A New Approach to Development and Validation of Artificial Intelligence Systems for Drilling

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Drilling operations for geothermal and hydrocarbon energy involves technology that controls a highly dynamic and complex process. A transition from assisted control to a higher level of automation not only requires a step-change in technology but also in infrastructure for development and validation of these technologies. The lack of realistic and scalable test environments for automated drilling systems delays qualification of new technology and limits the potential for the industry to reduce costs and minimize the carbon footprint. Since 2016, a high-fidelity drilling simulator has been established and tested for development and validation of Artificial Intelligence (AI) systems for drilling operations. The simulator can be accessed through a web Application Programming Interface (API) and run from a web client or as a Hardware-in-the-loop (HIL) simulator from a control system environment with programmable logic controllers (PLCs). The web enablement makes the simulator suitable for testing AI systems from anywhere in the world without any installation of software. The HIL functionality enables a workflow from early development stages to industrial pilots involving testing in a realistic environment. This paper describes the objectives of the project, the technical solutions, and the results obtained.

Keywords: AI Systems, Process modelling, Process control, Simulator, Web Application Programming Interface

I. Introduction

The scope of automation has expanded from automating the behaviour of machinery to automating the entire drilling and well process. Modern drilling automation systems involve complex AI systems [1-2]. Therefore, test environments for development and validation of new technology need to be in place to meet this transition. Earlier work has shown examples of testing AI systems in realistic environments [3]. Performance of new systems must be tested in normal and abnormal conditions of which the behaviour of the well is an essential factor [4]. During drilling operations large amount of data is collected. However, due to its sparseness, the amount of information that can be retrieved from the data is often limited, and the effort to use the data for analysis and process control purposes is challenging [5-8]. Full-scale test facilities, such as the Ullrigg test centre at NORCE in Stavanger, can not facilitate the variety of abnormal conditions that may occur during the drilling process. The lack of test environments and the risks associated with a failed drilling operation delays the development and the roll-out of new technology in the field [9]. Realistic and high-fidelity drilling simulators have been around for some years to address this challenge [10].

In this work, a simulation environment is presented which facilitates a more streamlined workflow for development and validation of AI systems .

II. The OpenLab Drilling Simulator

During the OpenLab Drilling Project, NORCE in cooperation with the University of Stavanger and industry partners, has created a new drilling simulation infrastructure for development and validation of AI systems for drilling and well operations. The motivation has been to facilitate a more user-friendly and effective workflow to accelerate innovation from early idea to a proven application in the field. It uses field proven high-fidelity models which simulates drilling operations realistically with respect to hydraulics, temperature, cuttings transport and drillstring mechanics, and their interactions.

In the first phase of the project a web-enabled drilling simulator has been developed. This is an online simulator suited for research and engineering on event detection, diagnostics and decision support systems, and for education in drilling engineering and computational.

In the second phase, a drilling control room with hardware-in-the-loop (HIL) simulators was built to enable development and validation of systems in a realistic environment with drilling control systems incorporated. One of the HIL-simulators is a digital twin of the Ullrigg test rig in Stavanger. This simulator includes the Cyberbase™ drilling control system and the NOVOS™ system from National Oilwell Varco (NOV). The NOVOS™ system is used for integration of third-party software. The other HIL-simulator is a digital twin of the Mariner Platform in the North Sea with an MHWirth drilling control system and the DEAL™ system. The DEAL™ system is used for integration of third-party software.

III. Web Enablement

The primary objective behind the development of the OpenLab infrastructure has been to stimulate education, research and innovation and to increase the acceptance and uptake of new technologies within automated drilling. A secondary objective has been to create a user-friendly

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interface to high fidelity models so that realistic (but artificial) data can be available for students, lecturers, and analysts (researchers and engineers).

