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Digital image correlation techniques for measuring tyre-road interface parameters: Part 1 – Side-slip angle measurement on rough terrain

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Abstract

This paper presents inexpensive methods whereby the vehicle side-slip angle can be measured accurately at low speeds on any terrain using cameras. Most commercial side-slip angle sensor systems and estimation techniques rely on smooth terrain and high vehicle speeds, typically above 20 km/h, to provide accurate measurements. However, during certain in-situ tyre and vehicle testing on off-road conditions, the vehicle may be travelling at speeds slower than required for current sensors and estimation techniques to provide sufficiently accurate results. Terramechanics tests are typical case in point. Three algorithms capable of determining the side-slip angle from overlapping images are presented. The first is a simple fast planar method. The second is a more complex algorithm which can extract not only the side-slip angle but also its rotational velocities and scaled translational velocities. The last uses a calibrated stereo-rig to obtain all rotations and translational movement in world coordinates. The last two methods are aimed more at rough terrain applications, where the terrain induces motion components other than typical predominant yaw-plane motion. The study however found no discernible difference in measured side-slip angle of the methods. The system allows for accurate measurement at low and higher speeds depending on camera speed and lighting.

Keywords: Side-slip angle; Digital image correlation; Camera; Rough terrain; In-situ

1. Introduction

The vehicle side-slip angle is an important measurement in the handling of vehicles. It can be used as a measure of the handling and stability of the vehicle. The side-slip angle can describe the over steer and under steer characteristics of a vehicle when measured on the front and rear axle of the vehicle. It can also be a measure of vehicle directional stability. Measurement of the sideslip angle is therefore important when performing high speed dynamic manoeuvres with vehicles.

The tyre side-slip angle is also of great importance when performing tyre modelling and evaluation. While the lateral tyre force generation is a complex phenomenon in which the deformation of the rubber during cornering is non-uniform across the contacts patch as illustrated by Fiala's mathematical formulation (Fiala, 1954) of tyre force generation. It can be shown that the side-force generation of a tyre can be sufficiently described using the average side-slip angle of a tyre (Fiala, 1954; Bakker et al., 1987). Accurate measurement of the side-slip angle is therefore crucial in validating and characterising tyre models. In many terramechanics tests the tyre tests are performed in a

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Nomenclature

$d_{sampson}$	Sampson distance
$\boldsymbol{I}_t$	frame at time t
I	image pixel intensity
$\boldsymbol{E}$	essential matrix
$\boldsymbol{F}$	fundamental matrix
$\boldsymbol{K}_1, \boldsymbol{K}_2$	camera calibration matrices
$\boldsymbol{P_1}$	point set 1
$\overline{\boldsymbol{P_1}}$	mean of point set 1
$\boldsymbol{p}$	homogeneous coordinate of point in image $\boldsymbol{I}_t$
$\boldsymbol{p}'$	homogeneous coordinate of point in image $\boldsymbol{I}_{t+1}$
$\boldsymbol{q}$	normalised homogeneous coordinate of point in image $\boldsymbol{I}_t$
$\boldsymbol{q}'$	normalised homogeneous coordinate of point in image $\boldsymbol{I}_{t+1}$
$\boldsymbol{R}, \boldsymbol{R}_a, \boldsymbol{R}_b$	rotation matrices
$\boldsymbol{t}, \boldsymbol{T}_a, \boldsymbol{T}_b$	translation vectors
$[\boldsymbol{t}]_x$	skew symmetric translation matrix
t_i	component i from translation vector
$\boldsymbol{U}$	left SVD singular vector matrix
$\boldsymbol{V}$	right SVD singular vector matrix
$\boldsymbol{\Sigma}$	singular values from SVD

laboratory with a controlled environment (Sandu et al., 2008; Krick, 1973). In these laboratory tests the side-slip angle can be controlled accurately, however, these test rigs are expensive and as such numerous tests are conducted in-situ with the vehicle travelling across the surface. In these situations the side-slip angle needs to be accurately measured. Since these tests are typically conducted at low speeds the estimation method is generally not applicable. Various stability and traction control algorithms can be improved if an online measurement of the side-slip angle is available and can be cheaply measured. The side-slip angle and its derivative offer more practical information about the vehicle stability compared to yaw rate for vehicle stability (Inagaki et al., 1994). Chung and Yi (2006) develop a side-slip angle based stability control scheme and shows overall improvement in vehicle performance.

In literature many studies concentrate on estimating the side-slip angle through other vehicle measurements. The side-slip angle is estimated using sensors such as accelerometers, rate gyroscopes and GPS (Botha and Els, 2012; Bevly et al., 2006). The main disadvantages of the estimation methods are that they rely on high dynamic situations such as high speed manoeuvres where sensor excitations are large in comparison to sensor noise. Additionally when considering off-road terrain the additional ground excitation may become too large rendering these methods unsuitable. While in off-road driving scenarios especially on deformable or very low friction terrains, such as mud, sand, loose gravel, ice and snow, the side-slip angle may become large when fully sliding and can also occur at much slower speeds as compared to hard roads.

A commercial side-slip angle measurement sensor, Kistler Correvit S-HR (Kistler), is available which uses both Doppler Effect and an absolute measuring method. However, the sensor generally provides unreasonable accuracy below 15 km/h and has a maximum measurable side-slip angle of ±20°. The sensor is also developed for use on mainly on-road vehicles where there is very little vertical body motion and the vehicle mainly undergoes planar motion i.e. high speed driving on smooth roads. It will however be shown that vertical motion as well as roll can have an effect on the measured side-slip angle.

This paper proposes three techniques whereby the side-slip angle is measured using either a single camera facing the ground or a calibrated stereographical rig containing two cameras. The three techniques make use of Digital Image Correlation (DIC) as well as other imaging techniques to determine the side-slip angle. The first proposed method is a simplistic technique which is very computationally inexpensive but only measures image longitudinal and lateral velocities. The second technique is a more computationally expensive method which can measure all rotational and scaled translation velocities. The last technique makes use of a calibrated stereographical rig to determine all rotations and translations in real world coordinates. All methods can measure any degree of slip angle and can accurately measure slip angles at very low speeds.

2. Digital image correlation technique

Digital Image Correlation (DIC) is a method whereby optical methods are used to track changes in an image. The methods can be used to obtain a variety of measurements from displacements and velocities of particles to the strain of an object in an image (Xavier et al., 2012). There are numerous methods which can be used to perform DIC, however the underlying methodology remains the same. The techniques try to match regions in one image to regions in another effectively tracking these regions across images. Often these images make up a time sequence of images, $\boldsymbol{I}_t\,[t = 0, 1, \ldots, n]$, taken with a constant time difference apart. In strain based measurements the displacement field is computed across the whole image, however to simplify and speed up the DIC smaller key point regions can be tracked as opposed to the complete image.

In order to track a subset of regions in the image first requires the identification of regions in the image which are easily identifiable and therefore easy to track. A simplistic feature to track in imaging are so called corner or edge features. These are features which there is texture