CAMERA-BASED SIDE SLIP MEASUREMENT FOR TYRE TESTING

CC DE SAXE[1], R BERMAN[2], A CLARKE[3*] and D REINECKE[3**]

[1]CSIR Built Environment, 627 Meiring Naudé Road, Pretoria, 0081
Wits University, School of Mech. Eng., 1 Jan Smuts Ave., Johannesburg 2000
Tel: 012 841 4013; Email: cdsaxe@csir.co.za
[2]CSIR Built Environment, 627 Meiring Naudé Road, Pretoria, 0081
Tel: 012 841 4986; Email: rberman@csir.co.za
[3]CSIR DPSS, 627 Meiring Naudé Road, Pretoria, 0081
*Tel: 012 841 3116; Email: aclarke@csir.co.za
**Tel: 012 841 3635; Email: dreinecke@csir.co.za

ABSTRACT

Tyre parameterisation is fundamental to vehicle dynamics research, as tyre properties have a significant impact on the behaviour of a vehicle. One way in which some of the primary tyre parameters can be extracted is a trailer-based tyre tester, multiple versions of which exist at the CSIR. Fundamental to this type of testing is the accurate measurement of the wheel slip angle. In the case of trailer-based tyre-testing, this is measured relative to the trailer body, and so accurate measurement of the trailer side-slip angle is critical. This may be carried out using a suitable sensor such as the VBox 3, OxTs RT3000, or Corrsys Datron Correvit sensor. The latter is used in the application by the CSIR. Each of these sensor options have drawbacks in terms of cost, size and measurement limitations, which have prompted investigations into alternative side slip angle sensing solutions. In this paper we present the implementation of a camera-based system, using open source software libraries, on the CSIR's medium tyre-tester. The system comprises a single camera mounted to the trailer and observing the ground, and a processing unit. The software was developed in Python, making use of Lucas-Kenade feature tracking, an outlier rejection scheme, and simple filtering. The system was evaluated in a number of tests and has demonstrated good potential for application to future tyre testing research. The system was further evaluated in limited tests involving the CSIR's Stress-In-Motion technology for possible additional future research functionality.

Keywords: Tyre parameterisation, Slip angle, Computer vision, Vehicle dynamics

1 INTRODUCTION

1.1 Tyre testing and parameterisation

Tyre parameterisation is fundamental to vehicle dynamics research, as tyre properties have a significant impact on the behaviour of a vehicle. Tyres are highly non-linear components with complex stiffness and damping characteristics which influence how the tyre generates lateral and longitudinal traction forces at the road surface. Tyre manufacturers typically conduct their own tyre tests in-house, to generate certain parameterisation data, but these data are usually considered valuable intellectual property and hence kept proprietary. Further, the level of parameterisation obtained through these in-house tests is not necessarily always consistent with the requirements of tyre models for vehicle dynamics studies. A variety of tyre models exist, with varying degrees of benefits and limitations, including Pacejka models (89, 94 and 2002) (Bakker, Pacejka and Lidner, 1989), FTire (Gisper, 1999) and SWIFT (Schmeitz, Besselink and Jansen, 2007). What these models have in common is the need for tyre parameter data specific for the tyre being modelled. The requirements differ from model to model, but at a minimum the models require some parameterisation of vertical stiffness and lateral stiffness, the latter as a function of vertical load and slip angle.

For a specific tyre size, brand and designation (e.g. “315/80R22.5 Michelin X Line Energy Z”), these parameters must be obtained via testing. Laboratory tests are typically carried out on either a drum-based tyre tester or a flat-belt tyre tester, both of which have limitations in terms of representativeness of on-road conditions or repeatability. Tyre parameterisation tests can also be carried out in the field on tarmac (or other road surface with suitable traction) using mobile tyre testers. These can be either fixed directly to a purposed vehicle, or in the form of a special purpose trailer. The CSIR has two such trailer-based tyre testers for different sizes of tyre, which were developed in the 1990s in collaboration with Armscor and the SANDF. The “medium-size” tyre tester is shown in Figure 1.

