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# Tyre-Soil Interface Determination by Photogrammetric Method

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**Abstract.** The paper presents an application of photogrammetric method to determine three-dimensional tyre-soil interface. Knowledge geometry of traces or ruts pressed by running wheels is important for terramechanical application, such as wheel-soil interaction analysis, soil compaction studies or wheel performance modelling. In this study we have aimed to reconstruct a 3D tyre – soil interface for an agricultural tractor running on soft, arable soil. Thee method utilizes simply photographing of wheel rut after a pass, possibly from different points of view. In order to enhance the analysis of the photographs, small markers have been applied to the wheel rut. Stages of image analysis have been presented in the paper. Final result, a complete reconstruction of tyre – soil interface with dimensioning has been included. It was concluded the method is simple yet precise and reliable for various practical applications.

## 1. Introduction

Terramechanics is a branch of science which deals with vehicle – terrain interactions by means of mechanical analysis. Most research problems in the terramechanics is focused on tyre – soil interactions, wheel performance and compaction effects on the soil. Basically due to high deformability of soft arable soils, off – road wheel and vehicle performance analysis is different from the on – road case [1, 2]. Rolling resistance increases, traction decreases as effects of volumetric and dilatational deformation of soil medium [3 - 8].

One approach, applied for solving those basic problems of terramechanics is determination of wheel (or tyre) – soil interface. Knowing the surface of the contact between the tread and the soil play a pronounced role in better understanding both the processes in the soil material as well as the resulting wheel performance and soil compaction. Effects of wheeling upon soil mechanical properties may be analysed by means of soil stresses and deformation method [4, 9], while the knowledge of tyre-soil interface enables to validate and verify models of contact stress distribution [7, 8].

Besides some basic and simplistic models, in which the tyre – soil interface is projected as a rectangular or ellipse [10], complex approaches have been presented in the literature. Błaszkiewicz has modelled the interface between the tyre and the deformable, homogenous soil as a analytical 2D surface, called it "*hypersurface*".

One frequently utilized approach in tyre – soil interface analysis is the Finite Element Method (*FEM*). Fervers has simulated tyre – soil interface using FEM and obtained two – dimensional results [11]. Mohensifah has presented a non-linear finite element model of the interaction of a tractor tyre with soil surface. The approach consists of two interface models: a tyre model, which considered the geometry and orientations of the tyre cords in each ply, the near-incompressible property of the tread rubber block, and the high and non-linear deformation of the carcass under the tread, as well as the soil model, which considered soil cross-sectional area of influence with layers separation, including three soil surface layers and a hardpan layer. Tyre–soil interaction model was developed using ANSYS FE software [12].

Some interesting research has been performed in the field of wheel – snow interaction. Since the snow is somehow similar to the soil, methods can also be applied for this purpose [10, 13]. Tyre – snow interface is determined by means of the FEM simulation of snow deformation with an assumption of snow to be a visco-elastic body [10] or to be modelled with an analog of "*crushable foam*" material [13].

The aim of the present study was to apply photogrammetric method to determine 3D tyre – soil interface surface. Expected advantages include the possibility of dimensioning of the interface as well as parametrisation through image analysis.

## 2. Experimental methods, and procedures

### *2.1. Test vehicle and tyres*

Two agricultural tractors were used for the field experiments. Their technical data is included in the table 1. The tractors are shown in figure 1. The tractors were driven on a wooden ramp, which was placed over the measurement point. Then, the tractor was pulled up by means of an excavator in order to remove part of the ramp, then the tractor was set down on the soil and the tyre loaded the soil surface for approx. 10 seconds, thereafter the tractor was pulled up again, the ramp was placed under the wheel so the tractor could drive away not damaging the interface underneath, which was photographed next. Some details of this procedure is shown in figure 1.

**Table 1.** Technical data of the tractors used in the field experiment

| | | Tractor type | |
|---|---|---|---|
| | | JD 5075E | CASE 95A |
| Front axle | | | |
| Axle loading | [kg] | 1339,8 | 1500 |
| Wheel load | [N] | 6569,47 | 7354,985 |
| Tyres | [-] | 320/85R2 | 340/85R24 |
| Inflation pressure | [MPa] | 1,6 | 1,6 |
| Rear axle | | | |
| Axle loading | [kg] | 1705,8 | 2200 |
| Wheel load | [N] | 8361,15 | 10787,315 |

| | | | |
|---|---|---|---|
| Tyres | [-] | 420/85R3 | 460/85R34 |
| Inflation pressure | [MPa] | 1,6 | 1,6 |

**Figure 1.** Agricultural tractors used for the field experiments: John Deer 5075E (upper photo) and CASE 95A (lower photo)

### *2.2. Soil material*

The field experiments have been performed in natural field conditions, on arable soil. The soil was loamy *Luvisol*, agriculturally utilized before the tests. Two measurement points (sites) have been prepared and in one of them, the soil has been rototilled up to the depth of 7cm, with resting vegetation parts after the harvest. The soil in the other measurement site has been plowed up to 25cm depth. In both cases, soil moisture content, measured with the use of a handheld meter, was approx. 30%.

