Advanced Vehicle Dynamics Evaluation System

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Abstract– ***this paper proposes a novel dynamic evaluation system for vehicle under standard manoeuvring condition.*** **The proposed system combines three sub-modules to conduct the aforementioned functions as follows: first, Turing radius measurement has been designed and manufactured using low-cost 3D printing. second, dynamics measurement module including on-board accelerometers, speed sensor and a custom-designed and manufactured fifth wheel. Data logging and acquisition from both modules has been conducted through a customized real-time data acquisition system by (NI-DAQs). The proposed system is capable of determining allowable cruising speeds of tested vehicles at different steering radii to ensure safe boundaries against roll over and side-kidding.**

I. INTRODUCTION

Background

Vehicle Dynamics is the engineering subject that is interested in studying movements of vehicles, such as acceleration, braking and turning, which is a response to vehicle ride [1]. Vehicle dynamics measurements are important for vehicle design and development. The later research of vehicle dynamics concentrated on various working conditions and service performances under external excitation [2].

currently, the vehicle ride comfort and handing stability research have been widely inspected. The handling dynamics deals with the lateral dynamics or transverse dynamics of the vehicle, which mainly refer to vehicle handling stability, vehicle sideslip caused by tire lateral force, yawing and roll motion. The vehicle driving dynamics is divided into longitudinal dynamics and vertical dynamics, which includes driving, braking and ride comfort. The problem of driving slip and braking slip are solved by the study of vehicle longitudinal tire force, which can also improve driving and braking efficiency. The ride comfort focuses on vehicle vibration and pitch movement caused by vertical tire force.

Relevant works in literature

A brief overview on relevant works in literature is summarized in Table 1. Vehicle speed estimation using accelerometer and wheel speed measurement has been presented by Uchanski et. al in 2002. A van with a fifth wheel speed measuring device has been investigated by Chengh et. al. in 2014. Comparison of tractor ground speed measurement techniques has been given by Tomkins in 2019.

Table 1: Previous works in advanced vehicle dynamics evaluation system.

Application	Author	Year
Vehicle speed estimation using accelerometer and wheel speed measurement	Michael Uchanski [3]	2002
A van with a fifth wheel speed measuring device	Chengh [4]	2014
Comparison of tractor ground speed measurement techniques	FD Tomkins [5]	2019

II. MATHEMATICAL MODELING OF VEHICLE DYNAMICS

Improving vehicle performance need to resist more of internal and external resistance which control on vehicle stable and velocity safety so that we need to calculate the slip and skid ratio, coefficient of under steering and Ackerman steering geometry of steering angle.

The skid ratio can be calculated as follows

$$i_s = \left(1 - \frac{\omega * r_d}{V}\right) * 100\% \qquad (1)$$

$$i_s = \left(1 - \frac{r_d}{r_v}\right) * 100\% \qquad (2)$$

Slip ratio and longitudinal slip

$$S = \frac{V_{th} - V_a}{V_{TH}} = 1 - \frac{V_a}{V_{th}} \qquad (3)$$

Longitudinal slip of tire when a driving force is applied

$$Si = \left(1 - \frac{r_V}{r_d}\right) \times 100\% \qquad (4)$$

Where:
ω is the angular speed of the tire.
r_d is the radius of the free-rolling tire.
v is the translational speed of the tire centre.

Coefficient of under steering $\{K_{us}\}$ [1]

$$K_{us} = \left(\frac{W_f}{c_{\alpha f}} - \frac{W_r}{c_{\alpha r}}\right) \qquad \text{(rad) (5)}$$

Where:
w_f is the normal load on each of the front wheels.

w_r are the rear wheels under static conditions.

