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Multi-CPU Real-Time Simulation of Vehicle Systems

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Abstract

In this paper the real-time simulation of an intelligent vehicle system is discussed. The simulation involves a hyrarchical control system paradigm that governs the control actions and characteristics of the various control subsystems in the car.

The objective is to define a real-time parallel structure that allows for a full-featured vehicle configuration to be simulated in a virtual reality without degradation of performance. A Multi-CPU system will be needed in order to maintain high fidelity.

To accomplish this objective, a high bandwidth local network is required and some flexible structure of interaction between the different dynamics and control system models.

Keywords Simulation, Real-Time, multi-CPU.

1 Introduction

The concept of an integrated intelligent vehicle control system encroaches all of the current automotive mobility control research. The safety and the character of the vehicle in the design process, define the implementation of the intelligent control structure which on its term defines the behavior of the subsystems.

The behavioral responses in terms of character, drivability and safety, can only be tested thoroughly by driving a concept vehicle on the test-track. Doing so under various driving conditions and in different traffic situations.

The effort that is presented in this paper, has resulted in a virtual prototype vehicle and a virtual test-track. This allows engineers to safely test their concept designs under any desired driving condition.

The challenge in the development of this system is to guarantee robustness, stability, accuracy and real-time performance when multiple subsystems interact with the vehicle dynamics simulation.

2 Implementation

An 18 degrees of freedom model for a vehicle has been developed at Oakland University [4]. The model can be considered as a black box process with inputs (brake force, throttle angle, steering position and ground surface) and outputs (position, rotation, wheel spin and -angle, and suspension lengths). The dynamics model has been implemented on a digital signal processing unit that is connected through a network bus to the rest of the simulation system. The peripherals that are needed for the input to the model are interfaced to the DSP system as well.

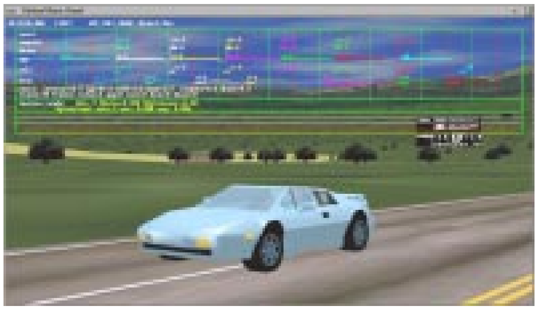

Figure 1: Screen shot of the Virtual Realistic animation of the vehicle dynamics simulation.

The simulation has been setup to provide a full-immersive man-machine interface with the vehicle system, in the form of a driver-console, mounted on a motion table, as can be seen in Figure 4. The visual output of the simulator is a stereoscopic representation of the scenery, as can be seen through the windshield. However, for research purposes, the simulator also provides real-time stereoscopic camera views around the vehicle, during simulation.

An SGI RE-II is used as the animation platform. A virtual environment of 20 miles of country road and a village have been designed in a geometry model. A digital model of a Lotus Esprit is used to represent the geometrical mockup of the simulated vehicle. An example of the graphical output of the animation is drawn in Figure 1.

The DSP serves as the basic foundation of the vehicle platform dynamics simulation. It is possible for other other CPU's that are connected to the bus, to attach to the simulation process as to add advanced features and control subsystems to the virtual vehicle. Such as cruise control, anti-lock braking, active suspension, traction control, ESP and so forth. The hardware configuration for the multi-CPU simulation setup is graphically rep-

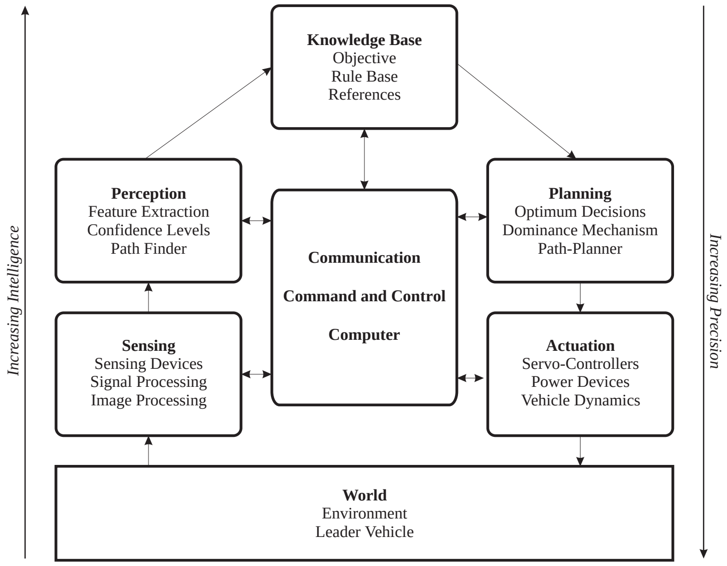

Figure 2: The generalized structure for an intelligent control system paradigm.

resented in the diagram in Figure 3.

We wish to design one global architecture as a top-down hierarchical intelligent control structure that incorporates the controls for all vehicle control subsystems. The general paradigm for a hierarchical intelligent control system is shown in Figure 2. The paradigm was defined before by Meystal in his talk on Intelligent Controls [2].