### *2.3. Photogrammetric method*

Basically, photogrammetry is a method in which information about physical objects and the environment is obtained through processes of recording, measuring and interpreting photographic images and patterns of recorded radiant electromagnetic energy and other phenomena [14, 15].

Photogrammetry uses methods from many disciplines, including optics and projective geometry. Digital image capturing and photogrammetric processing includes several well defined stages, which allow to generate 2D or 3D digital models of the object as an end product. The data model on the right shows what type of information can go into and come out of photogrammetric methods. The 3-D co-ordinates define the locations of object points in the 3-D space. The image co-ordinates define the locations of the object points' images on a photograph. The exterior orientation of a camera defines its location in space and its view direction. The inner orientation defines the geometric parameters of the imaging process. This is primarily the focal length of the lens, but can also include the description of lens distortions. Further additional observations play an important role: With scale bars, basically a known distance of two points in space, or known fix points, the connection to the basic measuring units is created.

Each of the four main variables can be an input or an output of a photogrammetric method. Algorithms for photogrammetry typically attempt to minimize the sum of the squares of errors over the coordinates and relative displacements of the reference points. This minimization is known as bundle adjustment and is often performed using the Levenberg–Marquardt algorithm [15].

A special case, called stereophotogrammetry, involves estimating the three-dimensional coordinates of points on an object employing measurements made in two or more photographic images taken from different positions (see stereoscopy). Common points are identified on each image. A line of sight (or ray) can be constructed from the camera location to the point on the object. It is the intersection of these rays (triangulation) that determines the three-dimensional location of the point. More sophisticated algorithms can exploit other information about the scene that is known *a priori*, for example symmetries, in some cases allowing reconstructions of 3-D coordinates from only one camera position. Stereophotogrammetry is emerging as a robust non-contacting measurement technique to determine dynamic characteristics and mode shapes of non-rotating and rotating structures [14].

*2.3.1. Photographing the interface*

In this study we have attempted to reconstruct a tyre – soil interface for an agricultural tractor running on soft, arable soil. First, a subject interface has been created by simple rolling (driving) the tractor forward with a velocity of approx. 1 – 1.5 m/s, with possibly no or minimal wheel slip (the vehicle has accelerated several meters before the photographing points). Then, we have selected a section of the track, where markers have been inserted. Markers used for the photogrammetric reconstruction should be of regular shape (circular or square), small in size and colored to enhance their visibility and contrast in different lighting conditions. There should be as many as possible of the markers inserted, especially in case of irregular objects – such as our tyre footprint in the soil. A schematic of the photographing spot is depicted in figure 2.

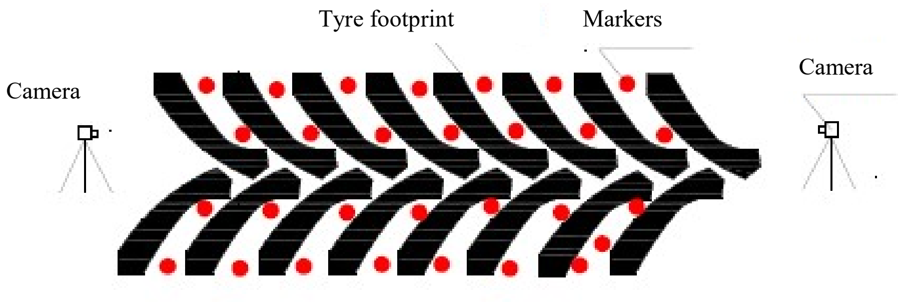


**Figure 2.** A schematic of the photographing spot

Thereafter, the prepared section of the track has been photographed and a number of photographs has been done from different heights of camera's location as well as from different directions of view. The set of photographs was then used for the next step, 3D digital reconstruction of the subject tyre – soil interface.

*2.3.2. Reconstruction of the 3D digital interface*

In order to obtain 3D reconstruction of the tyre – soil interface, a computer software was used. This software is based on 3D stereophotogrammetry algorithms and enables to determine 3D point maps from multiple photography of a given object. Coloured markers applied on the rut play the role of referencing points as well as calibrate the dimensioning module. Therefore, it is important that those markers are as small as possible and possibly visible in various lighting conditions (sun – scattered, etc.). The procedure with markers was applied after some early tries with powder colorant applied to the soil (fig. 3) – this method was not successful.