Because of the advantages over desktop applications, a web-based solution has been preferred to meet the objectives. Among the benefits are:

- Cost effective development
- Accessible anywhere
- Easily customizable
- Accessible from a range of devices
- Improved interoperability
- Easier installation and maintenance
- Adaptable to increased workload
- High security when deployed on dedicated servers
- Promotes e-learning

To reach out to as many users as possible the OpenLab Drilling project has focused on user friendliness for researchers and engineers, as well as students,. The graphical user interface (GUI) has therefore been developed in close collaboration with both experts in drilling and unexperienced students, lecturers of drilling courses and experienced researchers.

IV. Design principles

Each user group has specific needs and skills, which have been assessed through interviews and user tests.

Students	Are not familiar with the drilling engineering. Are familiar with web interaction. Are not familiar with the drilling process.
Lecturers	Needs accurate scenario-based simulations, still easy onboarding of students. Prefer the student to spend time on understanding the scenario rather than the software. Benefit from systems which allow easy collaboration and knowledge sharing. Need to design projects, tasks and assignments in an easy way.
Analysists/ engineer	Collaborate to a larger extent with other users in their daily work. Need a high variety in configurations and simulations.

Table 1: Characteristics of the user groups

Although these user groups and their individual users have different needs and expectations to a drilling simulator, there are some common requirements. These are mainly related to user friendliness in configuration and simulation, uptime and robustness of the software, simulation speed and storage capacity of configurations and results.

The comprehensive configuration process needed to run high-fidelity simulators is a barrier to entry. These models require a large amount of configuration parameters to be specified. By configuration we mean the description of all the elements and components that affect the circulation system and drillstring mechanics. In OpenLab the balance between simplicity, yet advanced configurations, has been addressed with a few complementing design decisions: Adequate defaults, deliberate choice of interaction components, and extensive input validation. Selection of default configurations have a big impact when lowering the barrier of entry. A simple choice of preconfigured wells which cover different use cases is therefore presented for the user at entry. Each of these is ready to be simulated interactively. The user is guided through the configuration of casing architecture, trajectory, drill string design, drilling fluid parameters, geo-pressures, and geothermal gradient. All of which comes with default configuration parameters. This allows learning in a step-by-step fashion while retaining sufficient flexibility for experienced users to input complex scenarios.

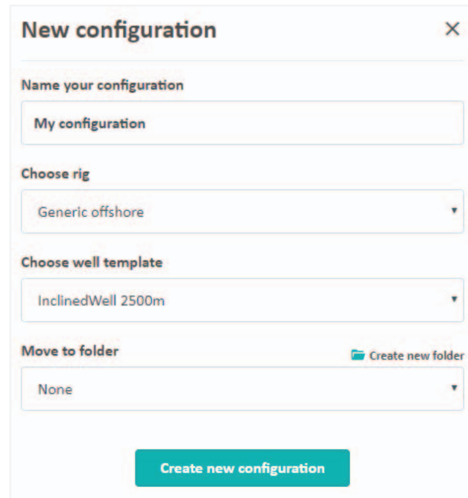

Figure 1:The input dialogue box to create a new configuration allows the user to choose between templates.

Although adequate defaults are provided, the user may adjust most interacting configuration options and setpoints. Without any validation of configurations and simulation setpoints, inconsistent options would result in invalid input to the simulation models. This is unacceptable since the user is not informed about the inner workings of the simulator. To remedy this, a validation layer has been developed that catches conflicting configuration parameters. Nevertheless, the default configurations can be changed based on the user's own specifications. A change in a configuration may lead to validation errors that is presented together with a message describing precisely which variables that need to be changed to regain validity. A configuration is not approved for simulation until all validation errors are addressed by the user.

V. Simulations in web client

OpenLab allows simulation of a wide range of drilling problems such as kick and los circulation, hole cleaning problems, pack-off, plugged bit nozzles, buckling, pipe, and washout. In addition, mechanical and hydraulic friction factors can be adjusted during a simulation to manually adjust obstructions to flow or drill string movement. To run a new simulation, a few initializations parameters need to be entered. The initial depth of the drill bit defines a starting point for the simulation. When running a simulation several setpoints (manipulated variables) can be edited at any time to simulate a drilling process. These are related to fluid flow, pit and mud system temperature and densities, drill string movements, adjustment of choke openings and controlling the blow out preventer.

