Review of hardware-in-the-loop - a hundred years progress in the pseudo-real testing

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In the last two decades, the electronics and mechatronics systems became undividable part of human life. With increasing of the number of application fields and functionalities, they became more complex and a lot more efforts need to be put in the process of verification. Hardware-in-the-loop (HIL) is an approach that optimizes this process. In many cases, it is the only efficient or even possible way for testing and thus a lot of efforts are put in it. There are a big number of proposals on how to use HIL for different applications. Maybe because its highly practical nature, the scientific definitions are still not clarified, the used terms are not summarized but used on a case by case bases. This paper presents an analysis of HIL systems' academicals and industrial publications and experiences. It goes through the HIL history and application, trying to clarify what it is for and how it is used. Based on this, it comes up with the definition of a HIL system and further classifies HIL systems' types. The biggest challenges are identified along with the applicable requirements for HIL systems engineering.

Keywords – ***Hardware-in-the-loop, HIL design, HIL architecture, HIL application***

Обзор на hardware-in-the-loop – сто години прогрес в псевдо-реалното тестване (Николай Браянов, Анна Стойнова). *През последните две десетилетия, електронните и мехатронните системи се превърнаха в неделима част от битието на човека. С увеличаването на броя на приложенията и техните функционалности, този тип проблеми стават все по сложни и изискващи повече усилия във връзка с тяхната валидация. Hardware-in-the-loop (HIL) предлага решение за оптимизация на този процес. В много случаи, това е единствената възможност за тестване, поради тази причина подобрението на методологията е продължава да бъде важна задача. Публикувани са значителен брой предложения за реализацията и приложението на този тип системи. Въпреки това, терминологията все още не е прецизирана, и се използва във връзка с конкретна реализация. Тази публикация представя анализ на академичните и индустриални публикации за HIL системи. Чрез историята и приложенията на HIL се достига до същината на подхода. Ная тази база се предлага дефиниция за HIL система и класификация на видовете такива системи. Идентифицират се изискванията към такъв тип системи и се изброяват и анализират предизвикателствата пред тях.*

Introduction

Hardware-in-the-loop (HIL) is already widely used for verification and integration of electronics and mechatronics systems. It is applied in a rising number of industries and different stages of the development's process. What makes it unchangeable is its usage for validation in cases it is very expensive, dangerous or even impossible to do it in a real environment. Thus, it is commonly applied in automotive, railways, aerospace industries.

A number of publications claim that HIL systems have become an irreplaceable, integral part of the development and testing of complex devices. Even if it is widely used, the terminology is not clear. Different terms are used for same or very similar systems and there is no common definition for HIL, because the term is still not included in IEEE taxonomy [1].

HIL history

In spite of its significant importance, it is not easy to find and arrange in the time an accurate history of HIL systems. Perhaps it is because of its highly industrial "in the kitchen" application, or maybe because of non-formalized and non-academic form that this approach still has. Most probably, the initial need and development of such kind of systems has started in high-technology dynamic systems used for military, aerospace or airborne applications, where high quality, but also confidentiality of applied technology is required.

The first known example of HIL system is a flight simulator. It could be considered as a HIL system with a physical control system (a pilot) placed in a physical sub environment (a real airplane mounted on the ground with a face towards the wind) and experiences the behavior of a virtual simulation of the environment. It was created in 1910 by the “Sanders Teacher” [2] in order to protect human’s life but also the machine. In this case, the virtual part of the HIL system is the wind, which of course can’t be controlled. This is the reason why the system was not very useful. Later, in 1917, more functional simulator was presented [3]. It includes controllable body which is used to represent different response and the feeling of speed. During 40’s this kind of HIL system utilized all up coming technologies – analog computers, servo systems, hydraulics [4], etc. During the 50’s and 60’s the digital computers were introduced and gaining popularity, but they were not capable to fulfil simulator’s needs. In the beginning of 70’s started their integration in hybrid systems. Anyway, HIL technology has been in wide use in Defense and Aerospace industry as early as the 1950s [5]. It was continuously utilized in flight and missiles control industry as in the Sidewinder program [6], NASA highly maneuverable aircraft technology (HiMAT) [7].

In the automotive industry, the HIL application has started with a vehicle driving simulator [8], [9]. Consecutively, HIL was integrated for testing and development purposes of different functionalities [4] - 1987 Dynamic motor test stands with a real engines and simulated by hardware(an electrical motor) vehicles gears controlled by a digital process computer; 1987 HIL is integrated for the needs of ABS (antiblock braking systems) system development; 1988 performance and quality evaluation are done for ASR(Anti-Slip Regulation); 1992 it is applied for simulation of vehicles’ systems dynamics

During the 90s the commercial HIL system were proposed [4] and HIL got widely integrated in number of industries. The HIL systems, started from a method of learning new pilots, became an unchangeable solution for complex devices development and testing. From very custom device, it ended up as standard industrial semi-automatic solutions. Its application defines its main objectives – correct recreation of the real life phenomenon and thus in hard real-time manner.