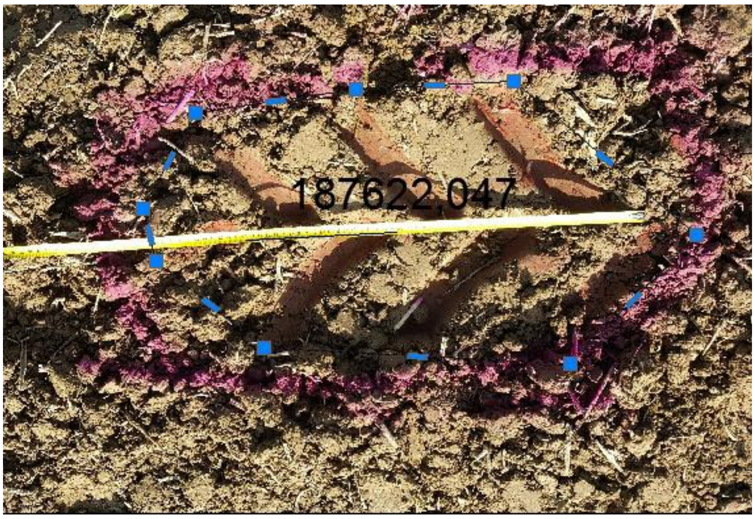


**Figure 3.** Sample tyre-soil interface with applied colorant around and a ruler for reference measurements

## 3. Results

Figure 4 shows a 3D dimensionless digital reconstruction of a tyre – soil interface obtained with the use of the presented method. The two graphics in this figure show two views of this reconstruction, aside and to the back. Note that this reconstruction saved the original colors of the soil surface in the rut. This is can be further used for investigations of soil material features, such as for example moisture content, etc.

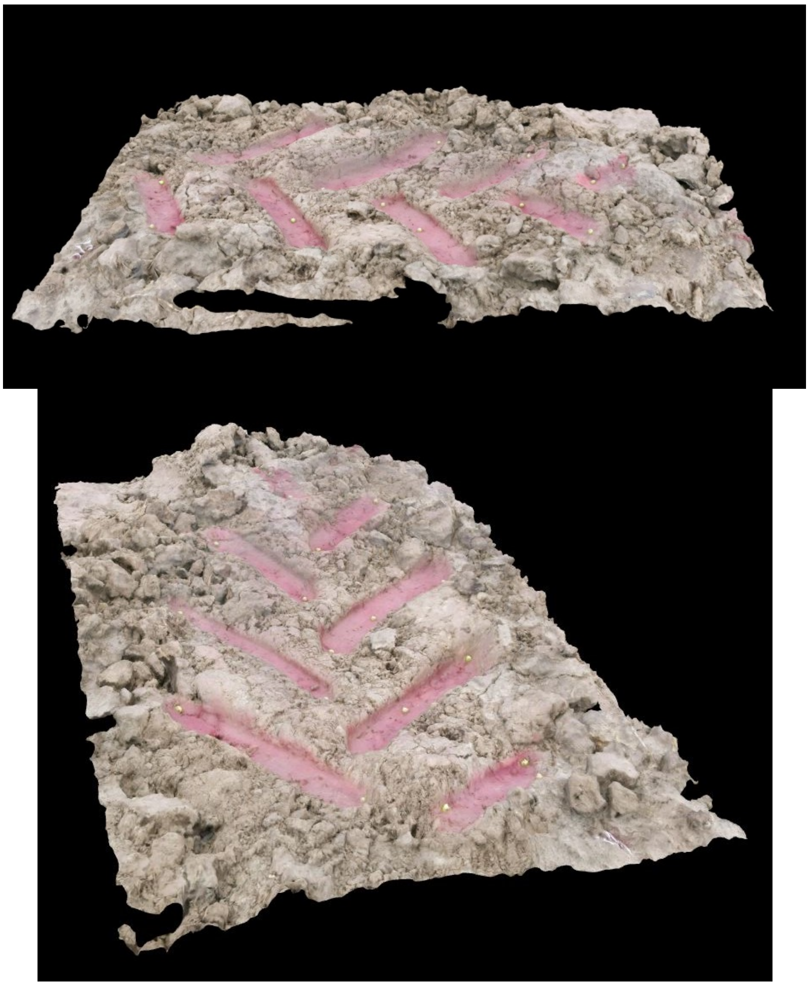

**Figure 4.** Reconstruction of a tyre-soil interface: side view (top graph) and aft view (lower graph). Markers are visible in the rut

Another step in tyre – soil interface reconstruction was to generate point maps with dimensions in order to obtain a full geometry of the rut. Results of this procedure is presented in figure 5. Here the reconstruction changes the original colours of the soil into a parametrized legend. This enables to quantify the tyre – soil interface in length dimensions, what can be used for determining the total contact area, absolute or local flotation, dimensions of soil aggregates, etc.

