Design and Control of a Mechatronic Vehicle Dynamics Simulator Pitch and Roll Dynamics

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***Abstract*—A pitch-roll simulator platform has been designed and built for the validation and analysis of control systems algorithms in vehicle dynamics. The system consists of a real time industrial computer, and an instrumented three degrees of freedom platform. A motion cueing algorithm has the function of translating the movement of a vehicle to the platform, moving three rotary actuators, while satisfying all boundaries. A set of encoders feeds back the actuators angle. Two control strategies has been designed and tested through simulation and experiments. Results show that a simple control scheme allows the driver assess the pitch and roll, however, a better control scheme is needed for vehicle design purposes.**

***Keywords*–vehicle dynamics, simulation, platform, simulation, motion cueing**

I. Introduction

Driving simulators are found in several areas of application: entertainment, research and advanced training. These simulators deliver motion cues to the driver. The fidelity of the cues depends on the degrees of freedom. These systems are called also motion cueing systems. Motion cueing systems in driving simulators join the physical motion of the simulated vehicle with the real-time image generation system. It allows the drivers to perceive and control their vehicle motion [1] as if he were inside the vehicle. Motion simulators have been a topic of great interest in last years [1]-[9]. The applications of interest are to test Advanced Driver Assistance Systems (*ADAS*), In-Vehicle Information Systems (*IVIS*), and the effects of noise and vibrations on driver performance [6].

The automotive industry in Mexico has a boom in manufacturing and investment [10]. However, important challenges remain for the future, such as the development of more research and development centers, local design and validation for automotive components [10][11]. Some efforts are being done between universities and automotive industry [12][13]. This research is under the goal of having better capabilities for the development of new technology in partnership between mexican universities and companies.

TABLE I. Nomenclature.

Variable	*Units*	*Description*
$\ddot{x}$	$\frac{m}{s^2}$	Longitudinal acceleration
$\ddot{y}$	$\frac{m}{s^2}$	Lateral acceleration
$\tilde{\theta}$		Washout pitch angle
$\tilde{\phi}$		Washout roll angle
$\hat{\theta}$		Estimated pitch angle
$\hat{\phi}$		Estimated roll angle
θ_d		Desired pitch angle
ϕ_d		Desired roll angle
u_θ	v	Command for θ_d
u_ϕ	v	Command for ϕ_d
$M_{1,\,2,\,3}$	-	Electric motor 1, 2 and 3
$c_{1,\,2,\,3}$	v	Step sequence from electric motor encoders
$u_{x,\,y,\,z}$	v	Output from gyroscope
$\omega_{M_1,\,M_2,\,M_3}$	$\frac{}{s}$	Mechanical angular speed
$a_{x,\,y,\,z}$	$\frac{m}{s^2}$	Measured angular speed by gyroscope axis
$p_{1,\,2,\,3}$	-	Generated pulses according to motor shaft, $M_{1,\,2,\,3}$

In this paper, a driving simulator of three degrees of freedom is presented and its control system for vehicle dynamics pitch and roll variables. The nomenclature used in the elaboration of this paper it is in Table I. The goal of this simulator is to validate *ADAS* including the biometrics systems and autonomous vehicle assessment, as well as the transportation of finish goods. The paper consists of VII sections. Key concepts are described in Section II. Section III describes vehicle dynamics simulator and the hardware platform. The proposed control algorithms are described in Section IV. Section V enumerates the process of design and validation of the control system. The results and discussion are shown in Section VI. Conclusion ends this paper in Section VII.

II. Literature review

The key parts of a motion cueing system are the driving simulator and the control algorithm.

Motion cueing allows the simulator driver to *feel* inside a vehicle in motion. The realism of simulation depends strongly on the fidelity of the motion platform and the motion perception by the human driver [3]. The human vestibular system located in head is found to be dominant in human motion sensation. It senses the rotational and linear motions, more details on [14]. Rendering vehicle motion cues in a driving simulator is possible within a small displacement envelope. Its physical validity is limited to the mid-frequency range, but its perceptual validity may be extended in the low frequencies by tilt coordination techniques [1].