Application industries

In recent years, HIL systems are applied in all industries, related to safety and impossibility of real live test. As already reviewed they are widely integrated in automotive (powertrain control module [10], brake system [11], suspension systems [12]; general control system [13], [14]; dynamics [15]) and aerospace (flight simulation [16], fan rocket control [17], general verification and validation of flight and mission-critical software [18], power electronics [19])

Apart, HIL is also used in the railways (wheel slide protection systems [20], braking [21] but also vehicle dynamic and electric systems [22]); power electronics and electrical systems(output power converters [23], power electronics [24], solar power station [25], microgrids [26], power converters and electric machines [27], thermal power plant control systems [28]); manufacturing and distributed automation [29]; underwater vehicles [30]; robotics [31].

Currently, HIL simulation is generally applied:

- in safety related industries where the process of verification is complicated and thus expensive
- in industries, where verification could cause a damage of expensive components
- in industries, where functionalities can not be tested in the real environment, either because it is dangerous(autonomous vehicles) or impossible(space vehicles)

All other industries, related to hardware/software interaction could benefit from HIL. Later in this paper are discussed the key challenges for the HIL systems, which could enable their application.

HIL systems as part of the development process

HIL could be applied literally everywhere, and different users find it helpful in different stages of the development process. Next review is based on the V-model, as commonly used and widely accepted process. Particularly used is the model defined in the automotive safety standard ISO26262 [32]. The reason is that it is based on the general standard IEC 61508, Functional safety of electrical / electronic / programmable electronic safety-related systems [33], but provides more detail representation of the V diagram Fig. 1.

During development and implementation of system and control software [34], HIL systems are used for “construction and implementation”, “System integration” and “Field tests”, as described in their V

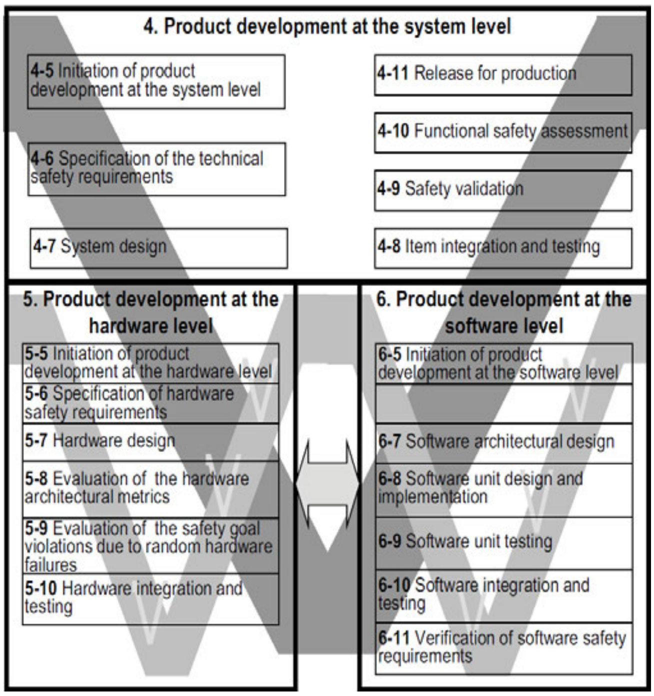

Fig. 1. Product development process V-style diagram. Credit ISO26262.

diagram. Mapped to already present diagram, the HIL is used for unit test, integration test, and product integration test. According to “HIL for automotive vehicle control systems development and testing” [35], it is used for item integration test and safety validation. A HIL simulation for electric drives and power electronics [36] uses HIL for “Subsystem Test” and “Subsystem integration”, which corresponds to used V diagram as unit test and integration test. A case study in application HIL during the development of ECU for hybrid electric vehicle [37] proposes a HIL system for “Unit test”, “System Test” and “Integration/Release test”. For development of ADAS, HIL is applied for “Module verification”, “System integration testing” and “System verification” [38]. For “Robustness and safety testing” and “System validation”, they use the so-called VEHIL, or vehicle HIL, discussed later, as a variation of HIL.

Depending on its integration, HIL could be used all over the right part of the V diagram, evaluating all different kinds of tests. This enables the usage of the same test cases during whole the process of development, enabling its integration into a consistent toolchain.

Definition for Hardware-in-the-loop

State of the art definitions

In the literature HIL systems are known with various names as well as descriptions:

- technique for combining of a mathematical simulation system model with actual physical hardware, such that the hardware performs as though it were integrated into the real system [39];
- system with primarily objectives to control and observe the interfaces of the system under test (SUT), often done on semi-automatic way [40];
- technique where real signals from a controller are connected to a test system that simulates reality, tricking the controller into thinking it is in the assembled product [41].
- real-time simulator constructed by hardware and software, which is configured for the control SUT and connected to the target system or component through appropriate interface. During testing with an HIL simulator the target system or component does not experience significant difference from its integration in the real system [42].
- system, operating real components in connection with real-time simulated components [4].
- combination of physical target electronics units and physical communication bus, where real-time simulation is performed based on data, loaded to the electronic control units (ECUs) [43].
- real-time simulation for embedded control systems, in presence of hardware and other control systems in which a dynamic simulator is replaced by the real system [34]
- non-intrusive test mechanism where the environment of a SUT is simulated in order to perform tests on the SUT [44].
- method in which one or more real sub-systems interact in a closed loop with sub-systems that are simulated in real time to test them intensively in this virtual environment [45].
- synergistic combination of physical and virtual prototyping or a setup that emulates a system by immersing faithful physical replicas of some of its subsystems within a closed-loop virtual simulation of the remaining subsystems [46].
- combination of simulated and real components, alternatively, a real component can be emulated, i.e. replaced by an artificial component that has the same input and output characteristics in a closed-loop configuration [38]