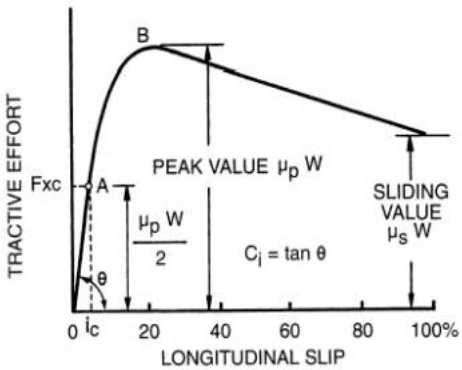

Fig. 1: Variation of tractive effort with longitudinal slip of a tire.

Ackerman steering geometry of steering angle of front outside and inner side wheels; δo, δi [1]

$$\delta_0 = \mathrm{Tan}^{-1}\frac{L}{R+\frac{B}{2}} \qquad (6)$$

$$\delta_i = \mathrm{Tan}^{-1}\frac{L}{R-\frac{B}{2}} \qquad (7)$$

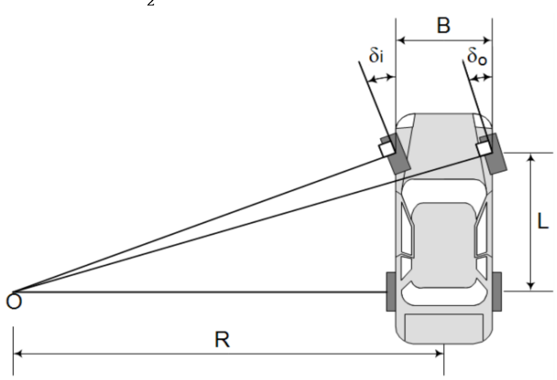

Fig. 2: Ackerman geometry of steering angle of front outside and inner side wheels.

For small angles values of δ up to 7 degrees, as are typical of most turning maneuvers, the arctangent of the angle is very nearly equal to the angle itself, in radians. At high speeds the radius of turn is much larger than the wheel-base of the vehicle. Small angles can then be assumed and the difference between steer angles on the outside and inside front wheels is negligible. [4].

Braking forces at front and rear

On rigid roads, neglecting f. [2]

$$R_{b_1} = \frac{G*\cos\alpha}{L}(l_2 + \phi * g_h) \qquad (8)$$

$$R_{b_2} = \frac{G*\cos\alpha}{L}(l_1 + \phi * g_h) \qquad (9)$$

$$P_{b_2} = R_{b_2} * \phi = \frac{G*\cos\alpha*\phi}{L}(l_1 * \phi * g_h) \qquad (10)$$

Where:

$\boldsymbol{p_{b_1}}$ **and** $\boldsymbol{p_{b_2}}$ are the braking forces at front and rear wheels respectively.

$\boldsymbol{R_{b_1}}$ **and** $\boldsymbol{R_{b_2}}$ are the dynamic reactions at front and rear wheels respectively.

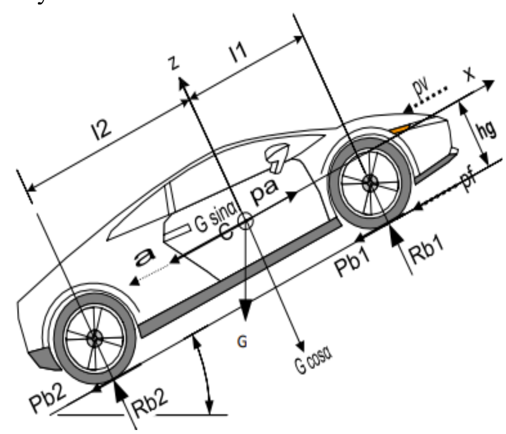

Fig. 3: Braking force distribution.

III. Design requirements of vehicle dynamics assessment system

General design and description:

The aim of our project is to develop an advanced system to evaluate the vehicle dynamics, this helps us to be able to judge the vehicle stability. This system will help us in choosing the vehicles that will serve in the Egyptian Armed Forces or to judge the stability of vehicle that Armed lately.

