HARDWARE-IN-THE-LOOP SIMULATION ENHANCED TEST METHOD FOR IWOCS

1	09.04.2015	Rune Lien	Mona Ulateig	Odd Kittelsen	Released for Information
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Rev.	**Date**	**Authors**	**Check**	**Approval**	**Change Description**

Abstract

This study describes how Hardware-in-the-Loop (HiL) can be applied in development and test of subsea control system software, and how improvements on safety and reduced development costs can be achieved.

HiL simulation is a technique for performing testing of embedded systems in a comprehensive, cost effective and repeatable manner. Continuous performance advances and price reductions in computer hardware have made it possible to develop cost-effective HiL simulators for a wider range of products.

Software errors can be discovered early in the development if the control engineers have access to the System Under Control (SUC) for testing from an early stage of the development. The final system is replaced by a mathematical simulation model running in real time in order to perform initial tests and also final system tests under extreme conditions. A mathematical representation of the SUC is often called a Plant Model for separating it from the real system. The SUC does not need to be the final system built with real hardware as long as the SUC responds to the control commands the same way as the final system.

Software-in-the-Loop (SiL) simulation can be set up to test the control code against the Plant Model. A SiL simulator is a simplified HiL simulator where only the control code is tested as a Co-simulation on a hardware emulator. SiL simulation offers a tool which can be used for development and debugging of the control algorithms at an early stage.

After finalizing the SiL test and the control hardware is ready for testing, the tested code can be installed on the control hardware. The controller is then complete with both hardware and software and can be connected to the Plant Model for full HiL testing. The HiL simulation can replace the SiL simulation when the physical control system is available.

The traditional way of testing Software is to put the major test effort into unit-testing, also known as component testing. Unit-testing is often ad-hoc based and have a low test coverage. Defects and failures are often discovered very late in the development process. Furthermore, traditional test methods might "mask" errors and make them invisible during a test. If a "masked" error is discovered late in the system integration test, the cost for correcting it is high.

Using HiL simulation technology for testing control systems makes it possible to perform extensive testing at early stages of the development process. Safety routines can be developed, optimized and verified against systems with same response as the real systems without damaging equipment or creating hazard situations for test personnel.

Keywords: Hardware-in-the-Loop, HiL, subsea, IWOCS, WAS, simulations, Software-in-the-Loop, SiL.

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1 Introduction

"We have always done it that way". This can be seven expensive words if used in an industry that continuously search for safety improvement and cost reduction.

This document reports a study performed by Data Respons Norge AS and Agito AS in Kongsberg, Norway, where the scope is to explain how Hardware-In-the-Loop can be applied in the development of and test of subsea control system software. The study points on what improvements can be expected on both safety and development cost.

The study is done as a joint project between Data Respons Norge AS and Agito AS, partly financed by Innovation Norway and NCE Systems Engineering Kongsberg.

The oil and gas industry has always improved their technology and pushed the limits for what's possible in harsh environments. New technology has continuously been applied, limits has been challenged and needs for new and enhanced test methods have been a result of this. Installation and Work-Over Control System (IWOCS) is a system which has local control of the well whilst operating on a live well. Risk for accidents with impact on equipment, personnel and environment is high. At the same time it is a constant demand from the operators that the well maintenance shall be performed as fast as possible and failures, which can result in extra hours of lost production, is not an option.

By introducing Hardware-in-the-Loop (HiL) as a test method on IWOCS, the risk for control system failures are reduced. System upgrades and reconfigurations to different subsea systems and environments, can be thoroughly tested onshore before sent offshore for installation. The required time for testing offshore can be reduced without reducing the level of safety in the process.

System level testing is one of the major expenses in developing Embedded Control Systems for offshore installations. The need to minimize time to market while simultaneously producing thoroughly tested products present tremendous challenges. Increasing levels of complexity in system hardware and software are making this problem more severe with each new generation of products. Additionally, any significant changes to an existing product's hardware or software must be thoroughly regression-tested to confirm that the changes do not produce unintended effects.

This study shall describe the Hardware-in-the-Loop (HiL) technology as an enhanced test method for the Installation and Work-Over Control Systems (IWOCS). Furthermore, the study will discuss the increased quality and safety and the reduced cost of applying HiL simulation in testing IWOCS.