Figure 1: CSIR’s medium-size tyre tester

For vehicle dynamics research, arguably the most important tyre characteristic is the lateral force behaviour in response to slip angle. The slip angle is distinct from the steer angle, and is the angle between the instantaneous heading of the tyre (the direction in which the tyre is steered) and the instantaneous direction of motion of the tyre. Lateral force typically increases approximately linearly with increasing slip angle for small angles, and then the relationship becomes non-linear. The lateral force to slip angle relationship also varies with vertical load on the tyre, and so tests must be conducted over both a range of slip angles and vertical loads.

1.2 The importance of slip angle measurement

The accurate measurement of slip angle is hence critical to tyre parameterisation tests. In the case of the trailer-based mobile tyre tester, two identical tyres to be tested are mounted to both the left and right sides of the axle. The slip angle is set by steering the left and right tyres by the same angle but in opposite directions (i.e. both toe-in, or both toe-out). The generated lateral forces are hence theoretically equal and opposite, meaning that the trailer remains straight, and the lateral forces developed on each tyre can be measured and recorded. The set steer angle between the tyre and the trailer body can be measured easily using a string potentiometer or similar sensor, and in the ideal case, this angle would be equal to the tyre slip angle.

However, due to small imbalances in the tyres, road surface, trailer etc, the forces generated by the tyres are not necessarily perfectly equal, and the equilibrium position of the trailer during testing will not necessarily be perfectly straight. The slip angle of the trailer itself must therefore be measured and subtracted (or added depending on sign convention) from the measured tyre steer angle to get an accurate tyre slip angle measurement. Measurement of the *trailer* slip angle is hence critical to trailer-based mobile tyre testing.

1.3 Current methods of slip angle measurement

On the CSIR's trailer-based tyre testers, trailer slip angle is currently measured using a Corrsys Datron Correvit sensor (Caroux *et al.*, 2007; Botha and Els, 2015). However the Correvit sensor has presented some limitations to tyre testing in the past, namely:

1. Limited high-resolution slip angle measurement range (±15°)
2. Increased measurement noise and reduced accuracy at speeds below 10 km/h
3. High cost
4. The equipment is heavy and bulky

The CSIR has hence embarked on a study to find an alternative solution to the Correvit sensor, for specific application to tyre testing activities within the CSIR. A study of the literature presents a few alternative possibilities for measuring slip angle. Typical GPS+inertial sensor units such as the OxTS RT3000 (Oxford Technical Solutions, 2004) are able to measure slip angle for such tests, but are limited by high cost, and noise and drift at low speed (Bevly, Gerdes and Wilson, 2002; Caroux *et al.*, 2007). Alternatively, state observers could fulfil the role (Grip *et al.*, 2009), in which inputs from various sensors such as accelerometers are coupled with a dynamic system model to estimate slip angle in real-time. However, such a solution would require multiple sensors (and hence increased cost), and reliance on the accuracy of the underlying system model.

Camera-based solutions to such measurement tasks are a comparatively recent idea, and such solutions have become increasingly practical with advances in computer vision algorithms and improved computational power. It is possible to use a camera as a sensor, measuring a constant stream of images as an input, applying image processing techniques to the image stream, and outputting the required measurement in real-time. Recent work has demonstrated the successful application of camera-based measurement to various vehicle dynamics tasks (Botha and Els, 2014, 2015; de Saxe and Cebon, 2019b, 2019a). Most relevant is the work of (Botha and Els, 2015) and (Johnson, Botha and Els, 2019) in which camera-based slip angle measurement was successfully demonstrated in real-time.

1.4 Scope of paper

In this paper, we give a high level summary of the camera-based slip angle measurement system developed specifically for tyre testing activities at the CSIR. First, an overview of the system is given, including details of the physical setup as well as the image processing algorithm used. This is then followed by details of field tests of the system with the CSIR's medium-size tyre tester.