The main aspects of a HIL system are easily notable – A combination of virtual and physical(real-world) systems; Based on a model of the environment; Executes in real time; Utilize the control signals, thus creating very close to the real environment for the controller; A possibility to replace a simulator with an artificial real time hardware system. This gives a general description about HIL as a system type and approach for testing. To come up with a definition, few questions need to be clarified:

- Which part of the system should be a real physical system and respectively – which virtual?
- Is it black/grey/white box testing
- Is HIL always a matter of closed loop system, or open loop is also applicable?

HIL system as combination between physical and virtual

The Greek word "systema" means the organized relationship among the functioning units, a collection of elements is discernible within the total reality. Thus, a system includes control part, processing the input data and responding with output data and the process itself, containing the environment together with sensors and actuators. Based on already proposed HIL descriptions, one could state that HIL system either has real controlling and virtual processing or virtual controlling and real processing. However, the majority of the papers claim that HIL system is a system with a real controller and possibly virtual sensors, actuators or environment. They state that if a virtual controller is used, the evaluation is called control prototyping [4] or rapid control prototyping (RCP) [47], [48], [49], but it could also be found described another way [50]. General graph of both systems in given on Fig. 2.

Fig. 2. HIL system (up) vs RCP system (down).

HIL system contains a PC that configures the HIL device. Once the simulation is ran, the HIL device executes simulation models and emulates the DUT's interface signals. RCP system is a platform used to evaluate the control algorithm, when the real one is not available [51]. It is configured with the DUT's software. When the simulations starts, the device executes DUT's software and attached real sensors and actuators interact with the environment. On Table 1 are described the main resources that both systems occupy. Obviously there is not that big difference between them. The fact is proved once again by the industry, which currently provides systems, capable to be used in HIL and RCP loop [52].

Table 1

Comparison of resources required for HIL and RCP systems

Resourse	HIL	RCP
Communication with the PC	Initially intensive, later floating	Initially intensive, later floating
Communication with DUT	real-time, intensivety depends on the system interface	na
Communication with Sensors/ Actuators	na	real-time, intensivety depends on the system interface
CPU load	simulation of the environment	processing the enironment data and control
Real time execution	Yes	Yes

The systems are very similar,but their application is essentially different. Recognition of the difference sticks to the common definition of HIL as a real controller system tested in simulated environment.

HIL test in the box

The type of testing is very important either as technology of the HIL system and as applicability. This is a consequence from the definitions – white box testing (WBT) is structural testing that is possible because of the deep knowledge for the SUT; black box testing (BBT) is a functional testing regarding the system's specification and with no understanding about its realization [53]. The term grey box testing (GBT) stands at the middle when the SUT is partially known.

Literature references HIL as a BBT systems, generally because they are used for system functional tests, which is a BBT by definition. Additionally most of the HIL systems are not able to access the SUT in real time in order to synchronize with its internal states and thus assure white-box treatment. However, proceeding WBT could have many advantages [54] and thus white box HIL systems are implemented. In such cases, synchronization between SUT and HIL is a big challenge, thus such kind of solutions are rare. It could be achieved by adding extra functionality in the main system [55] or by real time ECU access [56]. The solutions are very custom and thus expensive. Additionally, their implementation changes the execution of the SUT, which could introduce issues.

Commonly, the HIL test is GBT. The reason is that in the most of the cases the tested system is well known. Even though the functional testing requires BBT, in many cases using the knowledge about the system is beneficial, since one could improve the amount of covered code and execution paths.

HIL system in the loop

The topic if the HIL is close- or open- loop system is not particularly discussed in the literature. The most of the reviewed publications [46], [45], [57] etc. describe HIL as a close-loop system. However, there are papers state it other way [58], [59]. They describe:

- open-loop HIL - the generation of simulation data by the HIL simulator is independent of the previous output data of the SUT. The output of the SUT is only captured for future evaluation purposes but has no influence on the simulation data.
- close-loop HIL - the previous output of the SUT directly influences the calculation of subsequent input data. The HIL simulator must calculate the simulation data in real-time.

The benefits from open-loop HIL system are easier performing of unit level software verification and verification of the software and hardware interface of the low-level platform software [5]. Generally, it is simpler to integrate an open-loop systems and they are less resource hungry. There is no reason to neglect this kind of testing, even though the close-loop is more common.