2 Summary and Conclusion

2.1 Summary

The study shows that the traditional software development for IWOCS will see benefits by introducing HiL as an enhanced test method. Traditional test methods might "mask" errors and make them invisible during a test. If a "masked" error is discovered late in the system integration test, the cost for correcting is high. This study shows that discovering software errors early in the process might reduce the cost for fixing the error several decades compared to fixing the same error later. If the error is not discovered before the system is put in to operation the results might not only be loss of time but it might also be dangerous for the equipment and test personnel.

A HiL simulator can also be used to validate functions of safety loops and sub-routines that shall be activated in case of an emergency. Robustness of these functions are critical when the unexpected happens during operation.

2.2 Conclusion

We know that traditional software test methods is not perfect as described in section 5.1 in this document. Introducing HiL simulation as an enhanced test method will give advantages in both safety and economy.

HiL simulations as an enhanced test method is a valuable tool for the offshore industry and will reduce number of software errors through the project.

3 General

3.1 Changes from Previous Revision

Revision no.	Changes
-	First issue, no changes applicable.
1	General updated after internal document reviews.

3.2 Terminology and Abbreviations

Different terminology and abbreviations are used for the HiL simulations. This section defines the terminology and abbreviations used in this document.

3.2.1 Terminology

Terminology	Description
Co-Simulation	A Co-Simulation is a simulation where two simulation platforms are coupled together and runs in parallel with the same clock frequency. In SiL systems, this is a PLC simulator running in parallel with the Plant Model on a second simulation platform.
Embedded System	A computer system with a dedicated function within a larger mechanical or electrical system.
Emulator	A software program that represents the function of another system.
Hardware- in- the-Loop Simulator	A real-time simulator constructed assembled by hardware and software, which run the Plant Model, with appropriated physical I/O to connect to the control system. During testing with a HiL simulator the control system will not experience significant difference from being connected to the real system.
IWOCS	Installation and Work-Over Control System. IWOCS controls and monitors the deployment, the operation and retrieval of subsea production equipment. Main features are: Monitors and controls deployment and retrieval of Tubing Hangers, Landing Strings and Xmas Tress. Provides facilities for downhole operations, well testing and production testing.
Latency	Latency is the delay from input into a system to desired outcome. Latency highly affects how usable and enjoyable electronics and mechanical devices as well as communications are.
Model Validation	High-level checking validation of the model system response against real test data or theoretical calculations.
Model Verification	Detailed checking/verification of the mathematical models.
Plant Model	Real Time simulation model of the system under control
Real Time	A system is in Real Time if the total correctness of an operation depends not only upon its logical correctness but also upon the duration it performs the logical operations.
Regression testing	Is a type of software testing that seeks to uncover new software bugs, or regressions, in existing areas of a system after changes such as enhancements, patches or configuration changes, have been made. The intent of regression testing is to ensure that changes have not introduced new faults. One of the main reasons for regression testing is to determine whether a change in one part of the software affects other parts of the software.
Software- in- the- loop Simulator	A real-time simulator constructed by software only which run the Plant Model, with appropriated emulated I/O to connect to the control system. During testing with a SIL simulator the control system will not experience significant difference from being connected to the real system.
System Under Control	The simulation model that is controlled from the SUT.

System Under Test	In a HiL simulator is the SUT the control system that is tested. In a SiL is it the software code that is tested.

3.2.2 Abbreviations

Abbreviations	Description
CT	Coiled Tubing
EDP	Emergency Disconnect Package
ESD	Emergency Shut-Down
HiL	Hardware-in-the-Loop
HMI	Human-Machine Interface
HPU	Hydraulic Power Unit
IWOCS	Installation/Work Over Control System
LCP	Local Control Panel
LRP	Lower Riser Package
MCS	Master Control Station
MQC	Multi Quick Connector
OiL	Operator-in-the-Loop
PLC	Programmable Logic Controller
RTC	Real Time Computing
SCM	Subsea Control Module
SCU	Subsea Control Unit
SEM	Subsea Electrical Modules
SiL	Software-in-the-Loop
ST	Stack up Test
SUC	System under Control
SUT	System under Test
TH	Tubing Hanger
TPS	Test Procedure System
UPS	Uninterruptible Power Supply
WAS	Well Access Systems
WCP	Well Control Package
WL	Wire Line
WOCM	Work Over Control Module
WOCS	Work Over Control System
XT	X-mas tree