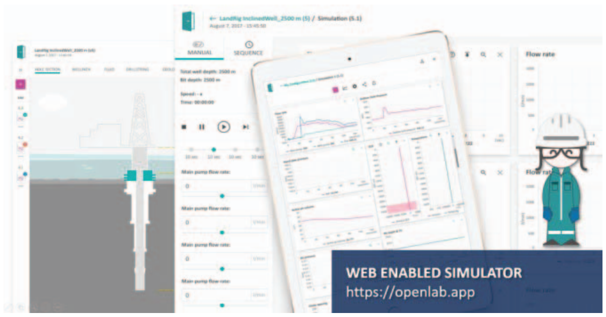

Figure 2: OpenLab can be accessed from a web browser created with the purpose of assisting the user to create configurations and run simulations..

All setpoints are constrained by upper and lower bounds to prevent the user from entering unphysical values or values outside a valid range for the simulation models. The validation of configuration parameters and setpoints guarantees that a simulation will start and run. However, as for real drilling operations the user (or driller) can end up in a situation where only careful adjustment of the drilling parameters will prevent the drill string to become stuck in the borehole, or severe gas kicks to destabilize the well. A simulation can be run into a state where the models can no longer produce a reliable result.

In simulation mode, all relevant time- and depth-based plots are available in the web browser on the user's demand and can suit the scenario at hand. During simulation, the user controls all the main drilling parameters at a time resolution at either 1 or 10 Hertz. The simulator can also run in fast-forward which typically implies up to 10 times real time when running on 1 Hertz, dependent on the client computer's performance and the network latency. The simulation process can be paused, perform a single step, or completed and shut down. A simulation can also run in sequential mode in which a predefined selection of setpoints is entered in a table. The user can then specify changes in any setpoint at a given time and construct a sequence. When executing a sequence, the user cannot interact with the simulator and change any of the setpoints. When the simulator runs in sequence mode, the simulation speed is typically around 20-30 times real time. The benefit by the sequential mode is that the user can run through the same scenario on different configurations and explore how a certain procedure will evolve for different wells, drilling fluids, etc.

Simulation results can be downloaded at any time during or after the simulation from the simulation GUI. For simplicity, all results are downloaded to CSV format for easy processing in e.g. Excel. As for the configurations, the simulations can be shared. Unlike other desktop applications, a web enabled simulator allows other people from anywhere in the world to monitor and interact with the simulation. By fetching the unique simulation ID, given as the Uniform Resource Locator (URL), a user can invite others to monitor ongoing simulations or explore the results on completed simulations. The receiver of a URL can also take control and run a simulation on behalf of the owner of the simulation.

In addition to the browser interface, a web API is available, making the simulator accessible to other clients which supports the HTTP(s) protocols. The OpenLab project has published examples of Matlab and Python clients and our collaborators have developed clients in C# and LabView. These interfaces require special knowledge about the particular programming language and a description of these interfaces is not part of this paper.

VI. Hardware-in-the-loop simulator

The simulation of the rig machinery is diverse and organized in a machine simulation layer in the HIL simulation software module. This layer receives actuator signals from the drilling control system and returns sensor signals to the drilling control system. Each machine (top drive, drawworks, mud pumps, chokes, etc.) is simulated in a separate module with different update frequencies to effectively use the available computational resources. To simplify the integration of these modules a reactive programming approach has been employed.

Since OpenLab supports different drilling control systems, different machine models are available. In the context of a web simulation, relatively simple models of rig equipment are used where accelerations are limited according to the rig parameters. In the HIL simulation context more advanced models are used. These generate many more sensor signals which might not be relevant to the drilling processes but essential for the functionality of the machine in the drilling control system. Also, the necessary signals for the downhole simulation are generated by these models and used there.