Similar Terms

Further literature review enumerates variations of the HIL systems. For it, a car-environment system is presented Fig. 3.

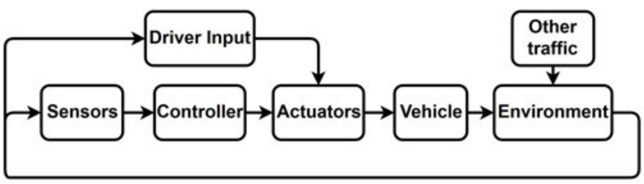

Fig. 3. Complex car-environment system.

As already reviewed, generally the HIL system contains a real controller in a loop with virtual or semi-virtual sensors and actuators. In this situation, if a human driver is included in the loop, the system could be called HIL [60], but alternatively driver- or human-in-the-loop [61], that could be also presented as type of HIL [62]. Later, if vehicle is added in the loop, so real car is on a real road and all its sensors are stimulated, then it is VIL (Vehicle-in-the-loop) [63]. And further - a real car, mounted on a stand with dynamometer and stimulating its sensors corresponding to artificial environment, this is called VeHIL (Ve stands for vehicle) [64], [65]. Alternatively VIL is described as placing the entire vehicle into a test facility, 'fooling' the sensors so that it senses it like real environment [66]. Finally, in case an engine is tested, using dynamometer, it is called Engine-in-the-loop [46], even though another paper [57] says, it is still HIL. Apart of these, one of the leaders in HIL systems defines Engine Environment HIL, Vehicle Environment HIL and Complete System Environment HIL up to nowadays distributed HIL solutions [67].

As reviewed behind, there are different claims about HIL systems and alternative pseudo-real simulations. In their research on Hybrid Powertrains, the authors claims that they are just different kinds of HIL [68]. From vocabulary point of view, hardware is mechanical equipment necessary for conducting an activity, usually distinguished from the theory and design that make the activity possible [69]. The phrase in-the-loop means included in a group that receive information about something [69]. Thus, generally either if the engine or vehicle is in the loop it should be called HIL.

HIL types

Referenced HIL types

The literature distinguishes several types of HIL, according to the level of the integration of the test platform. They are going to be analyzed, using a common mechatronics system graph Fig. 4. On it, the sensors measure the environmental signals, related to the environment, and provide low power electrical signals. It is later processed by Signal process and control, which in result generates actuators controlling low power signals. After the power amplifier, the signals are able to feed the actuators. Their act effects the mechanics and environment that closes the loop.

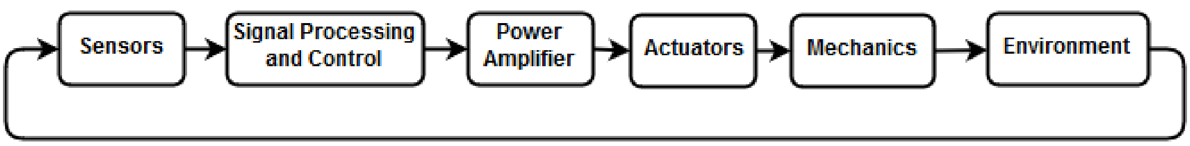

Fig. 4. Common mechatronics system form.

According to [70], HIL system could be established on signal level, power level and mechanical level. The authors describe signal level HIL (sHIL) as interconnection of a physical sub-system and a virtual residual system at signal level, which related to already proposed system, means that Signal Process and Control is real and the rest is simulated. The same definition is also supported by [56], [57] and [71].The concept of (electrical) power level HIL simulation (pHIL) summarizes HIL procedures which include a significant exchange of electrical power within the interface between the physical sub-system and the residual simulated system. Thus, aside from processing the real power amplifier is used, connected with some kind of physical loads. Mechanical level HIL simulation (mHIL) enables the close analysis of the mechanical interaction between a yet unrealized mechanical structure and an existing actuator system in the HIL test environment, so additionally in this case real actuators and mechanics are used.

For their proposal for hardware-in-the-loop model for electric vehicles [71] the authors analyze different HIL types. Power HIL system's realization includes real actuators. Additionally is proposed reduced-scaled HIL, similar to pHIL but loaded with equivalent subsystems with reduced power. The replaced subsystems have the same characteristic with the original ones. Similar definitions are given in Industrial Electronics Handbook [72].

At the electric power level the real power electronics could be simulated using electric loads [56]. At the mechanical level, simulation is done on a mechanical test bench, considering the effects of the real motor and additional real mechanical parts using the real controller and simulating environment. In difference with previously described mHIL, the DUT uses real sensors. This requires that HIL system contains reciprocal actuators, so it could stimulate the sensors. The same idea is published [44], however without having integrated real mechanics. Same HIL system is referenced as system for intelligent sensors and actuators [73].

pHIL is also definition as a test proceed over some of the real actuators [57]. Loads should be either real or with very close characteristics. Additionally, reduced scale power HIL is presented. It checks the operation principles, based on a load that is with significantly lower power, but similar load characteristics. Further, they describe "Mechanical power HIL" used to study the electric drive on a static bench. It fits to mHIL description. Regarding the last paper, "reduced scale mechanical power HIL" uses loads very similar to the original, but with smaller power.