3.2.3 References and Sources

J. A. Ledin, “Hardware-in-the-Loop Simulation,” Embedded Systems Programming, pp. 42–60, Feb-1999.
McConnell, Steve. Code Complete, 2nd ed. ISBN 0735619670

4 Description of the HiL Technology

4.1 What is HiL?

When developing control systems for mechanical/electrical systems or embedded systems, time can be saved and errors discovered early if the control engineers has access to the System Under Control (SUC) for testing from an early stage of the development. The SUC do not need to be the final system built with real hardware. As long as the SUC responds to the control commands the same way as the final system, it can be built differently. With the computer technology available today, a mathematical simulation model running in real time can be a good replacement for the final system to perform initial tests and also final system tests under extreme conditions. A mathematical representation of the SUC is often called a Plant Model for separating it from the real system.

Hardware-in-the-Loop (HiL) simulation is a technique for performing testing of embedded systems in a comprehensive, cost effective and repeatable manner. Continuously performance advances and price reductions in computer hardware have made it possible to develop cost-effective HiL simulators for a wider range of products.

HiL simulations can be used in different levels of the software development as shown in Figure 1).

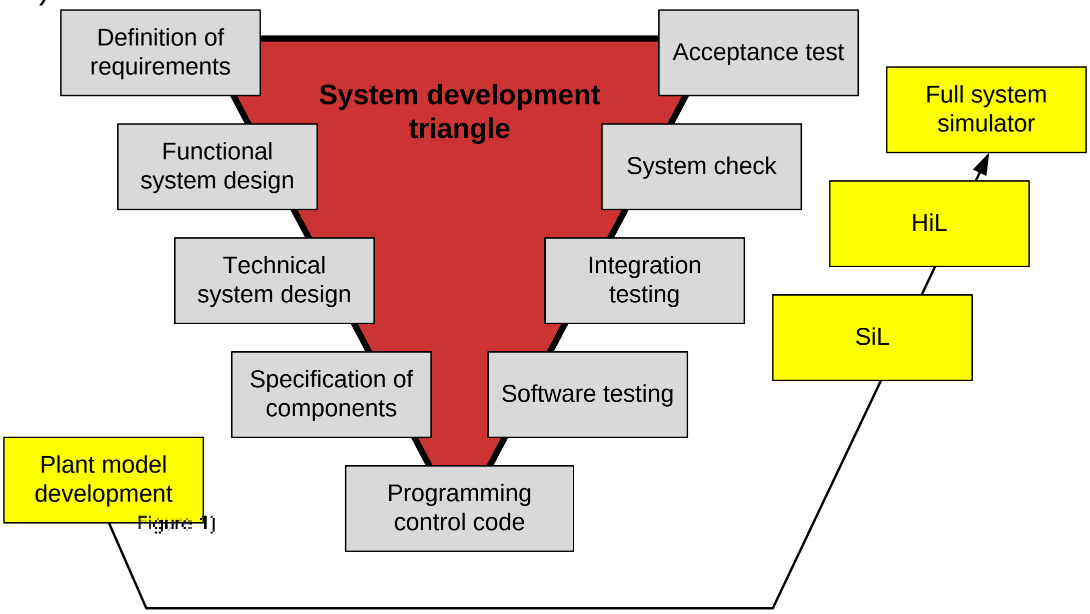


Figure 1) System development triangle

Typical system development tasks is shown as grey rectangles in Figure 1). The main tasks for HiL testing is shown in yellow rectangles.

As soon as the system with components are specified, a Plant Model can be built. The Plant Model can be based on the already developed system simulation model and its behavior can be verified against this.