2. SYSTEM OVERVIEW

2.1 Physical implementation

The overall slip angle measurement setup comprises a camera mounted to the tyre tester trailer, mounted such that the camera is facing downwards viewing the surface of the road. For the purposes of these tests, the camera was rigidly mounted to the rear of the tyre testing trailer viewing the ground, using the same rigid mount to which the Correvit sensor was attached. This would enable a comparison of camera and Correvit slip angle measurements. The camera must be mounted perpendicularly to the ground as accurately as possible. The effects of uneven terrain, trailer pitch and roll were not investigated at this stage. An overview of the Correvit and camera systems mounted to the rear of the trailer is given in Figure 2. A rugged housing for the camera was designed and 3D printed for this project, with thanks to Mark Teuteberg and Joshua Dehlen of University of Pretoria, as shown in Figure 3. The Correvit has been recently calibrated by the supplier.

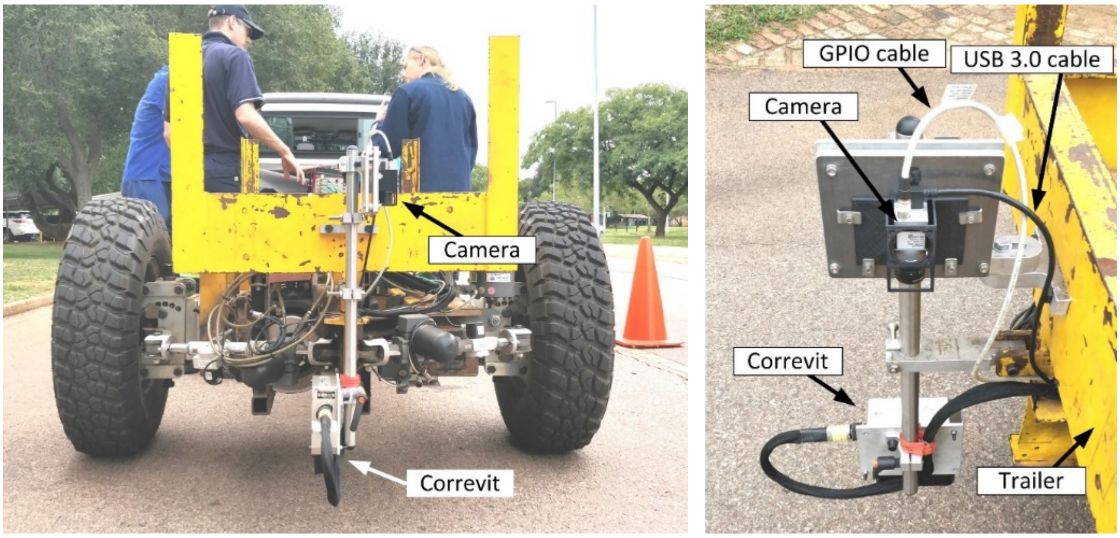

Figure 2: Camera and Correvit system mounted to the tyre tester

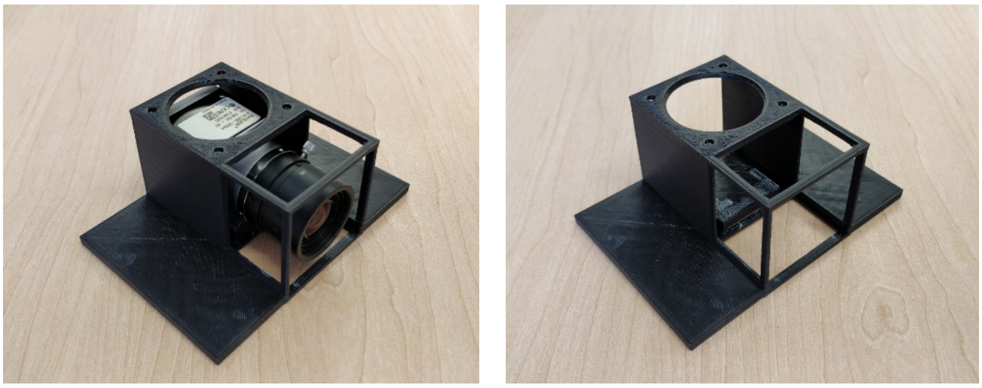

Figure 3: Custom 3D printed camera housing, with and without camera

The camera was coupled to a laptop computer via USB 3.0 in order for the image stream to be recorded and processed. The GPIO functionality of the camera was used to output a pulsed signal synchronised with each image frame which was logged on a central data acquisition system (Somat eDAQ) in order to synchronise camera data with other sensor data collected during the tests. The instrumentation setup is illustrated in Figure 4. A Basler acA1300 – 200uc USB 3.0 camera was used, with an 8 mm TAMRON lens. A resolution of 640x480 was used, and images were captured at 300 fps.