It is essential for the HIL simulation to remain in synchronization with the drilling control system. Therefore, the latency of the simulation as well as the communication must exhibit low jitter. To achieve this, a dedicated simulation machine has been placed near the drilling control system and connected through a dedicated network. UDP/IP has been chosen as the communication protocol between the drilling control system and the HIL simulator. Its wide support in programming libraries make this a practical choice. However, it does not guarantee constant packet delay, a problem that is avoided by dedicating network resources exclusively to the real-time communication.

The drilling control system network is not the only network on a drilling rig. Sensors and actuators are installed on a drilling rig which are not integrated in the drilling control system but essential to the operation of drilling process. By using another network interface, these additional systems can be connected with a real-time data source to provide realistic sensor data. Examples are downhole signals transmitted through NOV Intelliserv's wired drill pipe and surface mud property sensors. UDP/IP has been chosen as the communication also for these signals. Efforts are underway to create WITS and other standard consumers of this data to be used in different projects.

VII. Architecture and Simulation Modes

OpenLab is based on a layered architecture which is driven depending on context. The simulation engine is a function which uses the current internal state and waits for actuator signals (setpoints). It then generates the corresponding sensor signals and the next internal state. In the prototyping phase, the setpoints are provided by the client through the Web API for each simulation step. The client may advance the simulation faster than real time. This is useful when simulating long lasting and slow effects such as hole cleaning problems or well control incidents. Since the time resolution of the simulation can be selected between one second (default) and 100 milliseconds. Some parts of the simulation run with a higher time resolution to satisfy the fidelity requirements. The running time is independent of the time resolution. However, the length of the well influences the running time. One simulation step requires in the order of 50 milliseconds for a 2500 meter long well. In the context of a HIL simulation the input is periodically generated by an adapter layer driven by the built-in real-time clock. Thus, the simulation always runs in real time. The drilling control systems require a time resolution of 100 milliseconds.

The OpenLab data centre provides resources to run all simulations in OpenLab. Simulation requests are dynamically matched with available resources according to the requirements of the simulation providing load balancing and scalability. The HIL simulation computers make use of these mechanisms. This enables sharing of test cases and results while the simulation is running with world-wide collaborators. In times with many users of the web enabled simulator, additional servers on Microsoft Azure are used.

VIII. WORKFLOW

A typical workflow includes both the web enabled drilling simulator and the HIL simulator. Each part of the system is valuable by itself, but in combination the benefit becomes apparent. A first prototype of the AI system on an algorithm level, can be tested immediately using the online simulator. The user enters the OpenLab website and uses the graphical user interface to configure different test cases in terms of well architecture, well path, fluid properties, drill-string configuration and geology as well as the rig parameters. Using the Web API the algorithm is connected to the simulator.

A variety of scenarios can be simulated in parallel and quick succession. This enables rapid iterations of algorithm development to improve the performance and robustness and arrive at a workable design. An important aspect of these tests is the ability to trigger realistic simulations of abnormal and undesired drilling conditions. This phase of the development and testing can be done from anywhere with internet access. This stage is focused on arriving at a logically correct algorithm. In this mode, the simulation runs in lockstep with the algorithm. This provides fast testing in case of faster than real-time calculations and a low latency network.

When the prototype software has matured it can be implemented for deployment to the HIL simulator. Examples are a PLC communicating via the network or an app communicating through DEAL™ or NOVOS™. This replaces the Web API communication in the first test phase. Consequently, the real time behaviour of the system is affected. The prototypes then need to be physically installed in the OpenLab drilling control room for further testing. The test cases defined in the prototype phase can now seamlessly be reused for hardware-in-the-loop testing. The simulation is now controlled by the drilling control system and time dependent behaviour can be observed. The web interface can be used to monitor the simulation and trigger abnormal conditions. After the test has ended, the results are available in the web interface and can be accessed from any location for review and sharing with other collaborators.

