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A Hardware-in-the-Loop Facility for Integrated Vehicle Dynamics Control System Design and Validation

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Abstract: Due to the increased number and the complexity of the embedded systems in today's vehicle, there is ever increasing pressure to reduce the development cost and time to market of such systems. In recent years, Model based Development (MBD) is becoming a main stream in the development of automotive embedded systems, and Hardware-in-the-Loop (HiL) testing is one of the key steps toward the implementation of MBD approach. This paper presents the recent HiL facility that has been developed at Cranfield University. The HiL setup includes real steering and brake smart actuator, high fidelity validated vehicle model, complete rapid control prototyping tool chain, and driver-in-the-loop capability. The applications of HiL setup are including but not limited to: smart actuators system identification; rapid control development and early validation of standalone and/or integrated vehicle dynamics control systems. Furthermore, the facility can be employed for investigation on driver-vehicle interaction at the presence of standalone active steering and/or brake systems as well as various Advanced Driver Assist Systems (ADAS), such as lane keeping or adaptive cruise control systems. The capability of the HiL facility for validation of a several newly developed vehicle dynamics control systems is presented.

Keywords: Automotive Control, Integrated Vehicle Dynamics Control Systems, Rapid Control Prototyping, Control Validation, Model Based Development, Hardware in the Loop (HiL), Active Steering Control, Active Brake Control.

1. INTRODUCTION

As a result of the increased number and the capabilities of microprocessors, sensors and actuators that are being embedded in most of today's engineering systems (so called mechatronic systems), the functionalities, complexities and level of integration of these products have evolved considerably. Development of mechatronic systems is a complicated multidisciplinary task and often requires contribution from diverse technical disciplines. The use of Model Based Development (MBD) methodology together with the V-model development process is a well-accepted systematic development approach, (Nicolescu & Mosterman, 2010), where the product and process domains are considered (Aslaksen & Belcher, 1992). The V-model probably originates from system engineering and software development; however, this approach was adopted for mechatronic product development (Isermann R. , 2008; VDI 2206, 2004) as well as for development of automotive embedded systems (Nazareth & Siwy, 2013).

The V-model addresses tree main stages toward product development including *System Decomposition*, *System Implementation* and *System Integration* as shown schematically in Fig 1. (Holtmann, Meyer, & Meyer, 2011). It incorporates several seamless steps and feedback loops, starting from requirements definition and ending up with field tests and validation on the vehicle. These steps are called "Model in the Loop" (MiL), Software in the Loop" (SiL), "Processor in the Loop" (PiL), "Hardware in the Loop" (HiL), and prototype testing. These feedback loops are the key elements to reduce the development time and cost by ensuring that the Verification and Validation (V&V) are taking place in the early stages of development (Bringmann & Krämer, 2008). The objective is to test out the (embedded) System under Development (SUD), at its different levels of maturity, to ensure the system is designed correctly (i.e. meet the specifications) and also the customer requirements are satisfied.

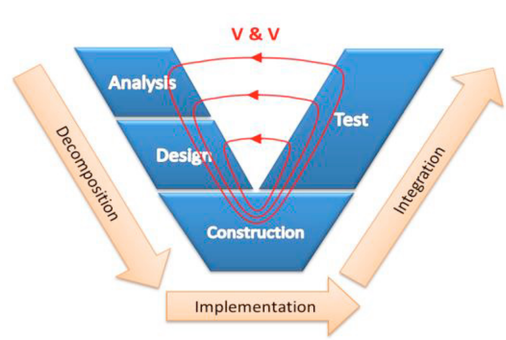

Fig. 1. The V-Model (Holtmann, Meyer, & Meyer, 2011)

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2. THE PRINCIPAL OF HiL SIMULATION