3 Vehicle Modeling

The fundamental vehicle dynamic relations have been formulated in [4]. The physical relations that make up for the model can be described in a state-space representation. In a deviation of the standard state space modeling technique, where states are single valued, we now let the states represent 3-dimensional vectors with respect to the x, y and z axis. The reference frames will not necessarily be consistent.

3.1 Body Dynamics

Take for example the following simplified diagram for the translational dynamics. The collected forces, acting on the CG of the body, cause an acceleration $\vec{a}^V$ on the chassis of the vehicle.

$$\xrightarrow{\sum \boldsymbol{F}_i^V} \boxed{\frac{1}{M_{F_i}}} \xrightarrow{\vec{\boldsymbol{a}}^V} \boxed{\frac{1}{s}} \xrightarrow{\vec{\boldsymbol{\nu}}^V} \boxed{\boldsymbol{M}_N^V} \xrightarrow{\vec{\boldsymbol{\nu}}^N} \boxed{\frac{1}{s}} \xrightarrow{\vec{\boldsymbol{x}}^N}$$

where $\sum \boldsymbol{F}_i^V$ is the collection of forces in the vehicle coordinate frame that contribute to the translational acceleration, and M_{F_i} is the mass that $\boldsymbol{F}_i$ applies to.

The indication ^{V} denotes that $\vec{a}$ is the acceleration with respect to the vehicle coordinate frame[1] and ^{N} for the earth reference frame.

Similar for the rotational dynamics,

$$\xrightarrow{\sum \boldsymbol{T}_i^V} \boxed{\frac{1}{I_{T_i}}} \xrightarrow{\dot{\vec{\boldsymbol{\omega}}}^V} \boxed{\frac{1}{s}} \xrightarrow{\vec{\boldsymbol{\omega}}^V} \boxed{\boldsymbol{M}_N^V} \xrightarrow{\dot{\vec{\boldsymbol{\theta}}}^N} \boxed{\frac{1}{s}} \xrightarrow{\vec{\boldsymbol{\theta}}^N}$$

where $\sum \boldsymbol{T}_i^V$ is the collection of torques that contribute to the angular acceleration, and I_{T_i} is the inertia that $\boldsymbol{T}_i$ applies to.

The forces $\boldsymbol{F}_i$ result from suspension dynamics, tire-ground slip, aero dynamics and the mechanical antiroll construction. The torques originate from the same forces, but are cross-multiplied with the vector $\vec{\alpha}$ that points from the CG to where the force applies. For example, the torques on the body caused by tire slip are given by

$$\vec{\boldsymbol{T}}^V_{slip,i} = \vec{\boldsymbol{F}}^V_i \times \vec{\alpha}^V_i \quad i = 1 \cdots 4. \tag{1}$$

3.2 Additional dynamics

Next to the body translational and rotational models, the vehicle dynamics model incorporate dynamic relations for wheel spin, tire deflection and suspension.

3.3 Dynamic inputs

Three user-inputs are effective to the vehicle model. The steering wheel applies directly to the torque in Eq.1. The slip vector $\vec{\boldsymbol{F}}^V$ for one of the steered wheels depends on the relative velocity between the tire and the ground as described in [1]. The steering angle will redirect this force vector.

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[1] The vehicle coordinate frame is defined with $\vec{x}$ pointing in longitudinal forward direction, $\vec{y}$ lateral left and $\vec{z}$ vertical up.