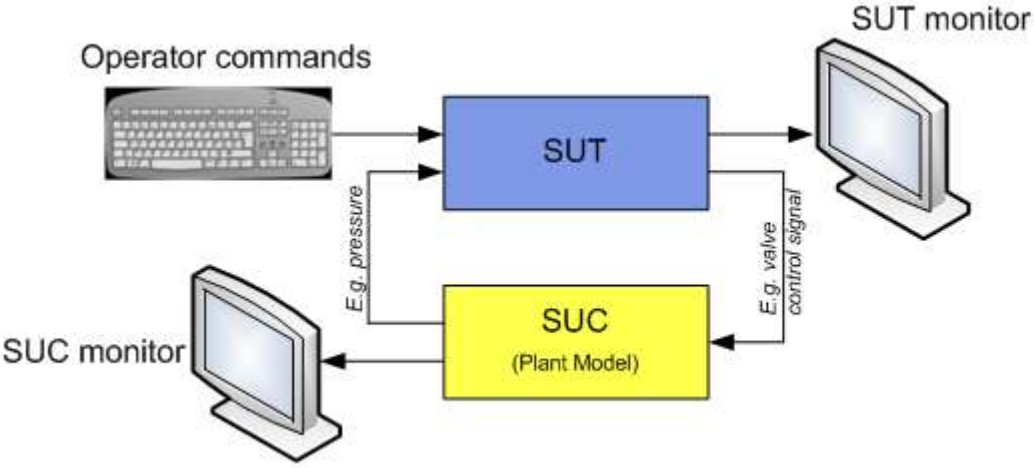
When the program code is ready, a Software-in-the-Loop (SiL) simulation can be set up to test the control code against the Plant Model. A SiL simulator is a simplified HiL simulator where the control code is tested as a Co-simulation where the control code is running on a hardware emulator for the control hardware in parallel with the Plant Model. The control code sends commands to the Plant Model and the Plant Model reverts sensor signals just as in the real system. SiL simulation offers an early stage development tool which can be used for development and debugging of the control algorithms. The SiL test shall be performed with a repeatable input from the Human-Machine Interface (HMI). This is important to avoid non-repeatable errors in the test.

After finalizing the SiL test and the control hardware is ready for testing, the tested code can be installed on the control hardware. The controller is then complete with both hardware and software and can be connected to the Plant Model for full HiL testing. The HiL simulation can replace the SiL simulation when a physical control system is available, and it offers not only a test facility of the control algorithm, but also an integration test whether all physical I/O's are coupled correctly and not at least, what is the consequences of failure on cables, loss of connection, latency etc.

Some industries goes directly from Plant Model development to HiL simulations. This is not recommended for systems where the level of innovation is high but for a traditionally system delivery where the code development is more a "code configuration" and the control hardware is well known products, it is considered to be opportune.

4.2 Typical HiL Simulation Set-up

As for the SiL simulation the HiL simulation set-up requires development of a Plant Model. The Plant Model represents the System under Control (SUC) and it continuously monitors output signals from the System under Test (SUT).The signals sent from the SUT is typically valve and actuator commands. Input to the SUT is typically sensor signals, from SUC, and operator commands.



HiL test set-up

The SUT is often provided with a monitor which will be the HMI. The SUC can also be provided with a monitor where animation of the SUC is of interest.
The operator commands can be from different sources. However, it is important to use input devices that can repeat commands 100 % if the system fails.

4.3 Areas of Attention

The reliability for a HiL simulation is, as for all simulations, dependent on the Plant Model's ability to reflect the response of the real world system. Before the HiL simulation can produce useful results, there must be a verification and validation of the HiL simulator.

4.3.1 Model Verification

The model verification demonstrates that the mathematical model used in the SUC represents the real system and its environment. This can be done by comparing the output results with a detailed simulation model of the same system or by comparing results with analytic calculations of the systems, or by comparing parts of the system with any available measured test data. Normally the Well Access System (WAS) is modelled and simulated to verify the system time response and shut-down sequences. If this model is verified against analytic calculations or test results, it can be used to also verify the HiL set-up.

4.3.2 Model Validation

The model validation demonstrates that the Plant Model used in the SIL/HiL simulation represents the real operational environment with a good accuracy. A standard approach to validation is to use the results of earlier system operational tests for comparison against simulation results. This type of validation test involves running the Plant Model through a test scenario that is identical to one that was performed by an actual system in an operational environment.