Another term is Component-in-the-loop (CIL) [74]. Authors define it as a system used for testing of a real entire sub-system (hardware / mechanics / software) emulating its environment interface based on models. Also a rarely mentioned term is platform- and hardware-in-the-loop (PHILS) [75], describing a system that evaluates not only the hardware performance, but also cooperative performance of a group of autonomous robots.

Signal HIL

sHIL is usually chosen, when the physical transducers are not available or a certain test scenario cannot be established interfacing it. For example, if a fault injection campaign involves transducers to exhibit a particular erroneous behaviour, the use of real one could be very hard or even impossible. Additionally it is the simplest and the most universal HIL system, thus the cheapest and the fastest to be integrated. The review found that publications are in consensus, that sHIL is a system, that consist of real controller and all the rest of the system is simulated Fig. 5. sHIL could be found with other names as

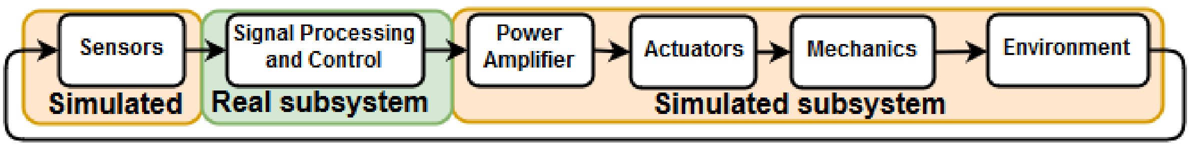

Fig. 5. Signal hardware-in-the-loop (sHIL).

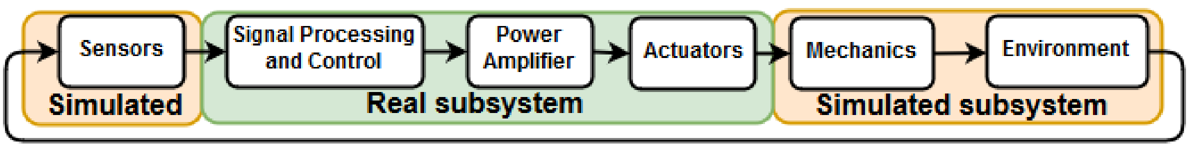

Fig. 6. Power hardware-in-the-loop (pHIL).

Controller-In-the-Loop (CIL) [46], Controller Hardware-In-the-Loop (CHIL) [76], [74] and even component level HIL [77].

Power HIL

pHIL moves the system in more realistic conditions [70]. The focus of the power level HIL tests is over power amplifiers and power electronics Fig. 6. In the context of the development of a controlled electromechanical system, an electrical power level HIL simulation enables testing of an existing power amplifier under realistic operating. There are number of variations in its definition and integration - reduced pHIL uses smaller loads; scaled pHIL with smaller load type with similar characteristics; pHIL with real loads.

In case the pHIL is used for evaluation of the electronics, it doesn't make sense to be used different loads. In some cases, using smaller loads with similar characteristics could be beneficial, especially in order to protect some high power devices, while reproducing the real system's behaviour. Because of the very similar characteristics of both pHIL and scaled pHIL could not be classified as different kind of HIL systems.

Mechanical HIL

mHIL adds extra level of reality, controlling the real actuators and investigating its real behaviour. Its evaluation is the closest to the reality test, the final one that could be done before the final product testing Fig. 7.

In this case, the border of integration is not that defined and solutions vary:

- real actuators simulated mechanics and sensors, based on the measured behaviour of the actuators.
- real actuators and real mechanics with additionally integrated sensors able to capture the systems dynamics. Thus, only the DUTs sensors and environment are simulated. In this case one should be caution on the way the mechanics is driven, since improper actions could damage it.
- real sensors and actuators and simulated subsystem of the environment. In this case pairing between the SUT's actuators and HIL sensors and SUT's sensors and HIL actuators should assure proper capturing of the environment and sensor's stimulation.

mHIL systems are very custom, and thus very slow for integration, complex and expensive. However their usage provides the closest to the real live simulation. This pseudo-real live testing is the only possibility if the environment is not accessible (the space), the equipment is very expensive (spaceships, airplanes, hi power modules) and as lately in autonomous vehicles, where there is high risks for the people's live.

Others

Based on the already defined types of HIL systems, component HIL [74] cannot fit to any of this groups. Its level of abstraction is undefined, so actually it could be part of any or all of the already classified groups. The given definition is very close to the general explanation of HIL. Platform-hardware-in-the-loop (PHILS) is a special case of a HIL system, that calculates a mathematical parameter based on hardware signals. Since the communication is on the level of standard communication signals, it could be encountered as one sHIL system.