In our system we need to find 4 variables;

- vehicle actual velocity without slipping
- vehicle actual velocity with slipping
- vehicle actual turning radius time by time
- vehicle acceleration in X and Y directions

All this data will be used to achieve the three tests of handling then take the results to the processing unit to analyze it.

System main component

The proposed system consists of following components:

- 5th wheel to measure the actual velocity without slipping
- encoder sensor to measure the actual velocity with slipping
- radius measuring tool
- accelerometer
- C-Daq (compact data acquisition card)

IV. Measurement of vehicle Turning radius

In the past we were using a GPS device to determine the vehicle position (radius) but this was a complex process And not accurate so we used a simple gear box with gear ratio 5:1, in the small gear there is a pulley with a robe, the big one has a potentiometer in the end of it as shown in Fig. 3 .

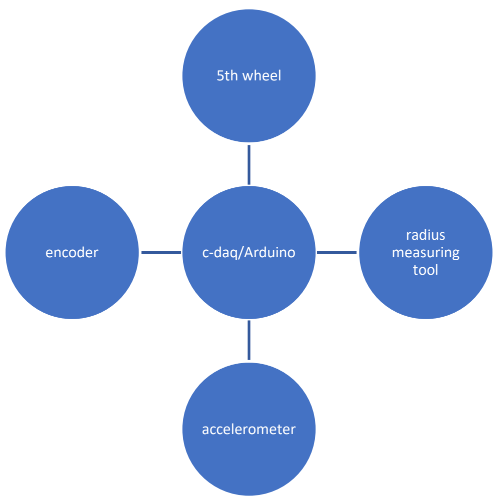

Fig. 4: illustrative chart shows the main component of the system.

The box is fixed in the vehicle and the robe is pulled and fixed in the centre of rotation, when the vehicle increasing It's velocity while taking a turn the centrifugal force pushes the vehicle outwards the rotary course so the robe is pulled making the pully to rotate the potentiometer , this send a signals to the Arduino.

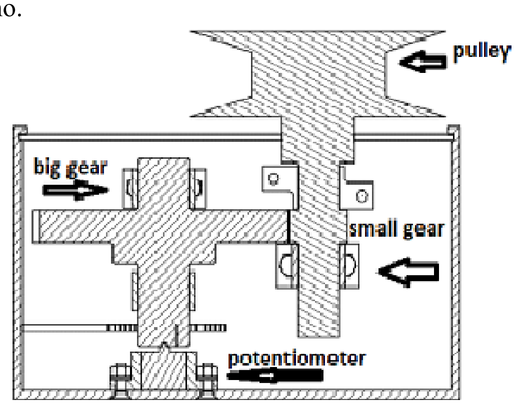

Fig. 5: section view in the custom of Radius measuring Tool.

Calculation of the roller disc radius:

From vehicle dynamic tests we get:
D = 5 m

For 10 turns potentiometer
D_0 = D/10 =0.5 m
Using spur gear with gear ratio =5
D_0 =0.5/5=0.1 m=10 cm
Where:
D is turning radius and D_0 is the roller radius

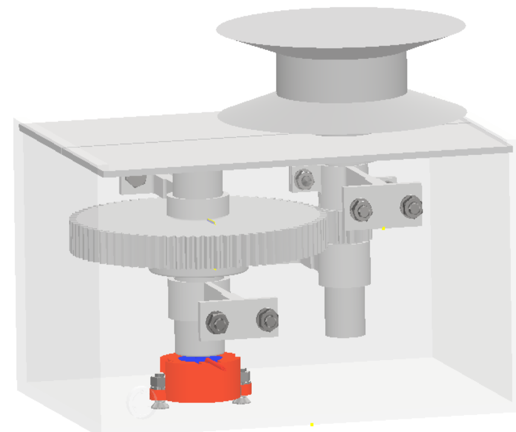

Fig. 6:3D view of Turning radius measurement

Manufacturing of the mechanism:
This mechanism is manufactured by 3D PRINTER as shown in Fig. 8.

