MODEL BASED DESIGN AND INTEGRATION TESTING OF OIL & GAS DRILLING TOOLS

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Motivation & Approach
Case Study
Wrap Up
We invent smarter ways to bring energy to the world

We are BHGE

Only BHGE has a fullstream capability: the portfolio, the technology, and the people to radically transform the industry and deliver unparalleled improvement in industrial yield for our customers.

120+ COUNTRIES

64K+ EMPLOYEES

$22B* COMBINED 2017 REVENUE

$600M+* COMBINED 2017 R&D SPEND
FULLSTREAM

Upstream
- Evaluation
- Drilling
- Completion
- Production & optimization

Midstream
- Pipeline & storage
- LNG

Downstream
- Refinery
- Petrochemical & fertilizer
- Industrial power & processing
DRILLING AND EVALUATION

FUNCTIONS
- Logic driven systems
- Control systems
- Signal processing

ENVIRONMENT
- Depth: 10 km
- Pressure: 2000 bar
- Temperature: 175 °C

LOGGING WHILE DRILLING
- Formation evaluation

POWER & COM UNIT
- Generator CTL
- Pulser CTL
- Communication (≤40 bit/s)

STEERING UNIT
- Trajectory CTL
- Directional measurements
MOTIVATION

SYSTEM LEVEL TEST OF OIL AND GAS DRILLING TOOLS

LIMITED ACCESS
- Deep black hole
- No diagnostic plug
- Mud pulse telemetry

EXPENSIVE
- Time consuming
- Offshore rig
  \( \frac{1}{2} \ldots 1 \text{ Mio. } \$ / \text{day} \)

LIMITED POSSIBILITIES
- Error insertion
MOTIVATION

TIME TO MARKET

COST OF FAILURE

COMPANY REPUTATION

![Graph showing Project Timeline, Profit, Cost of Failure, and Company Reputation with a rating of 5 stars.](image)
**APPROACH**

**INTEGRATE AND TEST EARLY**
- Requirements
- System Specification
- Sub-System Architecture
- Unit Design
- Implementation & Deployment
- Functional Acceptance Test
- System Integration & Test
- Subsystem Integration & Test
- Unit Test

**MODEL WHAT YOU DON’T HAVE**
- Sensors
- Mud Hydraulics
- Valves
- Formation

**INVOLVE „ALL“ DISCIPLINES**
- Electric
- SW/FW
- Mechanic
- Operations
CASE STUDY - DOWNHOLE ISOLATION PACKER

Introduction

Integration Testing on System Level
DOWNHOLE ISOLATION PACKER

**SCOPE**

- Mitigate risk related to fluid influx
- Isolate or reduce a kick
- Restore well stability

Lucas Gusher, Spindletop, Texas, 1901

(John Trost, American Petroleum Institute)
DOWNHOLE ISOLATION PACKER

SCOPE
• Mitigate risk related to fluid influx
• Isolate or reduce a kick
• Restore well stability

TOP LEVEL REQUIREMENTS
• Shut-in the drill string
• Shut-in the annulus
• Circulation through bypass
PLANT OVERVIEW

SURFACE

DOWNHOLE

Drill String
Blow Out Preventer
Annulus

Drill Bit
MUD PIT
PUMP
MUD PIT
DRILL PIPE
ANNULUS
DRILL BIT
SYSTEM OVERVIEW

FUNCTIONAL MODEL
- Main Logic
- Actuator Logic & CTL

PLANT MODEL
- Sensor
- Actuator
- Environment

Driller Inputs (e.g., Flow Rate)

Pressure

CMD
Status

$V_u, V_v, V_w$
$\varphi_{Motor}$
**ENVIRONMENT MODEL**

**PACKER ELEMENT (SIMSCAPE FLUIDS)**

\[ A_0 = \pi (r_2^2 - r_1^2) \]

\[ V_{Packer} = \pi r_1^2 l_{Packer} \rightarrow r_1 = \sqrt{\frac{V_{Packer}}{\pi l_{Packer}}} \]

\[ A_0 = \pi r_2^2 - \frac{V_{Packer}}{l_{Packer}} \]
ENVIRONMENT MODEL

PACKER ELEMENT (SIMSCAPE FLUIDS)

Completion Packer Element
(Baker Hughes, a GE Company)
CASE STUDY - DOWNHOLE ISOLATION PACKER

Introduction

System Level Testing
SYSTEM LEVEL TESTING

![Diagram of system level testing process]

- **Functional Model**
  - Main Logic
  - Actuator Logic & CTL

- **Plant Model**
  - Sensor
  - Actuator
  - Environment

- Driller Inputs (e.g., Flow Rate)

- Interconnections:
  - Pressure
  - $V_U, V_V, V_W$
  - $\phi_{Motor}$
  - Force
  - Position

- BAKERS HUGHES
  - A GE company
USER ACCEPTANCE TEST

HMI

FUNCTIONAL MODEL

Main Logic

Actuator Logic & CTL

1 Hz

100 Hz

1 kHz

CMD

Status

CMD

Pressure

V_u, V_v, V_w

\( \varphi_{motor} \)

PLANT MODEL

Sensor

Pressure

Environment

Valves

Formation

Driller Inputs (e.g., Flow Rate)
**User Acceptance Test**

**HMI**

**Input:**
- Operator CMD → Functional Model
- Drilling parameters → Environment
- Error insertion

**Output:**
- Tool status
- FSM state
- Plant status
**SYSTEM LEVEL MIL**

**APPROACH**

**Actual =? Set Value**
- Size of Set Value list
- Creation of set values
  - Based on Rules

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</table>
**SYSTEM LEVEL MIL**