To better realise the important role of the HiL simulation, it is essential to review the concept of Model Based Development (MBD) approach of the embedded control systems, in which, "*modelling*" of the physical system plays the central role in the development process. Modelling could be defined as an abstract mathematical description of a physical system (Bringmann & Krämer, 2008). In the MBD approach, the mathematical formulation of the system dynamics are modelled and represented graphically, within the modelling environment such as Matlab®/Simulink®/StateFlow®, in order to provide a common platform across different engineering disciplines, which lead to a simplified and more efficient design process (including control design process). Moreover, the low-level machine codes can be seamlessly generated from the models causing a dramatic reduction in time and cost required for system implementation and testing. The system dynamics include the (linear or non-linear) model of plant dynamics as well as the (linear or non-linear) models of sensors and actuators dynamics. The model development often involves several inevitable trade-offs between completeness and simplicity. As the construction of a model (especially for control design purpose) often involves several levels of simplification and abstraction, the outputs of the model deviate to a greater or lesser extent from the real values. Having concerns about the reliability of the simulation outputs, *fidelity* is defined as the measure of degree to which a model reproduces the state and behaviour of the real system. If a model includes sufficient fidelity, then the control performance can be evaluated through simulation and the risk and cost associated with experimental validation will be reduced considerably (Gerdes & Hedrick, 1999).

From a control design point of view, the model should be complete to ideally capture the fundamental dynamics of the system and remain simple enough to provide a basis for model based control development. This inevitable level of simplification means that there are some deviations exist between the real behaviour of the system and its virtual model. These may include (but not limited to):

- The simplified dynamics of the plant, actuators and/or sensors;
- The neglected nonlinearities (such as friction or backlash) in the plant and the actuators;
- The ignored delays and latencies on communication buses, such as CAN bus;
- The unmodelled external disturbances and noises exerted to the system.
- The difference between processing power and capacity of an off-line simulation computer (a PC, for example), a real-time control prototyping platform (dSPACE MicroAutoBox®, for example), and the final target processor (ECU);

The above mentioned differences mean that the performance of the final embedded product is not necessarily similar to the behaviour of the originally designed control system that was validated through off-line simulation. As the development of the product reach to some higher level of maturity within the left side of the V-model, it is necessary to validate the product in a more complex and realistic testing conditions, and to provide proper feedbacks for design correction. Although there are no definite agreement on the range and the definition of the validation tests within the context of MBD approach, but in general we can define the more common validation test as follow:

- The 'Model in the Loop' (MiL) stands for the off-line simulation and verification of the system models and controllers which are developed at different stages of the design process;
- The 'Software in the Loop' (SiL) is the real time simulation and verification of the software codes which are automatically generated from the developed models during the implantation phase and are executed on the prototyping ECU platforms (such as dSPACE MicroAutoBox®, ETAS, etc.);
- The 'Processor in the Loop' (PiL) is the real time simulation of the auto-generated software codes that are executed on the final target processor board (production ECU);
- And the 'Hardware in the loop' (HiL) simulation is defined as "a method in which one or more real components/sub-systems interact in a closed loop with components/sub-systems that are simulated in real time (real time dynamic models)" (Wältermann, 2009, April), as shown in Fig. 2.

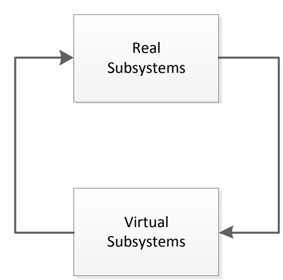

Fig. 2. Principal of a HiL Simulation

HiL system provides a fast, flexible and efficient means for verification of functional and non-functional aspects of the developed control systems (ECUs) in a real time environment in the presence of (actual and virtual) system dynamics (Mutz, Huhn, Goltz, & Kromke, 2003). The real part of the system consists mainly of one or more ECUs (controllers), and/or smart actuators and sensors which operate in a closed loop with components that are (mechanically and/or electrically) simulated in real time. If the simulated models reveal sufficient proximity to how the system behaves in reality, then the control performance can be evaluated through HiL testing with a high level of confidence and the risk and cost associated with experimental validation will reduce considerably. HiL systems are generally employed for validation of production ECUs for smart actuators (Hanselmann, 1996). However, integration of a HiL system with Rapid Control Prototyping (RCP) tools, such as dSPACE MicroAutoBox®, yields a suitable platform for control system development and validation in real time