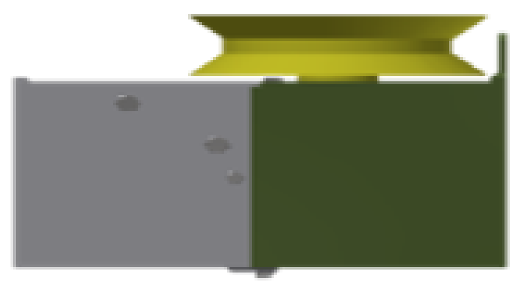

Fig. 8: final shape of the 3D Printed Radius measuring Tool**.**

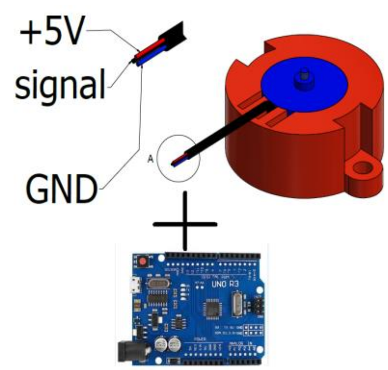

Fig. 9: Wiring of potentiometer with Arduino

LabVIEW software with the Arduino has been utilized to show the results of the potentiometer and make user interface. The main code was written in the Arduino ide then some modifications was added by the LabVIEW. We needed some programs to connect the Arduino with the lab view like visa ide to identify the Arduino COM, the rate and pin in use. installing the (LabVIEW interface for Arduino) from the Vi Package manager.

V. Measurement of Slip and skid ratio

principle of operation

The system consist of two- section.
Section 1:
Measuring of vehicle actual speed without slip and skid ratio used a device fifth wheel.
Section 2:
Measuring of vehicle actual speed with slip and skid ratio used a speed sensor fixed on wheel hub of the vehicle.
A bicycle like wheel is mounted from a spring-loaded arm on block of the car. Because the wheel does not slip, and because it is radius is well-know, the velocity can be calculated.

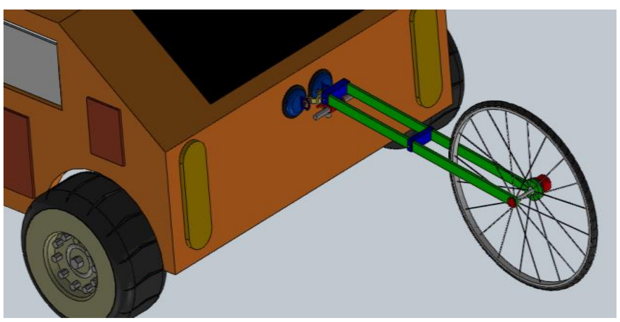

Fig. 10:fixation of fifth wheel with vehicle

Measuring of vehicle speed, braking time and distance covered (Peiseler wheel).

It's a main device to measuring actual speed so that we should know the all forces effect on fifth wheel to measure the right actual speed and the main forces effective it's traction force and braking force.
Traction force:
Tractive effort = Min. (force transmitted from engine, adhesion force).

$$P_{t\,\max,min} = \text{Min}\left(\frac{M_e * i_t * \eta_t}{r_d}, G_w \phi\right) = G_w \phi \quad (11)$$

To determine the road adhesion coefficient of traction-slip characteristics using Fifth wheel and Pulse generator to measure the actual rear wheel revolutions, then determine the actual vehicle speed of towed vehicle [2].

$$V_a = \frac{\pi * n_a * r}{30} \quad (12)$$

Braking force: [1]

$$P_{b_1} \leq R_{b_1} * \phi \quad (13)$$

$$P_{b_2} \leq R_{b_2} * \phi \quad (14)$$

$$P_{b_1} + P_{b_2} = p_b \quad (15)$$

Where:
$\boldsymbol{p_{b_1}}$ and $\boldsymbol{p_{b_2}}$ are the braking forces at front and rear wheels respectively.
$\boldsymbol{R_{b_1}}$ **and** $\boldsymbol{R_{b_2}}$ are the dynamic reactions at front and rear wheels respectively.
ϕ is the coefficient of adhesion due to friction.