A driving simulator typically consists of a seat, a vehicle dynamics model interacting with a driver through a steering wheel and pedals with haptic feedback, a sound feedback, a set of screens with a visual engine reproducing the vehicle dynamics results of the simulator's driver manoeuvre, and, in some cases, translational and rotational actuators for the motion cueing system. The driving simulators are mainly classified by the fidelity of the simulation level and its application. The simulation fidelity cllassification corresponds to low-level, mid-level and high-level fidelity. At a low-level simulator, the driver sits in a car seat, which is fixed to the ground. The driver looks at a screen, which is fixed to the ground too. The screen is designed such that the view angle is as large as possible. The driver manipulates a set of driving controls such accelerating, braking and steering wheel in order to receive visual cues corresponding to the actual driving situation. In some types of applications, it is desirable to provide a motion and haptic restitution to improve the simulation fidelity. Therefore, the driving simulators use a moving platform to restitute, in a limited and constrained workspace, a sufficient sensation of movement as closely as the one sensed in a real vehicle [1][2][15][16]. Low level simulators can include longitudinal axis motion in one axis while the mid and high level simulators include more motion axis, a detailed state of the art can be found in [9]. The main applications are Entertainment (*E*), Training (*T*) and Research (*R*). Table II shows a complementary summary.

TABLE II. DRIVING SIMULATORS COMPLEXITY, THE OBJECTIVES OF SIMULATION CAN BE ENTERTAINMENT (*E*), TRAINING (*T*), AND RESEARCH (*T*).

Level	*Components*	*Feedback*	*Degrees of freedom*	*Objective*
Low	Large screens, steering wheel, pedals, one linear actuator	Force Sound Longitudinal motion	0, 1 (x, y, or z axis)	E T
Mid	plus at least one linear actuator	Force Sound Longitudinal and rotational motions	2 or 3	E T R
High	plus at least four more linear actuator	Same as mid	6	T Advanced research

A three Degree of Freedom system is designed to have a rotation about the x, y, and z axes and it allows to simulate main vehicle dynamics variables. This system causes the sensation of acceleration through rotation around these three axes, maintaining a tilt angle (typically to a 45 degrees angle) and it uses the gravity. The tilt limitation in this system prevents to create an acceleration sensation over 0.707gs [9]. This research is focused in a *3DoF* driving simulator.

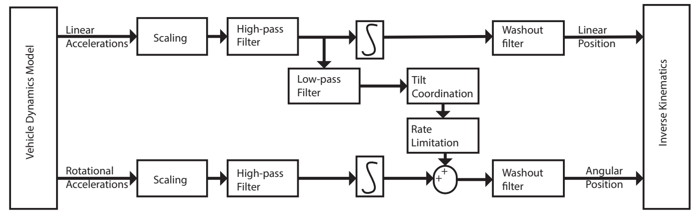


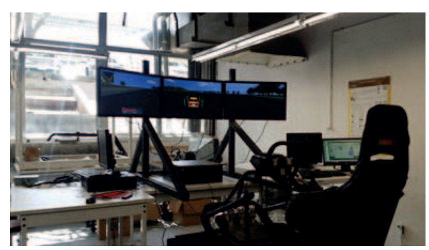
Figure 1. Washout filtering approach for motion cueing systems.

The control algorithm for motion cueing systems is called washout filtering with classical, optimal and predictive approaches [1][14], proportional-integral-derivative washout filtering [2], and optimal and model predictive control [4][8] among others. However, the classical washout filtering is the most common because of it is implementation simplicity and fair simulation results [9], Figure 1. The classical washout filtering consists of a combination of high-pass and low-pass filters. Commonly, the parameters of these filters are empirically determined. Its inputs are vehicle-specific longitudinal accelerations and angular rate and expressed in vehicle-body-fixed frame. Acceleration (angular rate) is high-pass filtered, and yields the simulator translations (rotations). To simulate the motion platform tilt, a tilt coordination algorithm supplies the low-frequency component of acceleration for rotation calculation.

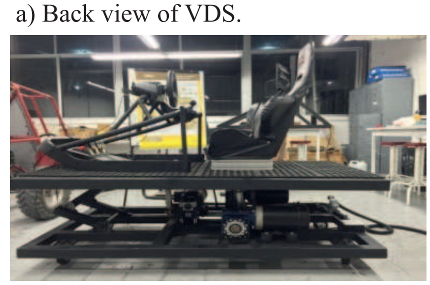
III. VEHICLE DYNAMICS SIMULATOR

The *Vehicle Dynamics Simulator (VDS)* consists of a real time vehicle dynamics model system interacting with a driver through a steering wheel, acceleration, brake and clutch pedals, speed control, a set of three flat screens and a set of speakers.

The real time vehicle dynamics model simulation system consists of the *Dynacar* system [17], which is a low level driving simulator, and a three Degrees of Freedom (*3DoF*) platform, Figure 2.



a) Back view of VDS.



a) Lateral view of VDS.