The results of the two tests are compared and any differences are analyzed to determine if they represents a significant deviation between the simulation and the real world. If the operational test results don't accurately match the SIL/HiL simulation results, improving the simulation set-up in particular areas might be necessary. Defects in software or hardware interfaces may also become apparent during validation. If changes are made to the Plant Model to correct problems it is important to rerun the validation to confirm adequate performance of the simulator.

5 Description of IWOCS

The Work Over Control System (IWOCS) is a stand-alone control system for monitoring, and operation of a subsea Well Access Systems (WAS). Systems for shallow water (water depth of approximately 400 meter or less) is often designed as direct hydraulic systems while systems designed for deeper water are multiplexed electro/hydraulic systems. A typical block diagram for a multiplexed system is shown in Figure 3).

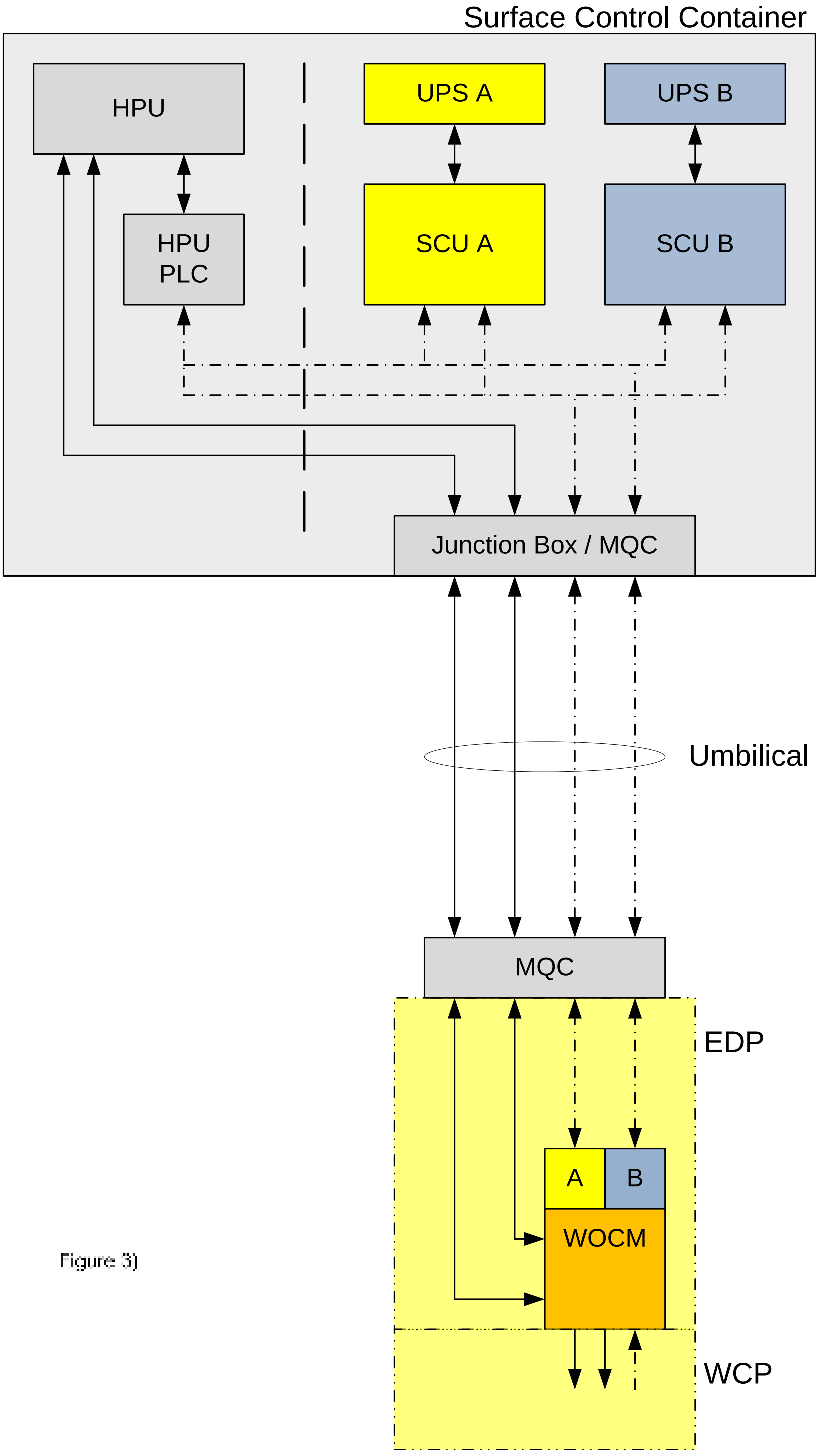


Figure 3)

Block diagram – IWOCS

The surface control container is a combination of Hydraulic Power Unit (HPU) and a control room where the Master Control Station (MCS) is located. The HPU supply hydraulic power to the subsea Work-Over Control Module (WOCM) through a multicore umbilical where the control signals are multiplexed in to hydraulic signals which opens and closes valves in the Well Control Package (WCP).

The MCS has two separate Subsea Control Units (SCU) labelled SCU A and SCU B in Figure 3). These two control units communicates with two separate Subsea Electrical Modules (SEM) in the WOCM, labelled A and B in Figure 3), through the multicore umbilical. One SCU is active and the other SCU is “hot” continuously reading transducers and valve status so it is easy to switch between SCU’s in operation.

5.1 Traditional Test of Control Software

The traditional way of testing SW is based on a waterfall development model, the V-model. Following such model often implies putting the major test effort into unit-testing, also known as component testing. Unit-testing is often done by the SW developer responsible for writing the code, and it is not unusual with poor test-documentation. The major part of unit-testing is often ad-hoc based and have a very low test coverage. Defects and failures are often discovered very late in the development process, maybe at integration test or in system tests. Finding SW defects late is of course far more expensive than revealing issues early.