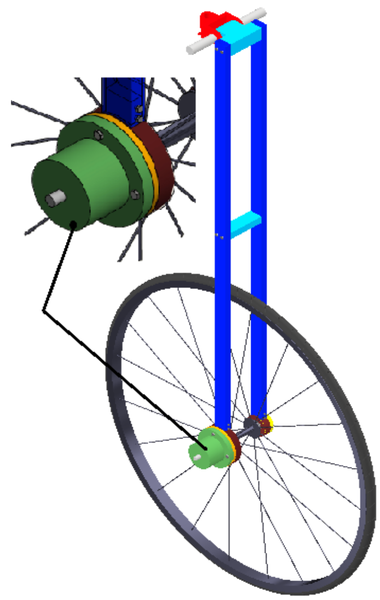

Fig. 11: peiseler wheel

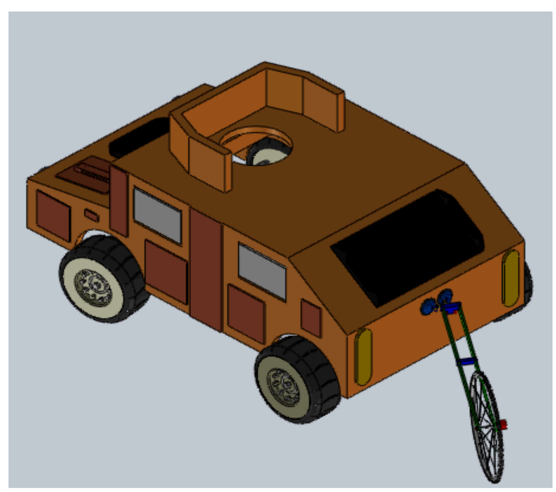

Fig. 12: ability of fifth wheel to tilt about Z-axis

Fifth wheel is a tool fixed in the vehicle to allow us to measure the actual vehicle velocity without slipping, this tool must have some requirements;
1-light weight
2-ability to rotate about Z axis (YAW)
3-ability to rotate about Y axis (pitch)
4-easy fixation method (suction cups)
5-ability to be fixed in variable vehicles with different shapes
6-sensor place should be protected

The fifth wheel is simply a bicycle tire fixed on the vehicle, this tire is connected with an encoder sensor so when the tire rotates with the vehicle encoder start to send number of pulses, these pulses represent number of revolutions and these revolutions converted to speed.

Type of fixation

a. fixation with suction cups

The idea of using the suction cups comes to be able to fix the 5th wheel in the modern cars that usually have a round surfaces, the cups that exists in the market is single, double or treble ,but in our application we use 2 single cups with rotating joints to be able to be fixed in a hard round surfaces and take the shape of the surface.

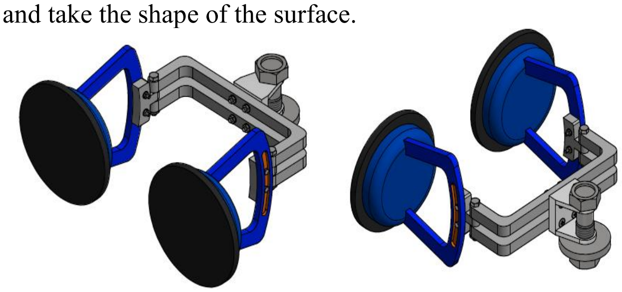

Fig. 14: Fixation of suction cups

b. fixation with magnets (cylindrical magnets with D=20, t=1.5mm).