Figure 2. Vehicle dynamics simulator in Automotive Engineering Lab, Universidad de Monterrey.

The full scheme of the *VDS* shows all the components and describes the interactions between the *Dynacar* and the *3DoF* platform, Figure 3.

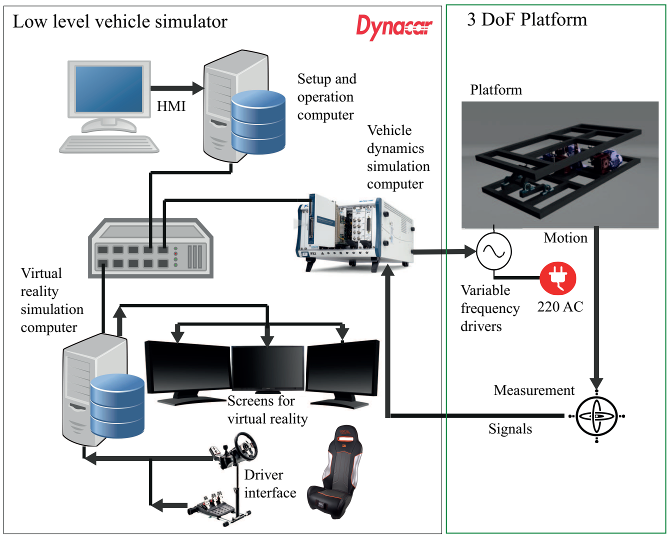


Figure 3. Experimental system: hardware in vehicle dynamics simulator.

The *3DoF* platform consists of two mechanical frameworks (lower an upper base) separated by an active suspension. The upper base holds the driver cabin, and the lower base holds three crank shaft mechanisms conforming the active suspension as well as a vertical sliding guide, Figure 4.

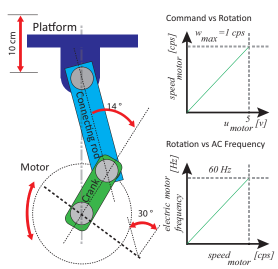


Figure 4. Crank shaft mechanism and input-output signals.

A set of actuators and sensors acts and measures the platform dynamics, Figure 5. Each crankshaft mechanism is governed by an actuator and a sensor. This consists of an alternate current induction electric motor and its electric drive. The motor shaft holds an absolute encoder allowing the angle measurement of the crank. The upper base has one sensor: a gyroscope. It is located under the driver seat. A Real Time (*RT*) computer (same as for the *Dynacar* system) reads the gyroscope and encoder signals. A set of reference signals is delivered from the selected vehicle dynamics model and compared with the measurements. The control algorithm computes in the *RT* computer the commands for each electric drive.

IV. *VDS* CONTROL ALGORITHMS

The *VDS* control system consists of: vehicle dynamics model (Dynacar), control algorithm, signal conditioning, power driving and platform. The control system considers two control algorithm modes: (a) conditional control, and (b) washout filtering with feedback, Figure 6.

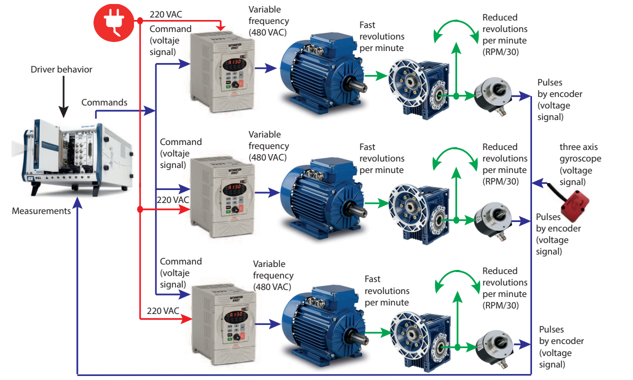


Figure 5. Actuators and sensors for platform.

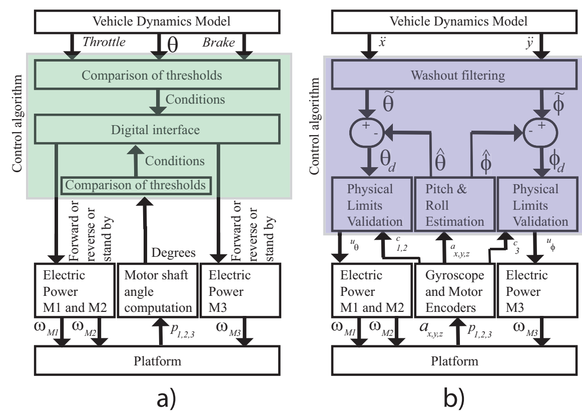


Figure 6. Control system proposal: a) physical-limits-based, b) washout filters.