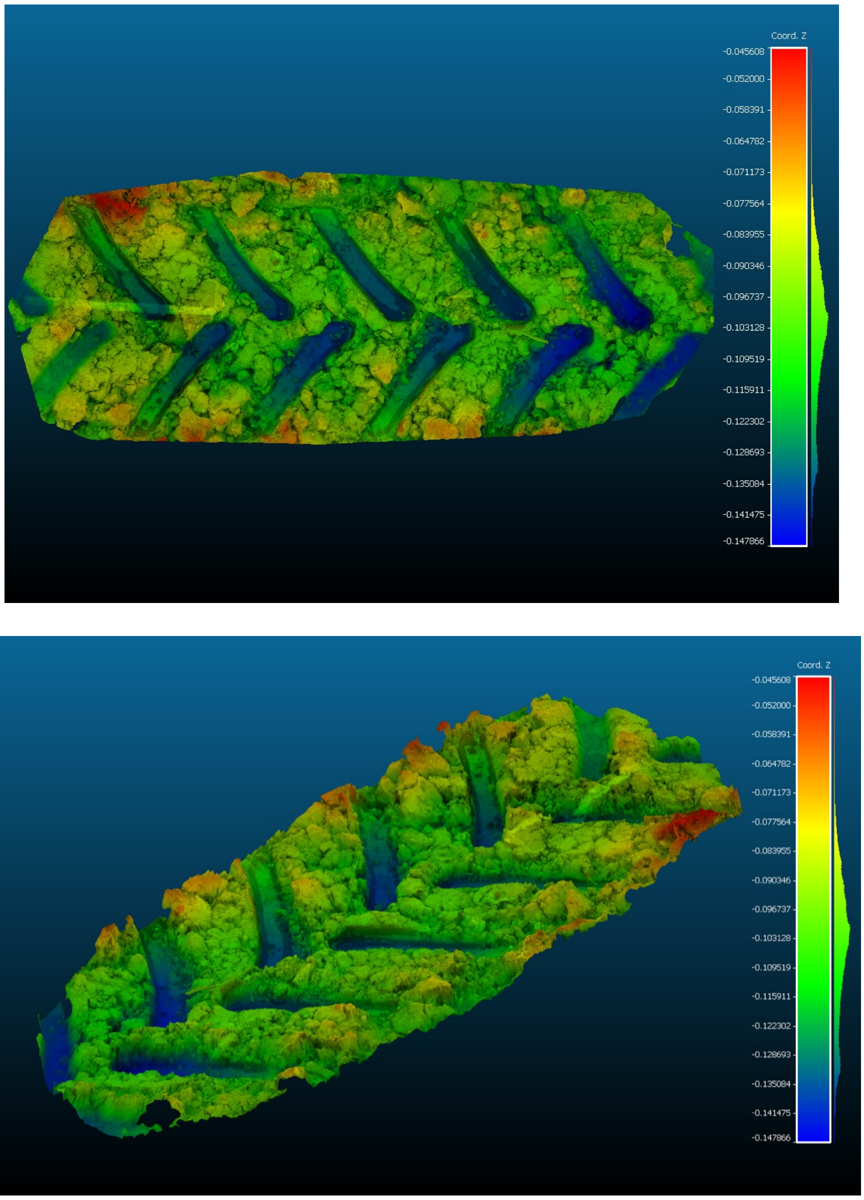


**Figure 5.** Parametrized reconstruction of a tyre-soil interface, shown in two perspectives.

## 4. Conclusions

Photogrammetric method has been applied to reconstruct tyre – soil interface for a tractor tyre running on agricultural soil. The method utilizes multiple photographing the interface from different views, then reconstructing the 3D image by means of image analysis software. The results obtained in this study proves the performance and usefulness of the method for terramechanical research of vehicle – soil interaction as well as for foresenic studies of accident reconstruction.

One possible application of the method would be the determination of contact surface area. This measure is useful for verification or parametrization of wheel – surface interaction models such as the Nominal Ground Pressure (*NGP*) model, Mean Maximum Pressure (*MMP*) model or NATO Reference Mobility Model [16, 17]. In these models, the contact area is a critical input data for contact pressure determination, followed by off-road performance prediction. The major advantage of the presented method is its high accuracy together with a low cost. Other applications include studies of soil compaction due to agricultural vehicle traction over arable soils. One well known model of soil compaction, the **So**il **Co**mpaction **Mo**del *SOCOMO* [18], utilizes contact pressure, which can be determined by means of the photogrammetric procedure described in the present study with a high level of precision.

Further research would focus on the use of different markers in order to minimize the number of photos required for the reconstruction.

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