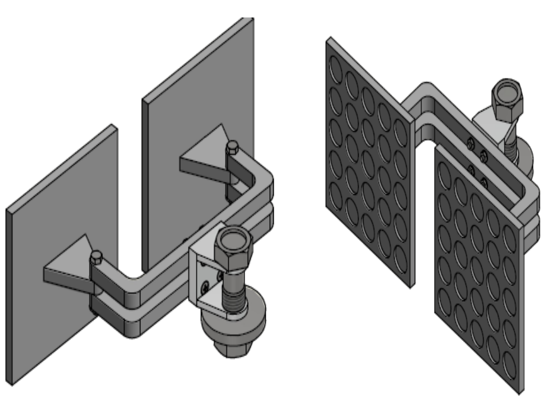

Fig. 15: magnetic fixation with cylindrical magnets

In order to have different ways of fixation we use 2 plates have the negative shape of a small magnets (25 cavities in each plate) this plate have the same idea of the rotating joints to be able to take the shape of the surfaces.

*c. fixation with magnets (rectangular magnets 50*10*=3mm)*

This way is used when the fixation place is too small to use the other 2 ways due to the small dimension of the magnets and it is small number (4 pieces).

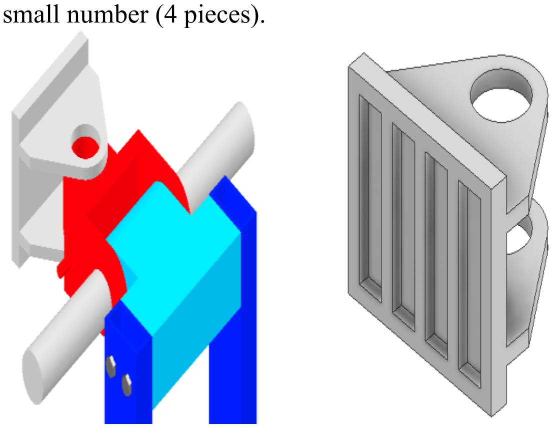

Fig. 16: magnetic fixation with rectangular magnets.

VI. MECHANICAL DESIGN

This design allows us to connect the encoder directly with the wheel axle without any mechanical linkage like in other models, this makes the design simpler and easier in maintenance and give us the ability to protect the encoder from the shocks.

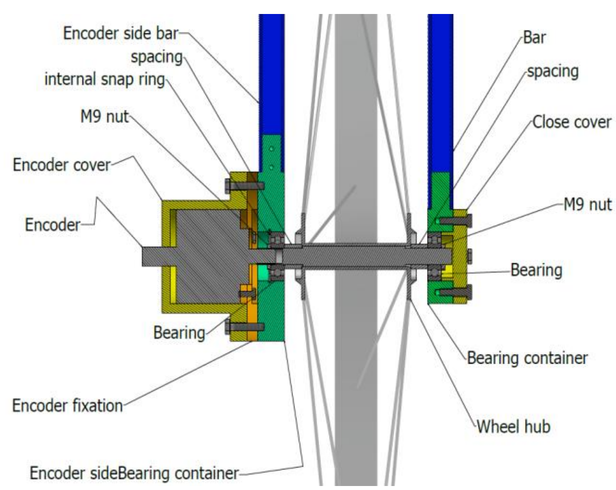

Fig. 17: Section of bearing and encoder fixation.

We removed the standard wheel axle and bearing with a new bearing and new designed axle to cover our requirements, like the design shows we used spacing rings to make a small gab between the wheel hub and the bars to prevent the friction between them, this fix the inner race of the bearing from one side, in the other side the shoulder of the close cover fix the outer race of the bearing ,this in the free side of the 5th wheel (no encoder side), in the other side (encoder side) we used an internal snap ring to fix the outer race of the bearing , and finally the 2 M9 nuts that collect all this components together in each side.