IX. STATE OF THE ART SIMULATION MODEL

Worldwide, there are several drilling simulators available that include both transient hydraulics- and drill string mechanic computations. In Norway, research and development at Rogaland Research (named IRIS since 2006, and NORCE since 2018) has created the well flow model RF-Kick, later commercialized in DrillBench, which later became part of a Schlumberger Software suite [11]. The RF-Kick was verified by data collected from Ullrigg in Stavanger and validated through various test campaigns both at Ullrigg and other wells [12]. The model was used for planning and special studies for drilling operations. From 2001, Rogaland Research initiated a large program to improve their well flow model and prepare for real-time (online) simulations [13]. A new numerical solver was developed, and the well flow model was integrated with other models such as a soft string (steady state) torque and drag model, and transient cuttings transport model, and recently a transient torque and drag model. This simulation model is commonly known as WeMod and is further described below. Another simulation model was developed during the 2000s by SINTEF [14]. This model, together with a torque & drag model is now used in software for training and real-time monitoring [15]. Another renown well flow model is the simplified well flow model developed at the Norwegian University of Science and Technology and Equinor [16]. A thorough review of these and other models are given in [17].

In OpenLab, the WeMod model can be used to simulate various downhole effects with high fidelity. The simulator consists of a set of fully integrated numerical models:

- A transient multi-phase flow model that solves mass and momentum balance to estimate pressure distribution inside the wellbore. [12, 18-19]. The flow model has been developed and validated over nearly 20 years. Mass flux and pressure in the well, inside the drillstring and on the rig is simulated. Mass flux between well and formation is calculated by an integrated near-well reservoir model.
- A transient cuttings transport model that estimates the distribution of the cuttings inside the annulus and determines whether the drilled solids are in suspension in the drilling fluid or accumulate in cuttings bed [20]. Transport of cuttings by bed erosion is also simulated.
- A torque and drag model that computes the tension and torque distribution along the drill-string. In the current version of OpenLab, the user can choose between a soft string model [21], and a new transient torque and drag model [22].
- A heat transfer model, which computes the temperature evolution inside the wellbore and in the formation near the well [23]. Forced convection, heat conduction, and convective heat transfer are accounted for in the simulations.

The above-mentioned models are integrated. To mention some of the dependencies, the hydraulic model uses the temperature profile generated by the heat transfer model to estimate pressures, densities and velocities in a numerical grid. The results are in turn used by the torque and drag model for buoyancy calculations and by the cuttings transport model for estimation of the transport capabilities. For density and rheology estimations, the hydraulic model uses the proportion of cuttings in suspension generated by the cuttings transport model.

X. PROJECT RESULTS

Until now, the use of simulators like WeMod and other high-fidelity simulators has been overwhelming for students as well as experienced engineers and erects a high barrier to use high-fidelity models for development and validation of AI systems. With OpenLab Drilling a new environment is made available for users who has a need for realistic but artificial drilling data provided by a high-fidelity simulator. This represents a new approach in drilling automation. It allows users with very limited experience to drilling to take it into use but at the same time offers capabilities for the most advanced users.

OpenLab Drilling is now being used as part of regular drilling courses at the University of Stavanger and the University of Calgary. In addition, Master and PhD students at other universities in Norway and abroad are using the simulator. A more detailed description of the types of projects and applications that uses OpenLab is given in [24]. During 2019 the use of OpenLab's web API has reached the target of weekly users which is set to 38 in average throughout the year, as can be seen in Figure 3. The total number of users since January 2019 is nearly 400. Most users are located in Norway with 128 users, followed by Canada and U.S, as given in Figure 4.