IWOCS systems always involve large complex subsea components as major parts of the complete system. SW testing in this context is very challenging since essential components are not available in early stages of the development. Testing the control system SW and communication with the subsea system is therefore often done by running parts of the system on more available platforms, like a PC. This issue reinforces the tradition of doing major parts of the testing in unit-tests.

The fact that SW development often have a head-start on other components, and the need for more extensive SW testing during development, makes it nearly impossible to do regression testing before the complete system is available. Therefore regression testing is seldom possible to do in development of IWOCS control systems.

Detecting SW defects and failures at integration tests and system level tests, are not unusual. The challenge of discovering failures at this stage in an IWOCS system is often a time-to-market issue. Use of the system involves very expensive off-shore operations, and there is an extreme focus on the time-schedule.

6 Using HiL for Testing IWOCS

Using HiL simulator for testing IWOCS' has not been a common activity in the oil and gas industry. However, with the ongoing performance advances and price reduction in HiL simulator technology, cost effective HiL simulators are now available for a wider range of products. And since the WAS equipment normally is modelled and simulated to verify the system time response and shut-down sequences, the simulation model of the SUC exists already and can easily be configured in to a Plant Model for HiL simulation.

6.1 Test Set-up

Figure 4) shows HiL simulator for IWOCS. For IWOCS the control system will be a combination of physical PLC's and computers holding the control software. These elements makes the System Under Test (SUT). The operator commands and the SUT monitor represents the real world HMI.

The surface HPU, hydraulic supply umbilical and subsea stack including the WOCM hydraulic equipment makes the System Under Control (SUC) and is parts of the Plant model.

Between the SUT and SUC is there an I/O module which includes required converters for translating the SUT signals in to computer signals readable for the Plant model and the Plant model transducer signals to a format readable for the SUT.

