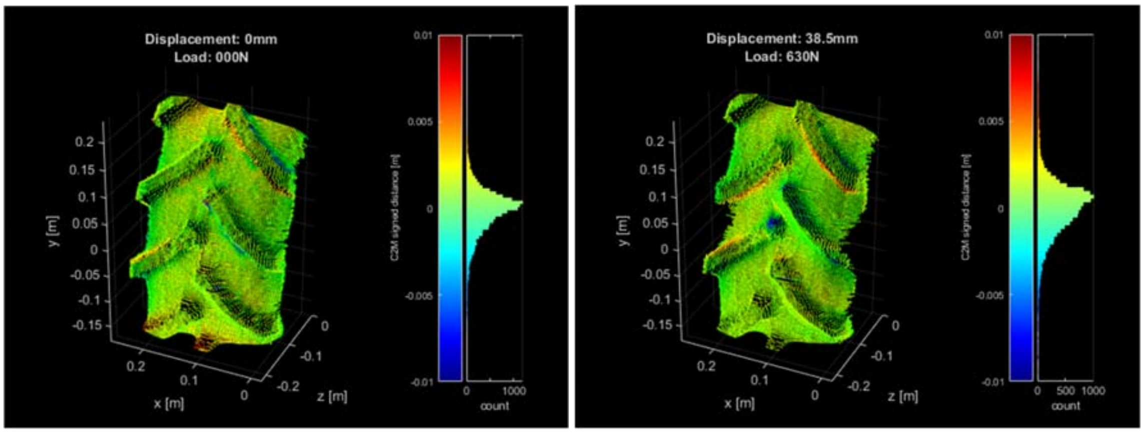

Figure 14. Distance of estimated tread to measured tread geometry with no deformation (left) and for a point load (right)

For the second test, a small point load was applied to the tyre. The right of Figure 14 shows the difference of this estimate to the measured tread. Like before, the estimate performed very well. Almost all the points are within 2.5mm of the measured surface. There is a large blue deviation in the middle where the point load was applied. The cleat obstructed the view on the outside in this region, thus, there are no measurements that the estimate can be compared to. The bottom sides of the top tread blocks have a larger error as well. These regions were particularly difficult to measure on the outside since the test setup obstructed clear visual access. This resulted in a poor-quality measurement mesh, increasing the difference.

Various longitudinal and lateral cleats were applied in further tests. The left of Figure 15 shows the fully displaced result for an offset longitudinal cleat. The results are again very good with most points estimated to within 2.5mm of the measured surface. The cleat obstructed parts of the measured surface, thus, there is a larger error present in those regions. Where the view of the measurement was unobstructed, the estimate performed well. Proving the validity of this method.

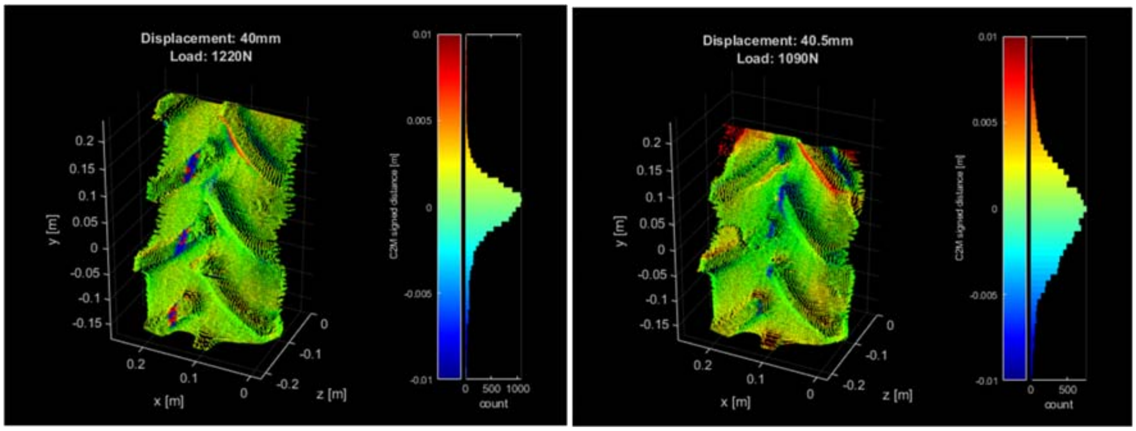

Figure 15. Distance of estimated tread to measured tread geometry for an offset longitudinal cleat (left) and distance of a poor tread estimate to a poor tread measurement for a centred longitudinal cleat (right)

Most of the tests resulted in errors like the ones shown so far. The right of Figure 15 is an example of a test where the already mentioned problems were more severe than normal. This test nicely highlights the measurement problems that skew the result of the estimation. The error distribution is very wide such that the estimate is now only within +/-5mm of the of the measurement of the tread geometry.

The left of Figure 16 shows a section of the measured tread. The missing geometry due to the position of the cleat is highlighted in blue in the middle. The sections highlighted in red on the lower sides of the tread blocks shows the poor reconstruction in those regions due to a lack of good visual access. These regions also have a larger error in Figure 15. Both these errors are problems with the validation measurements and not with the estimation. Since the rest of the estimate performed very well, it is expected that these difficult to measure areas were also estimated correctly.