The fixation of the encoder is simply done by using a cylindrical plate between the encoder cover and the bearing container to hold the encoder in its place by mean of 3 bolts.

Stress analysis:

Table 2: Bar physical properties

Material	Aluminium 6061
Density	0.0975437 lb mass/in^3
Mass	0.972244 lb mass
Area	163998 mm^2
Volume	163334 mm^3
Center of Gravity	x=15 mm y=501.413 mm z=-7.50001 mm

Table 3: Material property

Name	Aluminium 6061	
General	Mass Density	0.0975437 lb mass/in^3
	Yield Strength	39885.4 psi
	Ultimate Tensile Strength	44961.7 psi
Stress	Young's Modulus	9993.1 ksi
	Poisson's Ratio	0.33 ul
	Shear Modulus	3756.8 ksi
Part Name(s)	bar.ipt	

Table 4: Force exerted in the beam

Load Type	Force
Magnitude	22.481 lb force
Vector X	-22.481 lb force
Vector Y	0.000 lb force
Vector Z	0.000 lb force

Fig. 18 shows the different displacement on direction (X, Y and Z).

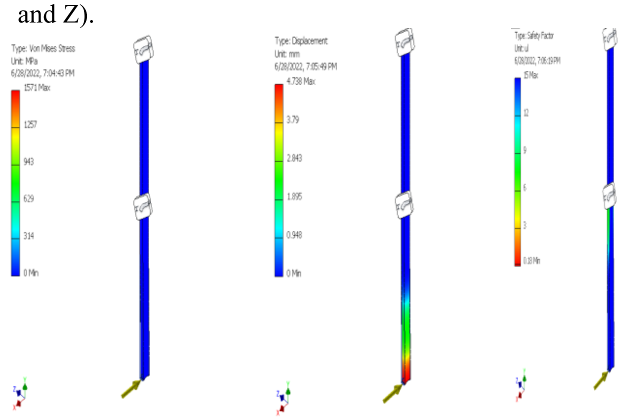

Fig. 18: Different displacement

The fixation marks in the previous Fig. shows the place of fixation in the bar, the bar consists of 4 holes from which the bar is fixed. The first part shows the von mises stress range along the bar, the second one shows the overall displacement that happens and the last one is the safety factor along the different bar sections.

VII. MEASUREMENT OF ROLL-PITCH-AND YAW

We use a sensor to obtain an accurate value of measurement.

a) Speed sensors

It's a sensor like the one is used in the 5th wheel but this time is directly fixed in the wheel hub of the vehicle to measure the velocity with slipping as shown in Fig. 11.

Fig. 19: Speed sensor

The MT pulse generator was specially developed for measuring the wheel speed of vehicles. It delivers 25 – 5000 pulses/revolution (others on request) and can be replaced uncomplicated. The calculation of wheel speed, distance, acceleration, and vehicle speed is possible. Applications are e.g. speed measurements, wheel slip measurements and ABS / ESP tests.

b) Accelerometer

It's a sensor that used to measure the vehicle acceleration. we use 4 sensors, one in each vehicle corner. That will help us to measure the acceleration in the 2 directions X any Y.

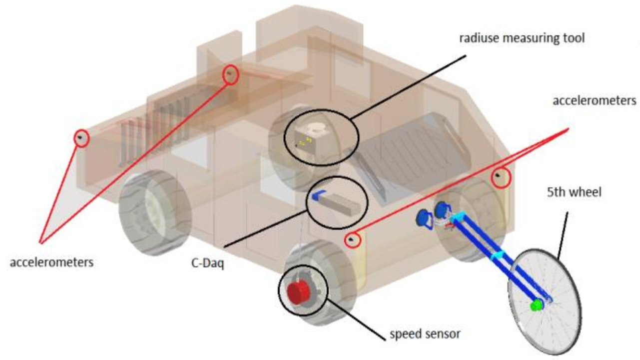

Fig. 20: all component system and all sensor.