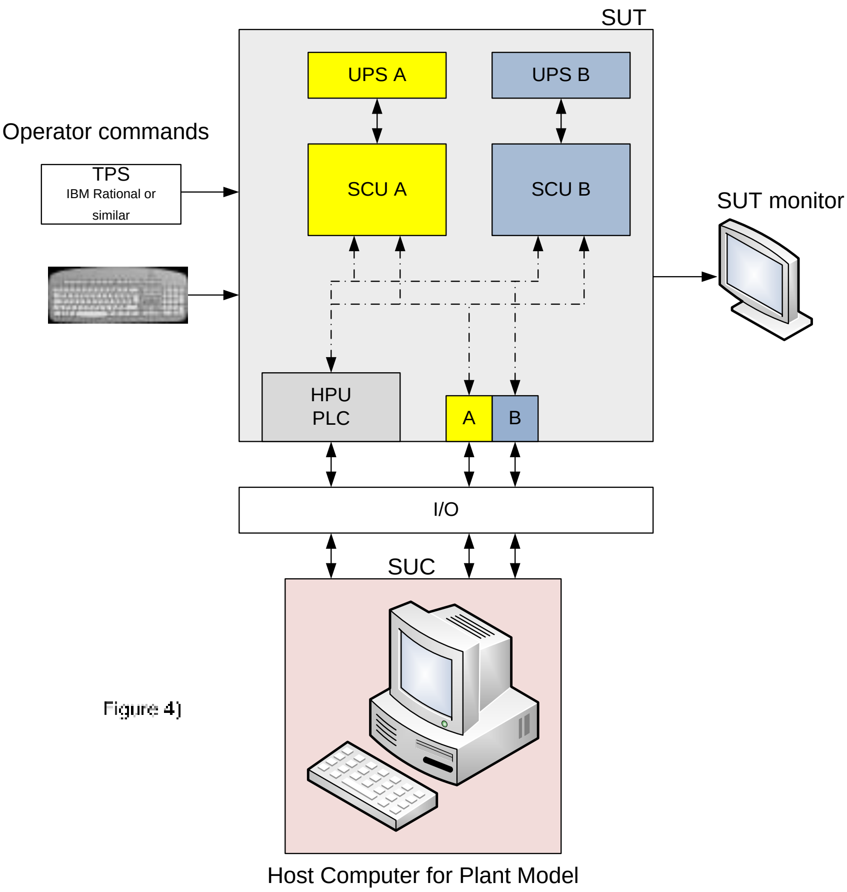


Figure 4) HiL Simulator setup for IWOCS system

In order to run a number of tests, a Test Procedure Software (TPS) is recommended to use as operator commands. This gives the advantages of automate tests, ensure repeatability, which is convenient especially for regression testing.

6.2 Expected Results

Using HiL simulation technology for testing control systems makes it possible to perform extensive testing at an early stages of the development process. Safety routines can be developed, optimized and verified against systems with same response as the real systems without damaging equipment or creating hazard situations for test personnel.

One example that is difficult to test in real can be shearing a subsea landing string with the Blow-Out Preventer (BOP) valve while producing on a gas well with high pressure. What happens when the BOP valve penetrates the shear joint and the gas evacuates to the BOP/Marine riser? Will the system return pressure increase above supply pressure? Will the safety functions still be available with high return pressure?

Another example can be regression testing. With a verified HiL simulator, testing can easily be performed on new software releases at any time. Some systems are continuously in operation, installed on the vessel offshore. They have limited access for testing new software configurations and a validated HiL simulator will be a good replacement for the offshore test in most cases.

During the IWOCS development phase, HiL simulation is a valuable tool for performing design optimization and hardware/software debugging. HiL simulations can help the IWOCS industry to develop products more cost effectively with improved test thoroughness. HiL simulations can also reduce the possibility of serious problems being discovered after a system has been delivered in to system integration tests or put in to operation on a subsea well.

In Steve McConnells book, Code Complete, is there a table showing the cost for fixing defects in different stages of the system development.

Cost to fix a defect		**Time detected**				
		Requirements	**Architecture**	**Construction**	**System test**	**Post-release**
Time introduced	Requirements	1 x	3 x	5-10 x	10 x	10 - 100 x
	Architecture	-	1 x	10 x	15 x	25 - 100 x
	Construction	-	-	1 x	10 x	10 - 25 x

As shown in the table, by identifying the software defects as early as possible will give an economical advantage.

We know that traditional software test methods are not perfect as mentioned in section 5.1 in this document. Introducing HiL simulations as an enhanced test method will give advantages in both safety and economy.