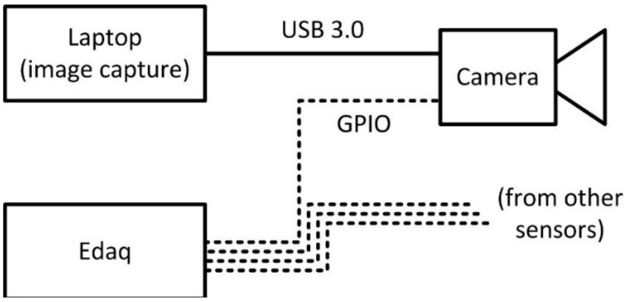

Figure 4: Camera setup for image capturing and synchronisation

2.2 Image processing algorithm

The overall method of image processing to extract the slip angle was based on the work of (Botha and Els, 2015). The algorithm detects and tracks visual features in the road surface as it passes beneath the trailer. By tracking the instantaneous direction of motion of these features, the slip angle can be calculated. Image sequences of the road surface were processed using Python code developed specifically for this purpose. Use was made of the *OpenCV*, *scikit-learn*, and *scipy* open-source libraries for image processing, linear regression, and signal processing functionality respectively. The overall logic of the processing code is given in Figure 5. Image data from the tests were post-processed, at processing speeds of up to 20 fps on a standard desktop computer.

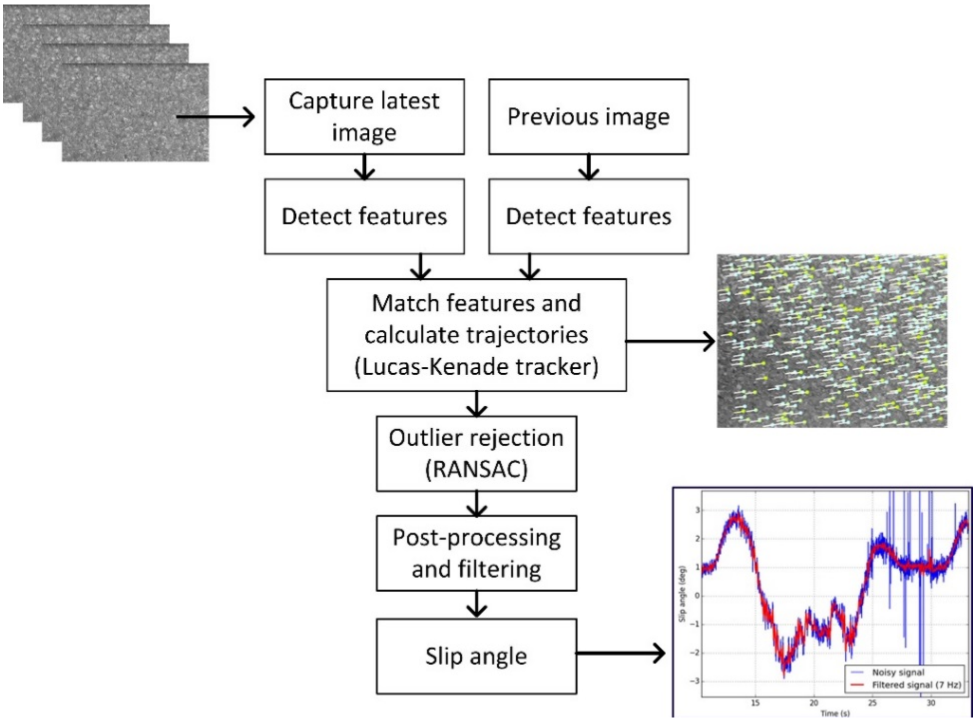

Figure 5: Functional diagram of the slip angle measurement algorithm

3. FIELD TESTS

3.1 Validation test

In order to verify the functioning of the camera system prior to tyre testing, an extra set of tests was executed in order to capture data for comparing the camera-based slip angle measurement to the Correvit. The Correvit sensor and camera system were mounted to a vehicle using the same mounting as used on the trailer, shown in Figure 6. During the test the vehicle accelerated from a stationary position to approximately 40 km/h. Thereafter the speed was reduced to approximately 25 km/h and the vehicle performed a U-turn by driving around a round-about. Upon exiting the round-about, the speed was increased and then reduced in order to come to a complete stop in the same area where it started.