HIL system designs

Non-standard solutions

In simplest decisions, the authors manage to proceed HIL tests, only with a personal computer (PC) [78]. This type of HIL system is possible, only because the required interface between DUT and the environment is RS232, commonly available on the PCs. Since Windows is not a hard real time operation system, such implementation cannot be used in case high simulation frequency or accuracy are required. Possible solution is HIL simulator based on a PC with Real-Time Linux [79]. Additionally, a programmable logic controller (PLC) based system is able to simulate the system even faster. The latest is applied only in HIL systems with PLC based system under test (SUT).

A distributed HIL system based on smart virtual transducers Fig. 8 is implemented over Atmel 4433 micro controller unit (MCU) [44]. Even rocket's HIL system is developed on a very simple ATMEGA 2560 8-bit MCU [17]. HIL realisations could be done on a low cost hardware [80]. The platform is not clarified,

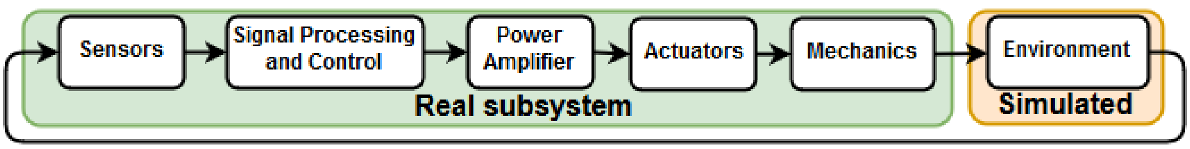

Fig. 7. Mechanics hardware-in-the-loop (mHIL).

but what is known, it is based on a target micro controller that is actually tested.

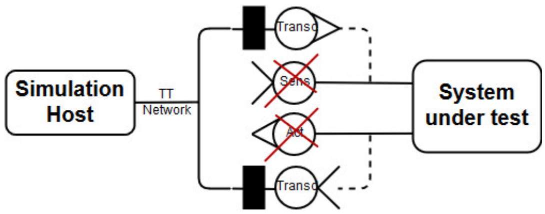

Fig. 8. MCU based smart virtual transducer HIL.

Mechanical level HIL on Arduino mega [81]. The SUT is unmanned aerial vehicle (UAV). A PC based flight simulator executes the simulation. The PC is connected to the MCU via RS232 and the controller takes care of the environment simulation.

Another paper proposes a distributed HIL system [82] using MSP430 series explorer board Fig. 9.

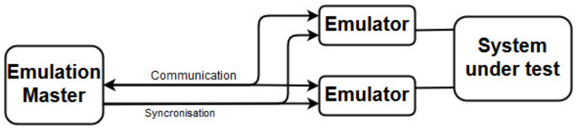

Fig. 9. Master-slave MCU based architecture for distributed HIL.

Development of a hardware-in-loop attitude control simulator [83], uses a computer connected via its USBs to a bunch of Arduino boards Fig. 10.

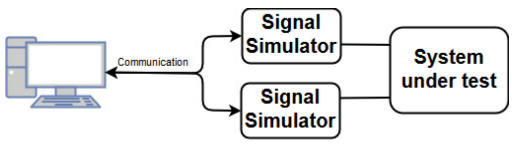

Fig. 10. PC mastered MCU based distributed HIL.

HIL systems for different power applications are implemented on field-programmable gate array (FPGA) [23], [24], [26], [84]. Aside from the FPGA, a digital signal processor (DSP) is used stimulate a solar systems [43]. Another proposal is a combination of FPGA and MCU [85]. Rarely but effectively, graphics processing units (GPUs) are used [75], in this case in combination with central processing units (CPUs) Fig. 11.

Standard HIL device are integrated in different ways. For example, they could be utilized with model based technics and code generation [50]. A low-cost real-time HIL testing approach [86] is based on a PC with bunch of specific tools and standard data acquisition devices. A HIL System for Active Brake Control Systems [11] contains two PCs. The Windows based host computer is used for simulation

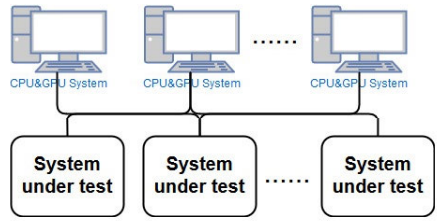

Fig. 11. CPU&GPU distributed HIL.

development and configuration. The target computer uses QNX operation system, capable to run the simulation and simulate the signal with standard data acquisition boards in real time manner. Advancing Subaru hybrid vehicle testing through HIL simulation [72] uses standard HIL devices to execute the simulation and output required signals. Additionally they synchronise an "ECU RAM monitor" interface, able to dump the ECUs memory Fig. 12. Thus, white box testing is possible.

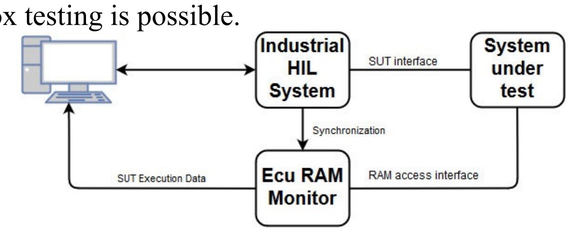

Fig. 12. ECU RAM monitor integration for white box HIL application.