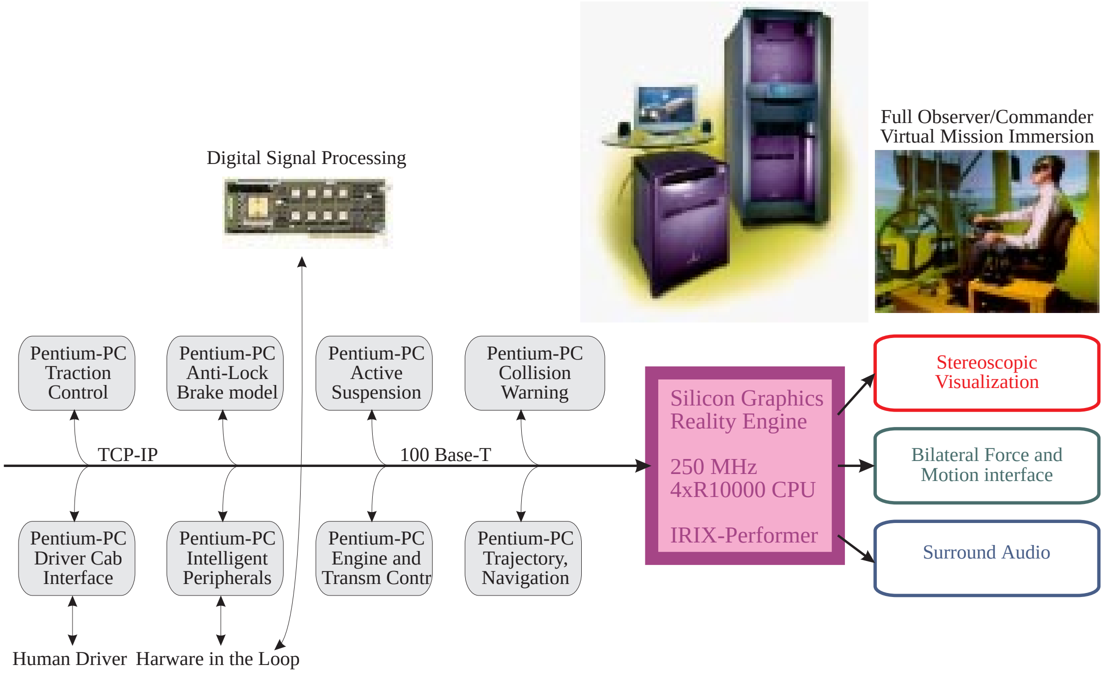


Figure 3: Hardware Configuration for the multi-CPU simulation.

The throttle angle relates via the engine and the transmission models (implemented as lookup tables) directly to the wheel spin dynamics. So does the brake force, through the brake actuator model. The wheel spin on its turn will influence the force in Eq.1.

3.4 Global Vehicle Model

With the above described dynamic relations for the vehicle model, the system can be described with a state space representation as

$$\begin{bmatrix} \vec{a}^N \\ \vec{\nu}^V \\ \dot{\vec{\omega}}^V \\ \vec{\omega}^V \\ \dot{\lambda}_i \\ \dot{\omega}_i \end{bmatrix} = \begin{bmatrix} 1 & & & & & \\ & M & & & & \\ & & 1 & & & \\ & & & M & & \\ & & & & 1 & \\ & & & & & 1 \end{bmatrix} \begin{bmatrix} \vec{\nu}^V \\ \vec{x}^N \\ \vec{\omega}^V \\ \vec{\theta}^N \\ \lambda_i \\ \omega_i \end{bmatrix}$$

$$+ \begin{bmatrix} \sum_i \frac{1}{M}(\boldsymbol{F}^V_{slip,i} + \boldsymbol{F}^V_{susp,i}) \\ 0 \\ \sum_i \frac{1}{M}(\boldsymbol{F}^V_{slip,i} \times \alpha_i + \boldsymbol{F}^V_{susp,i} \times \beta_i) \\ 0 \\ \Delta\beta_i - CG - G_{x,y} \\ \mathcal{F}(\alpha_{throttle}) \end{bmatrix}$$

in which β_i is the location of the suspension anchor at the i$^{\text{th}}$ wheel, $\mathcal{F}(\alpha_{throttle})$ is the engine and transmission model, and $G_{x,y}$ is the world surface altitude and gradient at x and y.

4 Asynch Parallel Setup

With the simplified vehicle dynamics above, a network structure has been setup, so that additional control laws can be incorporated. Therefore the system states, are accessible by every other processing unit on the bus.

Each of the additional control sub-systems is assumed to effectively change the elements in the system matrices, based on the state values. The sub-systems can either add or replace elements in the control matrix.

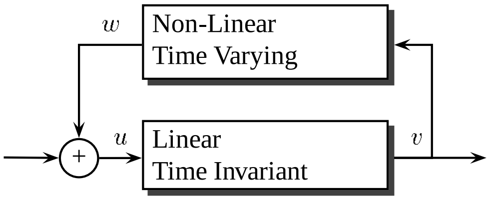
Generally there will be no conflict between control sub-systems, since for example, ABS and traction control are exclusive, and active suspension applies to different elements in the control matrix.

5 System Stability

The vehicle dynamic behavior now is described in state space representation. However, the states are vectors and the matrices now contain non-linear elements. Yet, it is desirable to study the vehicle stability with respect to certain state values.

In order to apply linear stability theory, we need to separate the model into a linear nominal system, fed back with the non-linear contributions. This will lead to the following general feedback system.

Figure 4: The user interface is implemented as a full driver cabin.



In order for the above system to be stable, with respect to the output error, we can find application for Popov's hyperstability theorem [**?**], which says that the above system is asymptotically stable if

1. the linear time-invariant feedforward block is SISO, it must be *strictly positive real*, and
2. $\eta(0,t_1) = \int_0^{t_1} \underline{v}^T \underline{w}\, \delta t \; \geq -\gamma_0^2$

For the linear feedforward system to be positive real, it must

- $H(s)$ is real for real s
- $\Re\{\text{poles}(H(s))\} < 0$
- $\Re\{H(j\omega)\} > 0, \; -\infty < \omega < \infty$

6 Conclusion

The approach described in this paper presents a general method for incorporating multiple control sub-systems into one dynamics model. This allows us to study a full-featured vehicle on is characteristics, stability and performance.

Furthermore, by changing the elements in the control matrices, the multi-CPU setup does not need to be synchronized. The characteristic matrix becomes non-linear and time-varying, but does not depend on integration step-size.

The presented configuration has shown to be successfull and very applicable to real-time simulation. The research is still in progress, and we like to thank ITT-Automotive and the National Automotive Center (NAC) at TACOM for their support.

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