Figure 6: Correvit sensor and camera mounted to the vehicle for validation

Figure 7 shows some tracking results from the test. The first image shows an example of feature tracking working effectively and giving a reliable slip angle measurement. The second image shows an example of where the tracking did not work as well. The second image is taken from an instance at higher speed, resulting in erratic slip angle measurements. This is due to the reduced overlap between successive image frames, negatively affecting the feature tracking performance. In the lower part of both images one can observe part of the mounting clamp for the camera and Correvit sensor. In later tyre tests, the image crop region of interest was adjusted to exclude this.

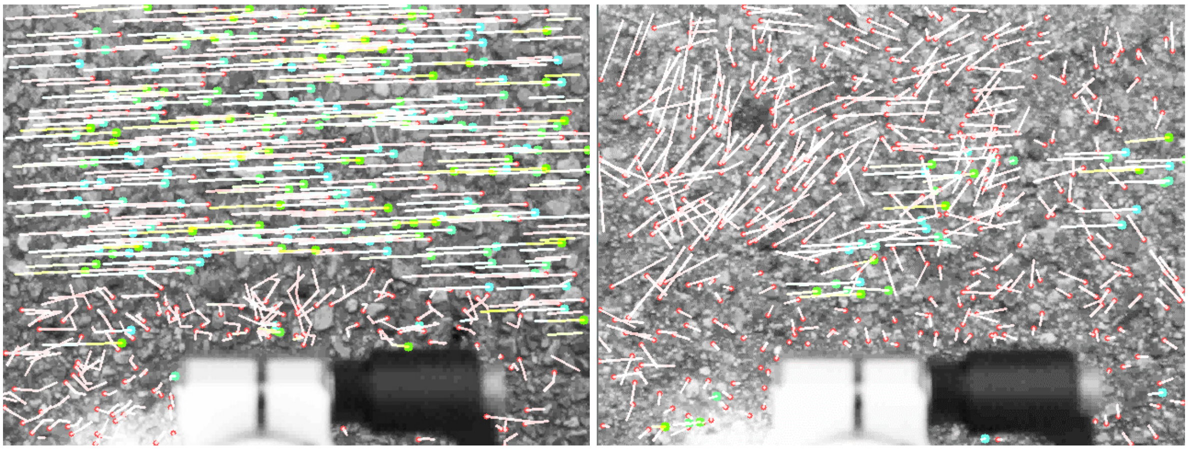

Figure 7: Feature tracking: Good (left) vs. poor (right)

The camera-based slip angle measurement is compared to the measurement from the Correvit sensor in Figure 8. The camera-based measurements were post processed using a Butterworth filter (with a cut-off frequency of 7 Hz), while the Correvit measurements were filtered with an Equiripple low-pass filter (band frequencies of 5 and 10 Hz). Phase shifts were added to compensate for the resultant delays. At the initiation of the test, the measurement from the Correvit sensor fluctuated significantly as a result of the low travel speed, and stabilised after about 2.5 s. Between 5 and 10 seconds into the test, the camera-based measurements became erratic, presumably either as a result of poor feature tracking, or due to the fact that the algorithm parameters were optimised for lower speeds. The two measurements correlate well, showing the same trend, but the slip angle measurement of the Correvit sensor is higher than the camera-based measurement for slip angles exceeding ±1°. The discrepancies in the measurements may be caused by misalignment in the mounting of the camera or Correvit, or by road grade or tyre camber.