VIII. Data Acquisition System (DAQ).

PURPOSE

In our test, we use a compatriot for data acquisition as it provides a high-performance capability, sensors specific conditioned I/O, and a closely integrated software tool chain that make them ideal for processing, industrial control and monitoring.

Fig. 21: CompactRio

USED MODULES

There are different modules available on the market to work with a variety of different types of sensor. The DAQ modules can be very specific in their nature or some can be quite generalised so that the software can be used to conFig. them in the way that is required. The main types of measurement include: Voltage: the analog input managed to give output voltage which is one of most common modules.

We used (NI 3229 simultaneous analog input) modules to measure the signals from the encoder sensor and potentiometer by giving output value of voltage with knowledge of encoder information (pulses per revolution) we can set up programme on lap view to transfer the output voltage value to revelations value.

Wiring

By using the (NI 3229 simultaneous analog input) modules, the 9137NI DAQ card, rotary encoder E50S8-250-S-I-24 and potentiometer we make a proper connection of wires to measure the signals. The encoder has 5 wires (4 for positive, 1 for ground and 3 for signals) we connect the positive and the ground of the encoder with external power source of 13.6 volt. one of the signal wires to the module in the DAQ. by rotating the sensor, the signals changes. Potentiometer has 3 wires (1 for positive, 4 for ground and the last for signal). we used the sensor wire connection in encoder but with low external battery source 5 volt.

PROGRAM

We use LABVIEW software for applying CompactRio code, LabVIEW simulation environment provides an easy solution for this problem. The Control Design and Simulation Module of LABVIEW can be used with the data acquisition, GPIB, CAN, and FPGA (field-programmable gate array) hardware platforms of National Instruments.

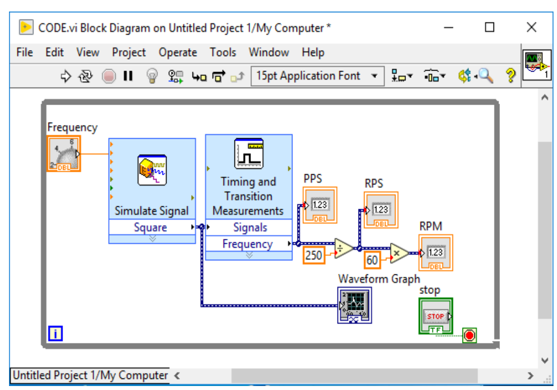

Fig. 22: block diagram from lap view

We use sensors fastened on the vehicle to measure various parameters to ensure and confirm our readings as the sensors converts a physical phenomenon into a measurable analogue voltage (or sometimes a digital signal) converted into a human readable display or transmitted for reading and further processing.

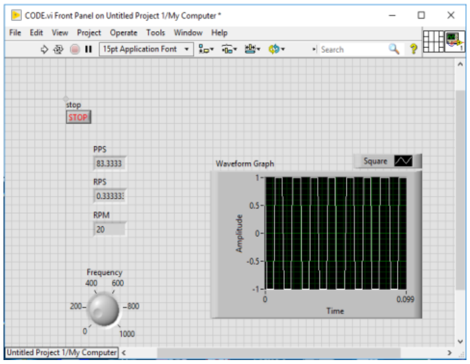

Fig. 73: Front panel from lap view

IX. CONCLUSION AND FUTURE WORK

This work proposes an advanced vehicle dynamics evaluation and assessment system the involves the multiple sub-modules integrated in a single house-made platform. The proposed system comprises individual measurement of vehicle turning radius, slip and skid ratio, roll, pitch, and yaw rates, connected via a data acquisition system using NI data acquisition system. The conducted work involves the mechanical design of a fifth wheel mechanism and respective sensors to ensure accurate measurement of vehicle speed. Assembly and testing of the proposed system has been successfully carried out. Next steps include real field experiments to yield accurate attributes of vehicle dynamics and stability.

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