**APPROACH**

**ACTUAL =? SET VALUE**
- Size of Set Value list
- Creation of set values

**RULE CHECK**
- Intuitive
- Rules derived from requirements
- Knowing when you are done

<table>
<thead>
<tr>
<th>Time Step</th>
<th>Variant Control</th>
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<td>...</td>
<td>...</td>
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<tr>
<td>996</td>
<td>2</td>
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**RULE SET**

- Rule 1
- Rule 2
- Rule 3
- Rule 4
- Rule 5
**System Level HIL**

**Model Based Design**
- **Matlab Simulink**
  - Test Cases
  - Main Logic
    - Act. Logic
    - Act. CTL
  - Generated Code (Embedded Coder)
  - Generated DLL (Embedded Coder)

**HIL Testing**
- Test Cases
- FW on Tool
- Actuator Hardware
- Real Time Environment
- Pressure
  - Sensor
- Environment
  - Sensor
- Valves
- Plot Hydraulics
- Valve Position
- Force
- Valves
- Formation

**Actuator Hardware**
**SYSTEM LEVEL HIL**

**SURFACE SOFTWARE**

<table>
<thead>
<tr>
<th>Sensor inside drill</th>
<th>Temp. [°C]</th>
<th>Mode</th>
<th>Node Status</th>
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<tbody>
<tr>
<td>MD</td>
<td>187.3</td>
<td>1</td>
<td>✔️</td>
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<tr>
<td>Sensor inside pad</td>
<td>187.3</td>
<td>0</td>
<td>✔️</td>
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<tr>
<td>Sensor annulus drill</td>
<td>187.0</td>
<td>1</td>
<td>✔️</td>
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<tr>
<td>Sensor annulus pad</td>
<td>187.0</td>
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<td>✔️</td>
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</table>

**Actuator Logic & CTL**

<table>
<thead>
<tr>
<th>State</th>
<th>Node Status</th>
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<tr>
<td>Closed</td>
<td>✔️</td>
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<tr>
<td>Running</td>
<td>✔️</td>
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**Environment State**

- TCP/IP

**Error Insertion**

- TCP/IP

**REAL TIME ENVIRONMENT**

**HARDWARE**

- Actuator
- Sensor
- Mud Hydraulics
- Formation

**Driller Inputs**

- Flow Rate (e.g., 1 Hz)

**Drill MDC**

- Motor
- Valve
- Position
- Force

**Setup**

- S1
- S2
- S3

**CMD Status**

- 1 Hz

**Model Visualization & CTL**

- Visualize drilling process [TCP/IP]
WRAP UP
Wrap Up

Early, Flexible

Collaboration

Reusability

MI, HIL

Electric

Mechanic

Operations

SW/FW

Model Visualization & CTL

Environment State [TCP/IP]

Error Insertion [TCP/IP]

Driller Inputs (e.g., Flow Rate)

Real Time Environment

Environment

Sensor

Mud Hydraulics

Valves

Pressure [°C]

Valve Position

Sensor

Valves

Formation

Environment

TCP/IP

Real Time Environment

Environment

Sensor

Mud Hydraulics

Valves

Pressure [°C]

Valve Position

Sensor

Valves

Formation

TCP/IP
BACKUP SLIDES
ENVIRONMENT MODEL

ACTUATOR MECHANICS (PLANT)
CASE STUDY: HIL REAL TIME SETUP

Real Time Target

Real Time

Host (Windows)

Visualization Driller I/O

I/O

Real Time

 DLL

Environment Model

FPGA

TCP/IP

Model State

Driller Inputs

Error Insertion

PSENS

Pos.VALVE

i²C

PSENS

Baker Hughes
a GE company
CASE STUDY: FIRMWARE ARCHITECTURE

Dhip Ctrl
- dhipMainLogic_C
  - dhipMainLogic_SC
    - lib_dhipMainLogic
  - dhipActuatorLogic_SC
    - Lib_dhipActuatorLogic

DhipActuatorLogic_C
- dhipActuatorLogic_SC
  - Lib_dhipActuatorLogic

DhipActuatorProbe_C
- dhipActuatorControl_SC
  - lib_ActuatorPosCtrl
  - lib_CmdHandler
- SensorlessMotorCtrl_SC
  - observerDQ
  - lib_CalcWM
  - MotorCurr Ctrl

Component
Sub-Component
Project Specific Unit
Common Libraries
SYSTEM LEVEL TESTING

UNIT TEST COMPLETED

STATIC:
• V&V Toolbox
• MAAB (subset)
• Custom rule set

DYNAMIC:
• XLS based test cases
• Actual =? set value
• Coverage
• Report generation

“Per testcase“ XLS Sheet

<table>
<thead>
<tr>
<th>Time Step</th>
<th>Input_1</th>
<th>Input_2</th>
<th>Out1 Act. Value</th>
<th>Out1 Set Value</th>
<th>Out2 Act. Value</th>
<th>Out2 Set Value</th>
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</thead>
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<td>x2(0)</td>
<td>0</td>
<td>0</td>
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</tr>
<tr>
<td>1</td>
<td>x1(1)</td>
<td>x2(1)</td>
<td>10</td>
<td>10</td>
<td>-3</td>
<td>-3</td>
</tr>
<tr>
<td>2</td>
<td>x1(2)</td>
<td>x2(2)</td>
<td>10</td>
<td>20</td>
<td>-5</td>
<td>-5</td>
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