Figure 16. Poorly measured tread geometry highlighting missing sections of geometry (left) and poor reconstruction of measured inner surface showcasing different photogrammetry reconstruction problems (right)

The right of Figure 16 shows the inner surface used to calculate the estimate shown in Figure 15. This is one of the worst reconstructions of all the tests. Any measurement errors on the inner surface will directly translate to the estimate. A small region (highlighted in white) is offset from the rest. This is present as a larger 3mm error on the left in Figure 15 (right). The step in the left in Figure 16 (right) can be seen as the large red error show in the top of Figure 15 (right). This example highlights the importance of good measurement results on the inner surface of the tyre. Any problems on the inner surface measurement will directly translate in the estimate.

Considering these results in the context of Terramechanics, where say a 100mm rut depth is not uncommon, this model would only result in a 2.5mm error of estimating the tread position relative to the rut. Overall, the model performed extremely well. The tests proved that offsetting the inner surface along its normal direction is a feasible way of estimating the geometry of the tread of a deformed tyre.

3.4.2 Contact area estimate

A few initial tests were done with a flat plate as an initial feasibility study to determine how well the model can be used to estimate tyre contact patch area. The tyre was pressed against a flat plate with a piece of paper. Tyre contact area prints were taken by applying paint to the tyre before pressing it against the plate.

The contact patch area was calculated for each tyre print. The inner surface of the tyre was measured with T2Cam as before and the tread geometry estimated with the 3D model. A plane was fit through the flat region of the estimates contact patch and points within a 2mm region from the plane selected. This resulted in a good similarity between the contact area of the estimate and the tyre prints.

Figure 17 shows the tyre print and the contact patch area derived from the tread estimates. The estimate looks good. The estimated contact area has the shape of the tread blocks and most of the area covered is the same as the tyre prints. With the full displacement of 42mm, the tyre is overloaded, resulting in bulging in the centre of the contact patch region. Tyre prints will always first contact in the middle and thus cannot show this behaviour. The estimated contact patch area was able to predict that the tyre will bulge and lift off the surface in the centre as expected. This test successfully demonstrated how the T2Cam system could be used to obtain accurate tyre contact patch area estimates.

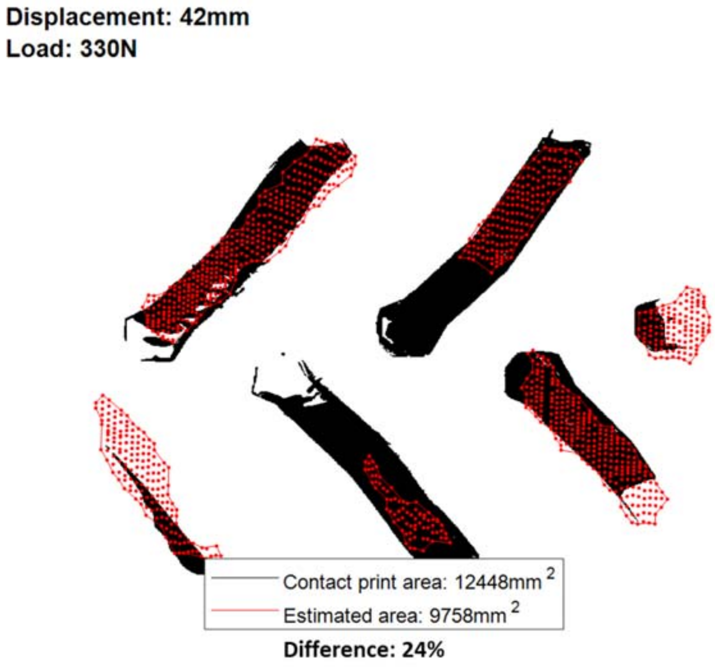

Figure 17. Tyre contact area print and contact area estimate

4. Conclusions and future work

This study proposed a measurement technique to estimate outside tyre deformation in the contact patch region of a tyre. A 2D model was developed to investigate the feasibility of the proposed solution. The solution involves measuring the geometry of the inside of a tyre and then offsetting this along its normal direction by the tread thickness. The 2D model successfully showed that the simplifications with this method will result in decent estimates of the geometry of the tyre outside. Compared to Finite Element Models, this simple geometry offset is quick to compute and provides results of decent accuracy.

A full 3D model was developed that is capable to estimate the tread deformation in the entire contact patch region. Photogrammetry was successfully used to capture the complete tyre and then use the results to bake the displacement map of the tread. The inner surface of a tyre is captured with T2Cam. The developed 3D model offsets the measured inner surface along its normal directions based on the tread displacement map. Validation tests showed that the estimated deformed tread geometry is within about 2.5mm of measurements of the deformed tread. The error introduced by the assumptions and simplifications is smaller than the measurement error of the surfaces. The system was also successfully used to estimate contact patch area against a flat non-deformable surface. From the perspective of terramechanics research, this error is very small compared to the current assumptions made. The ability to determine the contact between the tyre and the tyre at the accuracies achieved in this study, is expected to provide extremely valuable information for the better understanding of 3-dimesional tyre-terrain interaction. The ability to determine the actual contact patch size and shape will assist researchers in applying terramechanics theory to a 3-dimensional contact area compared to the current cylinder assumption.

The next step is to use the tread deformation to estimate soil deformation underneath a rolling tyre. This can be combined with measurements of the soil deformation and used to determine elastic and plastic deformation under moving vehicles. The entire system needs to be implemented on a vehicle. It remains to be seen if soil parameters can be estimated from this.

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6. 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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