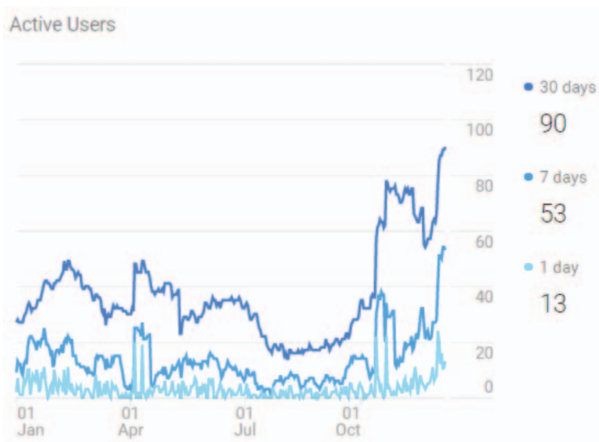

Figure 3: Registered user of OpenLab from January 1st to December 9th, 2019. (by Google Analytics).

There is a large variety in type of systems tested in OpenLab. During 2019-2020, several publications have been published showing the results from AI systems developed and validated with use of OpenLab. The topics include drilling process optimization [25], detection systems using machine learning [26-27], and a system for digital drilling operational planning [28]. Through user surveys the feedback from the users of the web enabled drilling simulator show that most users have a very good impression of OpenLab and that it is much easier to edit configurations and run simulations compared to other simulators available. Around 95% of the users run it from a desktop computer, and less than 5% from tablet or mobile phones. Statistics from Google Analytics show that in 2019, around 67% uses Google Chrome to access OpenLab, while around 7% uses Edge, Safari or Firefox.

In the HIL simulator several projects are being run in 2019. Among these are the "Demonstration of Automated Drilling Process Control", a large development and demonstration project involving Canrig Robotic Technologies, NOV and Sekal among others. OpenLab is used to integrate NOVOS and DrillTronics^{TM} and to develop and validate algorithms for fully autonomous drilling sequences before full-scale demonstration on Ullrigg in Stavanger. This development and testing would not have been possible without the capabilities of OpenLab.

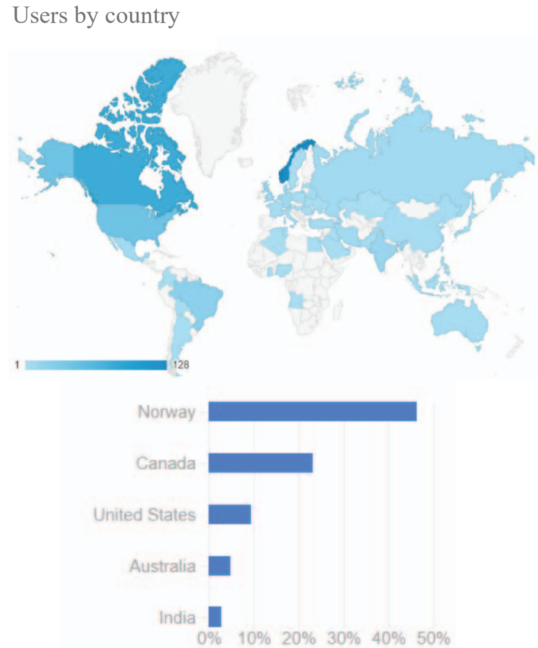

Figure 4: Users in OpenLab by country, registered from January 1st 2019 to May 29th, 2020. (by Google Analytics).

XI. Future Work

In the next years, OpenLab will be extended to provide field data from historical drilling operations. Preliminary work done at the University of Stavanger has shown promising results for importing recorded data from the Volve dataset hosted by Equinor, and automatically create configurations in OpenLab. This is a first step towards an online software that provides a user-friendly interface to recorded drilling data. Today, these data are only available for download as zip-files at data repositories. A better interface to present and utilize drilling data will represent a major improvement for development and validation of AI systems for drilling.

XII. Conclusions

A new infrastructure has been developed with the purpose to accelerate technology readiness for planning and automated drilling software systems. By creating an infrastructure following a principled layered architecture, a flexible and efficient workflow is supported. This accelerates innovation from the conception of an idea to practical testing in an HIL lab involving vendors of drilling control systems. In addition to the accelerated readiness of technology, the infrastructure also helps to ensure that tomorrow's engineers and decision makers have the right competence with respect to programming skills and understanding of the complex and highly dynamic process involved in drilling operations.

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