HIL systems could be implemented over different computational platforms – CPUs, MCUs, GPUs, FPGAs, DSPs, PLCs. Authors prefer to choose the PC, as it is standard equipment. Further integrations use MCU platforms, often the same as the target. The implementation platform is chosen mainly because of authors experience and availability and current review of the nonstandard approaches is not able to demonstrate any dependency between used hardware platform and the application. Thus, industrial solutions for particular applications are going to be analysed.

Standard solutions

Standard solutions classification

Commercially available HIL simulation systems are classified based on their architecture, as simple simulators and complex simulators [87]. Simple HIL simulators contains a single hardware target (FPGA, MCU, etc.) connected to a development PC that proceeds an environment simulation. The complex HIL simulators are separated as monolithic and distributed HIL simulators. The monolithic HIL simulator is a single device that is modularly configured to offer all required interfaces for a particular SUT. In contrast to the monolithic, a distributed HIL simulator consists of several interacting nodes that are capable to execute a distributed simulation model [49].

HIL systems are also classified as close and open architecture solutions. Close architectures, are hardly expandable, but offer whole hardware/software solutions for a particular problem. Opened systems provide different interfaces and thus could be integrated with many technologies. The cost of the openness is the more complicated set up and in result – increased configuration time [88].

Standard solutions platforms

DSpace proposes large line of HIL devices. A processor board based on CPU is designed for complex calculations [89]. It enables the combination of up to 20 modules of this kind, working distributed in parallel, in order to multiply the performance. CAN interface board is based on DSP [90]. Generally, the measurement of common signals like digital, analog, PWM, etc. are hardware implemented with so called "piggy modules" [91], [92]. To achieve fast parallel emulation of electrical signals are used FPGA based boards [93]. Another possibility is MCU based I/O board [94] and A/D board [95]. When it comes to the simulation and measurement of special automotive signals, the same provider proposes I/O board, combining an Angular processing unit (APU) and a DSP [96].

National Instruments does not provide particular information about the implementation. They claim their HIL system uses a CPU for computation and real time simulation processing and FPGA for electrical signals emulation [97].

Speedgoat uses a CPU base line real time target machine [98] and I/O modules, based on either FPGAs (hi-end realisation [99]) or MCUs (for the low-end products [100]).

ETAS proposes CPU based carrier board or housing [101] and FPGA I/O boards.

Currently all types of HIL system are in production, mainly because the simplest architecture defines the lower price that in many cases is the most important parameter. The implementation platform is also very important for the price, so the cheapest HIL systems are implemented over MCU. This defines their limitation, regarding calculation power as well as parallel signals emulation. The most of today's HIL system contain multi CPU part responsible for the calculations and FPGA, capable to handle very fast emulation of big number of signals in parallel.

HIL pros and cons

Waeltermann summarizes the benefits of HIL [45] - with HIL a reduction of development costs is achieved by moving function tests and diagnostics tests from tests drives or test bench experiments to the laboratory. The result is reduction of the number of expensive prototypes and time spent at the test bench. HIL tests can be often reproduced and automated, so it could automatically run, evaluate, and document. This allows the test operators to concentrate on assessing tests, implementing and adjusting tests. Automation provides better test coverage than manual tests, enhancing the quality.

HIL is a testing method that enables testing in different virtual situations, keeping the context on maximum possible reality level that is the last option before the real test. It is a trade-off between accuracy of test and cost and time consumption Figure 13. Because of its semi-virtual nature, HIL provides many benefits:

- Repeatable and stable - In contrast to road vehicle test, HIL is able to test complete feedback control systems in laboratory environment without disturbances from unrelated systems [25], [102].
- Cost effective - Extensive and expensive testing periods may be reduced, if HIL testing is applied for complex sub-systems [70]
- Verisimilitude, fidelity - By prototyping in hardware components, which dynamics or other attributes are not fully understood, HIL simulators often achieve higher fidelity levels [46].
- Non-destructive testing - HIL simulation often makes it possible to simulate destructive events eliminating the possibility for costly destruction [4].
- Comprehensiveness - HIL simulation often makes it possible to simulate a given system over a broader range of operating conditions than with purely physical prototyping [103].
- Flexibility – a minor changes in the HIL system could acknowledge changes in virtual system's behaviour or if SUT has to be evaluated for a multiple applications [70], [34]
- Parameter study, sensitivity analysis and optimization are easily proceeded [70].
- Safety - HIL simulators can often be used to train human operators of safety-critical systems in significantly safer environments [46].
- Concurrent systems engineering – A sub-system may be tested even if the remaining components

are only partially or not at all available, without losing sight of integration issues [29].

- Accelerates shift left - HIL enables the application of a consistent toolchain along the development and validation, thus using same test scenarios [65].
- Enables additional savings in personnel and equipment [104].