The *conditional control* is a physical-limits-based control using a continuous comparison of signals with a priori defined thresholds. The Revolution Per Minute (*RPM*) of each *AC* motor is constant. The signal conditioning consists of: a) processing of sensor signals in order to obtain crankshaft angles, b) acquisition from *Dynacar* of roll and proportional values of throttle and brake pedals, and c) digital outputs activation according to controller output. The controller inputs are roll, proportional brake, proportional throttle, and degrees of each motor shaft. The controller outputs are sixteen digital outputs whose control three motor conditions in the *AC* drive are: move forward, move reverse and stand by. When the driver accelerates/brakes the vehicle, the front motor ups/down the platform. The control system emulates proportionally the pitch motion. Regarding to the roll platform emulation, when the simulated roll (reference) from *Dynacar* is between a priori interval, the platform moves in a direction according to the sign of the reference until a threshold is reached. Then the platform stops and the control system waits until the change of sign in the reference signal. This sequence is repeated during all *VDS* driving operation. For a higher speed platform motion, the *RPM* in each motor must be set according to the driver assessment.

The *washout filtering with feedback control* consists of

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a physical limits validation including backslash exclusion, a classical washout filtering algorithm, Figure 1, an estimation algorithm of pitch and roll, and a proportional gain. The physical limits validation is continuous in each sample time, however the algorithm adds an offset to the controller output voltage in order to avoid the inertia under two system conditions: stand by and low speed of the motor. The controller computes the *RPM* of each *AC* motor and the sense of rotation around the zero angle. The signal conditioning consists of: a) processing of sensor signals in order to obtain crankshaft angles, b) acquisition from *Dynacar* of longitudinal and lateral accelerations, c) conversion from pulses to angle for each motor shaft, and d) conditioning of controller output in order to obtain the *AC* motor drive input voltage (proportional to the revolution per minute of the *AC* motor). The controller inputs are longitudinal and lateral accelerations from *Dynacar*, angular speeds for x, y, and z from gyroscope, and each motor shaft angle obtained from encoders. The outputs of the controller are three: voltage command for each *AC* motor drive. The command has a range with an offset. The magnitude of this signal indicates *RPM*s of the *AC* motor. Over the offset the voltage indicates forward direction, below the offset it indicates reverse direction. The control system emulates both movements: the pitch and the roll. The estimated pitch ($\hat{\theta}$) is subtracted from the simulated pitch (output of washout filtering, $\tilde{\theta}$) conforming a pitch error signal (θ_d). Then θ_d is validated through a physical limits algorithm and multiplied by a gain (P controller) and it becomes controller output u_θ as the command voltage to the *AC* motor drive. The same control sequence applies for roll control.

The power driving (using any control algorithm) converts the controller outputs in mechanical motion.

V. METHODOLOGY

The design and validation of the control system in the *VDS* consist of open loop and closed loop tests. The computation of parameters and the programming of the control algorithm are done with *Matlab*®. The methodology consists of:

A. Design of Experiments

The main goal is to define the frequency response of the platform from the manipulation variable to the pitch and roll motions in open loop. A set of experiments is applied to the platform in order to analyze the input-output relationship. There are two experiments: (a) driver test under random scenario, and (b) sinusoidal test for actuator characterization.

1) *The driver test under random scenario* consists of using the Dynacar system with an specific driver, track and vehicle in order to get the frequency response of the simulated roll and pitch of the given vehicle model. The experiment considers ten replicates. The peak value of the roll (ϕ_{max}) and pitch (θ_{max}) as well as the cut-off frequency $f_{cut\ off}$ for each one are the experiment outputs computed with the Fast Fourier Transform, Figure 7.
2) *The sinusoidal test for actuator characterization* explores the frequency response according to the bandwidth and magnitudes obtained from the first experiment. Each experiment consists of a sinusoidal excitation of the electric drive manipulation in order to observe the encoders and the pitch (roll) responses with a constant frequency and amplitude. The amplitude remains constant and at least five cycles are completed ending the experiment. Then the frequency is incremented and the experiment repeated. This *DoE* ends when the cut-off frequency is reached. The magnitude of roll and pitch at the given frequency of each experiment allows to build a pseudo-bode diagram. This *DoE* consists of a total of three replicates, Figure 8. The function of this experiment is to obtain the frequency response of the motor under controlled inputs in the operation domain according to the vehicle model. The control algorithms will take into account this information for its design and to consider these parameters for a safety operation.