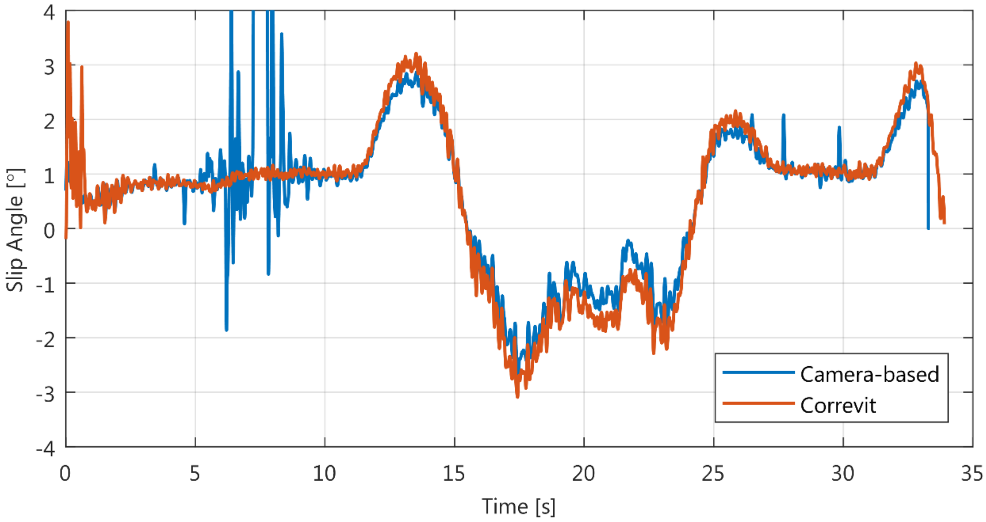

Figure 8: Slip angle measurement comparison: Camera system vs Correvit

3.2 Tyre parameterization tests

After the initial validation tests, the system was tested on the tyre tester trailer. Tests were carried out on the CSIR campus on a straight section of tarmac, at speeds of less than 10 km/h. A range of slip angles were tested, and different vertical loads were assessed by loading weights onto the trailer. The trailer and towing vehicle used are shown in Figure 9. As part of the higher level testing programme, it was decided to combine the tyre tests with the CSIR's Stress-In-Motion (SIM) system. The SIM system comprises a set of load cells embedded into the road surface, which measure the vertical pressure distribution within the tyre contact patch. This has typically been used for research into the impact of vehicle loads on road wear.

Figure 9: The medium tyre tester and towing vehicle ready for testing

The section of road chosen for testing included a section where the tyre tester would be driven over the SIM system. The SIM system presented additional challenges for the camera system, as it comprised some smooth steel plate around it (used to cover the system when not in use). The SIM system and surrounding steel plates are shown in Figure 10. These plates would result in a difficult task for the image processing, given that a smooth surface provides significantly fewer visual features to track, compared with a rough asphalt surface. So this would be a good test of the robustness of the algorithm.

Figure 10: The CSIR Stress-In-Motion (SIM) system

Slip angle measurements for two selected tests are shown in Figure 11. Measurements from the Correvit sensor are included for comparison. The tyre tester reaches the SIM system at around 11-12 seconds in both cases. In the first case the steer angle is high and the trailer has no load. When the right-hand tyre reached the SIM, the significant change in traction properties between left and right tyres caused the lightly loaded trailer to jolt rapidly and then oscillate. This is evident in the rapid change in slip angle from to -10 and then +6 degrees and could be clearly observed by eye during testing. In the second case, the oscillation is less pronounced as the steer angle is less and the trailer is laden. In both cases the camera-based measurements seem to exhibit less noise than the Correvit sensor measurements.