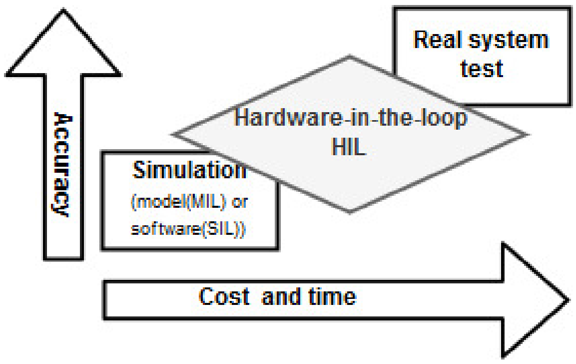

Fig. 13. Testing methods as a trade-off between accuracy of test and cost and time consumption.

Because of its great benefits and because there is no alternative for particular situation, one could hardly criticize it as approach. There are just few identified critics:

- No internal SUT information - HIL simulator will not directly give any information about the state of the tested control system since it only acts as a black box tester [85].
- Simulation speed is constant and actually the real execution one - The HIL simulators are able to run in real time and cannot be paused or slowed down [85], neither accelerated.
- No standard solutions, slow integration [85].
- Particular issues, related to non-perfect virtualization and parameters like bus length, terminations (for communication), back-feeding voltages(power circuits), etc. [35]

Generally, the HIL system could hardly be capable to utilize information for internal states of SUT, but as already reviewed it is possible and WBT could be done with it. As a matter of execution time, the real-time work of any system requires it can't tilt it. Thus the testing process could be accelerated only indirectly, e.g. improving HIL integration time. It is considered later as requirement for future improvement, since it is key enabler for wider HIL integration and price reduction. In any case, for faster integration time one would need standardization of the problem, and thus particular tight cases could not be in the focus.

HIL Requirements and challenges

A HIL simulation framework enumerates minimal set of functions that are present in all the HIL systems with similar terms [102], [105], [17]: numerical simulation, hardware interface, and real-time constraints. These functions should satisfy a number of requirements:

- Hi computational power –It could be a matter of possibility to integrate a high-fidelity simulation of the environment and virtualized subsystems, with resolution suitable for the SUT [106]. Computational power should assure sampling rates as low as 1ms [73]. Even real-time operating systems (RTOS) is pointed as mandatory for the hard real-time work of the HIL system [46]. But generally it is a trade-off between acceptable accuracy and achievable simulation time-step [36].
- Flexibility - Hardware platform and specially the interfaces should be very flexible so that a HIL system could be used either for rapid prototyping or for testing [106]. It also should be easily integrated in different applications [10] and capable to abuse special IOs e.g. for simulation of crank and camshafts, generation of knock signals, PWM signals, CAN interface), while using HIL Simulation to Test Mechatronic Components [73].
- Hi level of automation – Automation is needed on each level of the simulation, from injection of representative faults [106] up to the entire HIL system, e.g. in a script for signal generation and capturing in real time, complex test sequence structures, access to external devices [73]
- The price – even not engineering, it is always an important argument [106]

Apart from the general requirements, there are others, based either on particular needs or on different points of view:

- The computational platform should be expandable. A modular interface is going to enable cost effective modifications [10]
- Integration with different tools - The software architecture must be flexible enough to allow the use of products from existing tools, and products from other areas of research [106], [73]
- Enabled for scripting configuration for easier management and documentation [106].
- Modularity, standardization and expandability at microscopic and macroscopic levels [73], [44].
- Tight integration deadlines, more importantly, deadlines that can be planned and met [73], [85].

- Supplier competence in the particular industry [73].
- And others like Open- and close- loop testing capability [44]; Functional and non-functional testing [62]; Equipped with system debugging tools [10]; Connecting the test cases to requirements to ensure test coverage; Evaluating regression tests for faster and qualitative validation [72].

Conclusions

The idea for estimation or simulation of the unknown or unavailable is not new. It is applied in many ways, but HIL is definitely an enabler for integration and testing of nowadays high complex mechatronics and cyber physical systems. Even if a hundred years have been spent, even if last 20 years it is a hot topic, the application of this approach is still very time consuming, very custom and very expensive. Moreover, this field still doesn't have its state of the art terminology, which introduces a big number of different terms for very same or identical phenomena referenced in the publications.

The paper proposes a definition for HIL system: **Hardware-in-the-loop system is a non-intrusive test approach, containing physical controller connected in open- or close-loop with virtual or semi-virtual subsystems, providing faithful physical replicas of the real world and evaluating the SUT in either black / grey / white box manner.** Three main types of HIL systems were identified, based on the level of their integration – signal, power and mechanical HIL. The last one, is the most complex, but provides closest to the real live test, where everything but the environment is real. Obviously it is not possible to fully validate today's complex systems, without a faith in the models, so this is a very important issue, even not directly related.

The HIL systems are applied in many fields of the industry and thus it needs to implement a big number of requirements. However the most common identified parameter is the integration time. Small or complex, calculation intensive or with a large number of different signal interfaces, everyone needs to setup his HIL system fast and iterate with it. The best way to have this is higher level of automation and thus easily configurable interfacing with different tools and hardware platforms. There should be enough processing power to assure required frequency and accuracy of virtual world simulation. Last, but not the least, the price is important parameter, enabling the mass integration.

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