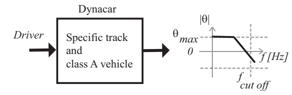

Figure 7. Input to output relationship in the driver test under random scenario.

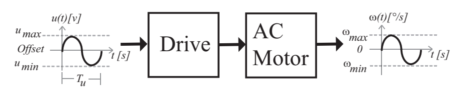

Figure 8. Input to output relationship for the *sinusoidal test for actuator characterization*.

B. Domain Operation and Design of Control Algorithms

The results of the *DoE* will allow to specify domain operation of the *VDS* as well as the parameters for the control algorithm. The domain operation consists of the electrical and mechanical thresholds of the *3DoF* platform . The electrical thresholds consider the maximum frequency and amplitude to be applied as input to the *AC* motor drive, The mechanical thresholds consist of the initial motor shaft positions as well as the angle intervals of safe motion for each crankshaft mechanism.

C. Control Algorithms Performance

The driver test under random scenario is repeated with the *VDS*: Dynacar and the *3DoF* platform simulating the pitch and roll vehicle motion. The goal is to evaluate the closed loop performance under the two control modes. The assessment of the driver and qualitative plots are the results of this test.

VI. RESULTS

The results of the control algorithm implementation are presented.

The driver test under random scenario shows the frequency domain to explore is 0.5-2.0 Hz according to the pitch and roll frequency content. This bandwidth has been obtained from data analysis from DynaCar simulated variables. The ranges of the simulated pitch and roll are $\tilde{\theta} = \{-5, 5\}$ degrees and $\tilde{\phi} = \{-8, 8\}$ degrees.

The sinusoidal test for actuator characterization shows a linear relation between shaft speed and drive command, Figure

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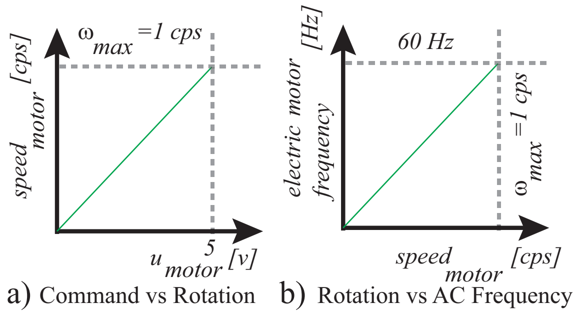

Figure 9. Experimental relation between *AC* motor drive command and shaft speed.

9. The maximum voltage command allows until 1 cycles per second for each motor shaft, Figure 9a. One *cps* is proportional to 60 Hz of *AC* voltage frequency in the *AC* drive. So, this is the maximum speed.

A comparison of the command voltage versus motor angular speed versus initial angle in the motor shaft shows non linearities on the speed regarding low command voltage, Figure 10. There is an offset in the voltage since the drive requires 5 V in order to stop motor. Any voltage over/below 5 V moves the motor shaft in the forward/reverse direction. Moreover, the motor do not respond in the range $5 \pm (0.5, 1)$

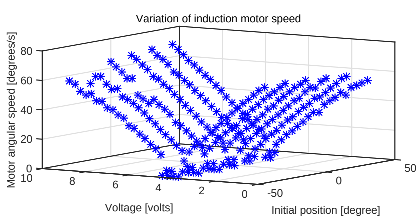

Figure 10. The command voltage of the *AC* drive versus shaft angle speed versus initial angle of the shaft.

V. When the command is over $\sim \pm 6$ V the motor starts the motion. Regarding to the initial angle position, the angular speed remains the same response, Figure 11.

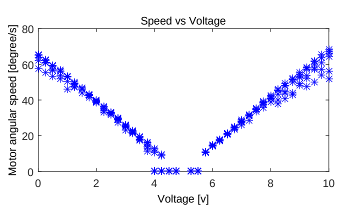

Figure 11. Command voltage versus shaft angular speed.

The design of the *conditional control* algorithm utilizes thresholds for roll from *Dynacar*, two absolute encoders, and throttle and brake pedals. Pitch and roll functional values are between defined parameters, greater than 0.8 or less than -0.8 in the case of the roll. In the case of the pitch, it was established the minimum of acceleration greater than 0.5 and the brake greater than 0.4. In the case of pitch, it has to be in the limit of 10 degrees and in the case of roll, the limit is between 0-5 degrees.