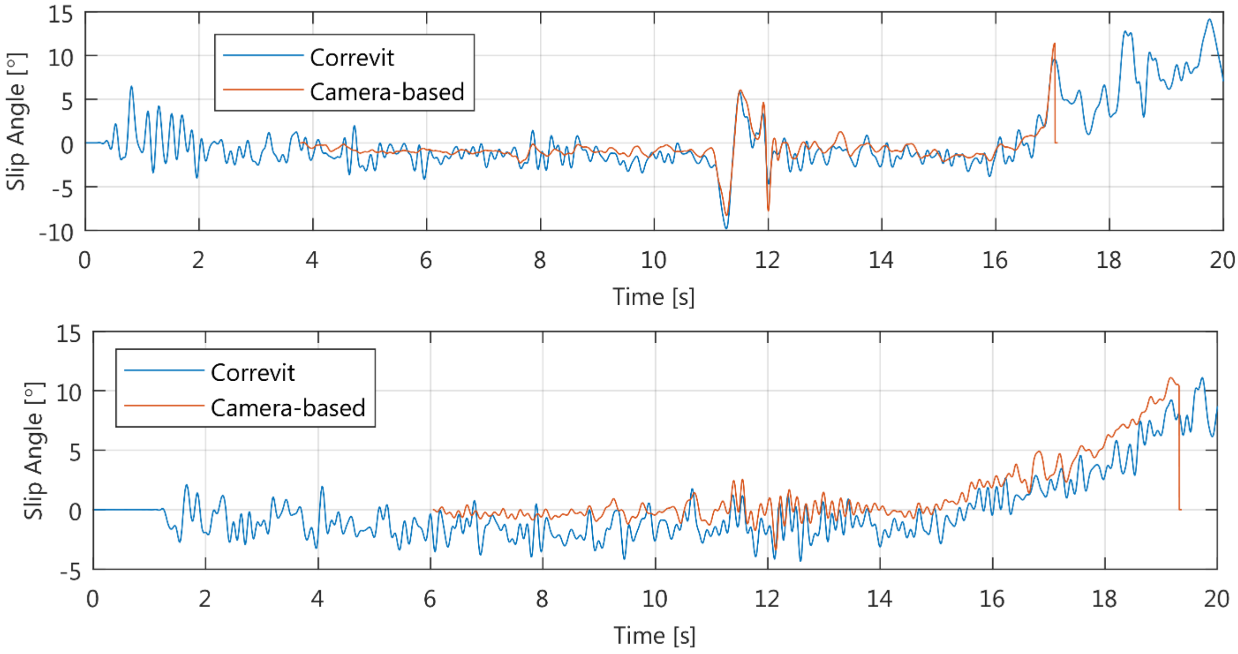

Figure 11: Slip angle measurements. (Top) 9 degrees steer angle, unladen. (Bottom) −3 degrees steer angle, laden

Some feature tracking results from the tests are given in Figure 12, giving insights into how the system performed under different conditions. In the top left is a "normal" case, where the road surface is uniform with clear features and feature tracking performance is good. In the top right, it is clear that the system performs well when road markings are encountered. The bottom two frames show performance when the trailer and camera traversed the SIM system and surrounding steel plates. From the bottom left image there is a clear reduction in the number of trackable features in the steel plate, compared with the asphalt. However, as is clear in the lower right image, the algorithm is still able to detect and track at least a few feature points, enough to maintain good slip angle measurements over this region.