The design of the washout filtering with feedback control considers the design of low and high pass digital filters using *Matlab*, Figure 12. The output of this algorithm is the simulated variables pitch and roll. Classically these signals will be converted to voltage and then feed to the *AC* motor drives. However, this control system considers the feedback of *measured* pitch and roll. In order to translate the rotational

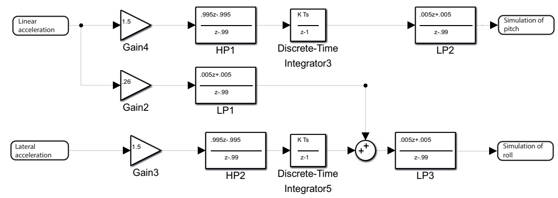

Figure 12. Washout filter algorithm: final parametrization.

angle of each motor shaft to the upper base plane, a set of trigonometric operations is done. Then the result is transformed to an estimation of pitch and roll signals based on the angular speeds delivered for gyroscope using the proposal from [18]. An offset of ± 0.7 is added to each controller output in order to avoid the dead zone of the command versus the shaft speed response. The proportional control gain multiplies the controller output. The complete scheme shows the computation blocks, Figure 11.

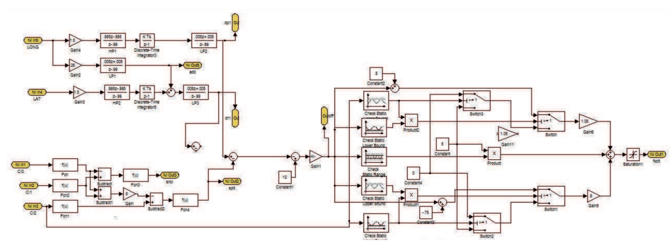

Figure 13. Design of control algorithm.

The results of closed loop test show the advantages of both control algorithms proposals, Figure 14.

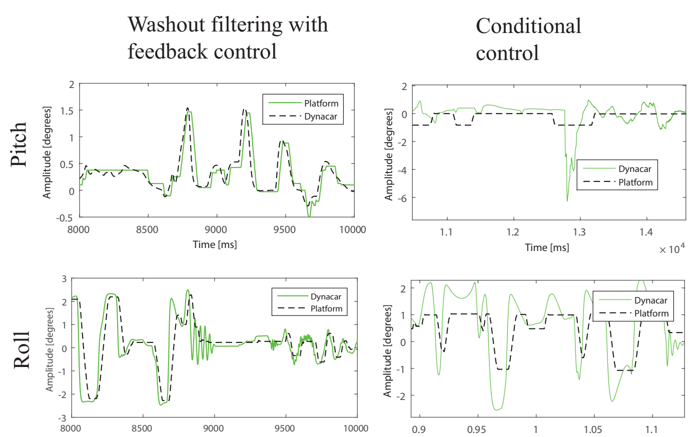

Figure 14. Pitch and roll comparison versus *Dynacar* simulation. The first and second row shows the pitch and roll variables. The columns defines the results for washout filtering and conditional control respectively.

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Both approaches move the platform in the right direction. The frequency response is limited by the frequency response of the AC motors and its manipulation. The conditional control performs an inertial control where the motion is felt by the user. However, the final application of this control can not be training due to the lack of fidelity of the pitch and roll platform simulation. The delay of this algorithm is enough to be notice by the user. However, its simplicity allows to tune the control system with thresholds under constant motor speed, see second column of Figure 14.

Regarding to the washout filtering with feedback control it can be seen a high fidelity in the platform motion regarding the simulation in Dynacar. The control is continuous and tracks the reference delivered by the washout filtering algorithm. The user experiences a real time motion synchronized with the visual engine of Dynacar. This experience is a added value that allows to use this control mode for training and for evaluation other vehicle systems in the full user experience. The delay is considerably small when compared with the one of the conditional control, see first column of Figure 14.

VII. CONCLUSION

The control system of a VDS with three degrees of freedom motion platform has been developed. It uses the positions of each motor shaft and the angular speeds of a gyroscope. The variables of interest are the pitch and roll and simulated in real time according to the DynaCar software. Two control schemes have been validated. Despite the configuration of hardware is commercially available by several companies, the control algorithms always are the challenge. This platform has a low cost in the hardware because the use of AC motors and it can be integrated to another vehicle model simulation using the proposed algorithms. The results show it is possible to use this AC motors for motion control in this application.

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