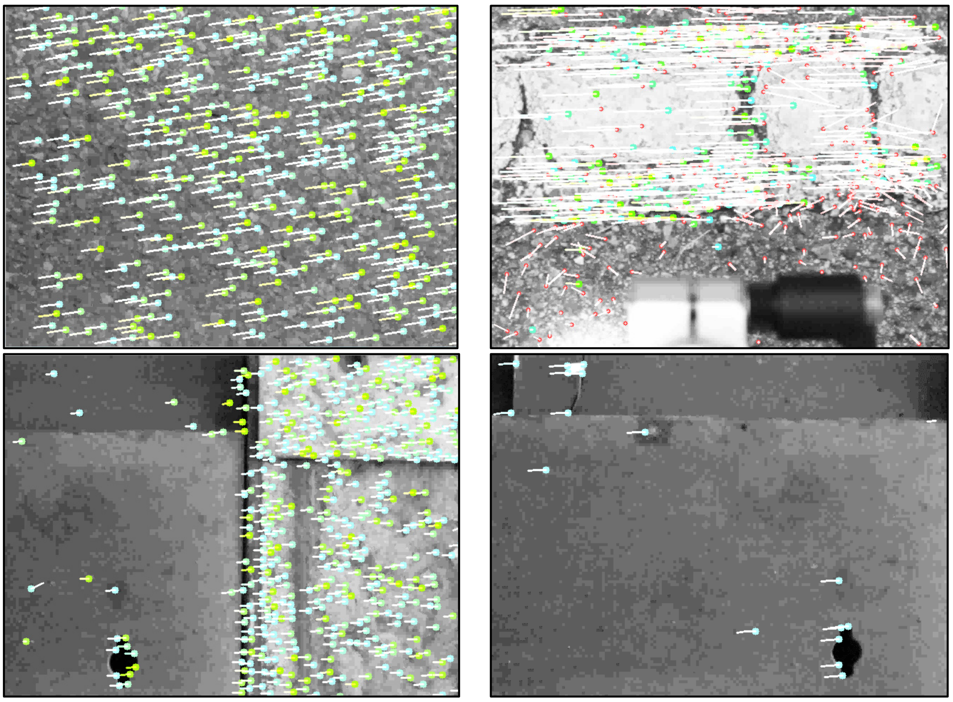

Figure 12: Variation in surface types tested, and resultant variation in feature tracking

4. CONCLUSIONS AND FUTURE WORK

In this paper we have demonstrated the implementation and testing of a camera-based slip angle measurement system, specifically tailored for mobile tyre testing applications. The system has been shown to perform well under a range of conditions, and has proved effective over smooth surfaces, enabling its use with the CSIR's Stress-In-Motion system. This paves the way for potentially novel combined tyre testing activities in future. The system will be developed further to improve the levels of flexibility, automation and computational efficiency.

5. ACKNOWLEDGEMENTS

This work was jointly funded by Armsor and the Department of Science and Technology DST via the CSIR's parliamentary grant. The authors would like to thank Joshua Dehlen and Mark Teuteberg of the University of Pretoria for their valuable contributions in compiling the Python code for image processing, and designing and 3D printing the camera housing.

5. REFERENCES

Bakker, E, Pacejka, HB and Lidner, L, 1989. ‘A new tire model with an application in vehicle dynamics studies’, SAE Transactions, Section 6: Journal of passenger cars, 98, pp. 101-113. Available at: http://www.jstor.org/stable/44472260%0D.

Bevly, DM, Gerdes, JC and Wilson, C, 2002. ‘The Use of GPS Based Velocity Measurements for Measurement of Sideslip and Wheel Slip’, Vehicle System Dynamics, 38(2), pp. 127-147.

Botha, TR and Els, PS, 2014. ‘Tire longitudinal slip-ratio measurement using a camera’, in International Conference on Advanced Vehicle Technologies. Buffalo, NY: ASME p. V003T01A043. doi: 10.1115/DETC2014-34886.

Botha, TR and Els, PS, 2015. ‘Digital image correlation techniques for measuring tyre-road interface parameters: Part 1 – Side-slip angle measurement on rough terrain’, Journal of Terramechanics, 61, pp. 87-100. doi: 10.1016/j.jterra.2015.04.004.

Caroux, J et al., 2007. ‘Sideslip angle measurement, experimental characterization and evaluation of three different principles’, IFAC Proceedings Volumes, 40(15), pp. 505–510.

Gisper, M, 1999. ‘FTire: A new fast tire model for ride comfort simulations’, in International ADAMS User Conference. Berlin.

Grip, HF et al., 2009. ‘Vehicle sideslip estimation’, IEEE Control Systems Magazine, 29(5), pp. 36-52.

Johnson, DK, Botha, TR and Els, PS, 2019. ‘Real-time side-slip angle measurements using digital image correlation’, Journal of Terramechanics. Pergamon, 81, pp. 35-42. doi: 10.1016/J.JTERRA.2018.08.001.

Oxford Technical Solutions, 2004. RT3000 Inertial and GPS Measurement System: User Manual. Oxford: Oxford Technical Solutions.

de Saxe, CC and Cebon, D, 2019a. ‘Estimation of trailer off-tracking using visual odometry’, Vehicle System Dynamics. Taylor & Francis, 57(5), pp. 752-776. doi: 10.1080/00423114.2018.1484498.

de Saxe, CC and Cebon, D, 2019b. ‘Measurement of articulation angle by image template matching’, Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering. doi: 10.1177/0954407019833819.

Schmeitz, AJC, Besselink, IJM and Jansen, STH, 2007. ‘TNO MF-SWIFT’, Vehicle System Dynamics. Taylor & Francis, 45(sup1), pp. 121–137. doi: 10.1080/00423110701725208.