2nd IFAC Workshop on Automatic Control in Offshore Oil and Gas Production,
May 27-29, 2015, Florianópolis, Brazil

A Simulation Environment for Automatic Managed Pressure Drilling Control

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Abstract: Drilling automation initially gained acceptance in the oil & gas industry as a solution to increase rigsite safety. While safety-related drilling automation has been implemented, many companies are beginning to recognize that drilling automation offers possibilities of performance enhancement also. There has been a rapid increase in the number of wells being drilled, primarily in unconventional reservoirs with the diminishing of easy oil. In unconventional plays, managed pressure drilling has been gaining importance because of its many advantages. Pressure balance through a choke manifold is the principle of Managed Pressure Drilling. Automatic choke control, as opposed to manual operation on field, provides better control on the operations. Different control methodologies (viz. PID, MPC etc.) can be designed to implement the control system. It is important to test the designs on a simulator to determine the optimal methodology before implementing it on the field. A Drilling Simulator designed in LabVIEW with in-built control design and simulation functions solves this purpose.

Keywords: Drilling Automation, Managed Pressure Drilling, PID Control, LabVIEW, Simulation.

1. INTRODUCTION

Put simply, automation is the replacement of human labor by machines. This may be true in many engineering disciplines, but in this paper we will refer to Automation as a technique that makes a system to operate automatically assisting in the human decision-making process. Since the Industrial Revolution, there have been innumerable technological advances used to help humans work more efficiently. From the simple use of pulley systems to highly sophisticated Human-Robot Interactions (HRI), many industries have been quick to adopt these advancements, while some have progressed at a slower pace. Two examples that stand out are the aviation and automotive industries (Thorogood, Florence, Iverson 2013). Both have achieved high levels of automation in their processes, so why not in the case of oil and gas drilling? Perhaps it‘s all the years where drilling was considered an art based on experience rather than science, effectively creating a lag in the adaptation of automation. Just recently, though, the industry has seen rapid changes in terms of drilling automation where completely automated drilling systems are becoming a reality (Eustes 2007).

The main objective for any driller is to simultaneously drill fast and drill safe, ensuring quick and accurate execution (Noynaert 2014). Typically, drilling faster means less time spent drilling, which in turn works to reduce costs. At the same time, though, people are a company’s most valuable asset and keeping their well being intact is of the utmost importance. These objectives can be achieved and maximized with the introduction of automated drilling rigs. This is indeed the main objective of any drilling automation process: increase safety by ensuring that well dynamics does not exceed the ones specified by its natural behavior.

With respect to efficiency, there are many drawbacks in the manual drilling process, mostly because of the constraints on human labor. Most drilling rigs are located in harsh environments, which produce considerable amount of stress on the people working there. The combined effect of an employee‘s workload, stress and fatigue affects performance, creating a greater chance for human error. In an automated system, those same limitations are essentially eliminated and drastically reduce the occurrence of such errors. When it comes down to it, an automated system is faster, more reliable, and more consistent compared to human operations none of which compare to its positive impact on human safety (Iversen et al. 2013).

Safety is the most important aspect of drilling automation. Automating a drilling rig means performing the drilling activities with the help of automated control systems rather than human labor. This results in a reduction of the number of people on the rig floor, away from the process area. Drilling as a whole is a very complex process with several key sub-activities such as the rotary, pipe racking, pumping, cementing, casing, and directional drilling systems to name a few. These systems contain several parameters for the driller and his crew to monitor and control. An automated system can ultimately provide better control over these parameters. This is even more evident in emergency scenarios due to the system's ability to immediately recognize abnormalities. To this end, simulation environments that can handle these challenges are of great value in training personnel in this new paradigm of drilling automation. It also serve as a test bench for rigorously validating physical drilling models and in testing new forms of advanced control systems applied to several drilling processes.

This paper introduces a simulation environment for the case of a Managed Pressure Drilling (MPD) operation. In Automatic MPD, one is concerned with automatically controlling the downhole pressure via a surface choke. Here, we use LabVIEW as a tool for creating this simulation environment. LabVIEW is a simple, user-friendly interface with associated graphics that can be developed such that even non-technical people (rigsite personnel in our case) can operate the program (Bishop 2007). We also developed a joystick-based control capability and designed a PID controller to obtain the desired pressure trajectory.

In the next sections, we provide some historical perspective and the status of drilling automation and MPD and then introduce the mathematical background and software developments used here. We finish the paper with some results obtained with our simulation environment and the introduction of PID control for MPD.

2. DRILLING AUTOMATION - CURRENT STATE OF AFFAIRS

Automation in the drilling industry is less advanced compared to other industries (Thorogood, Aldred, Florence and Iversen 2010). Failure to adopt new technology in any industry can occur for a variety of reasons. The oil and gas industry and the drilling sector in particular, has always been slow to take up new technologies due to economics, safety concerns and the drilling environment. In addition, a mistrust of automation exists, especially of automation of downhole pressure control. This mistrust is based on the inaccurate assumption that a human can better process the data and make better decisions. Another reason for this slow adoption can be attributed to the fact that drilling activity takes place in extreme working conditions, above ground in unhospitable areas and downhole with high temperature, high pressure (HTHP) formations. Finding control equipment and sensors to handle this environment is difficult. It is also important to note that the drilling process is not standard for all wells every wellbore's construction is unique in its own way. Therefore, the modeling of this process cannot be definite, but, instead has to be adaptive. All of these contributing factors make automation in drilling a difficult task. However, with each technological advancement, these limitations are being overcome. It is also no surprise that the recent boom in unconventional reservoirs is adding more motivation for transitioning into automation.

Unlike the automotive or aviation industries, one of the greatest things holding industry back is the lack of a common communication protocol or standards pertaining to drilling automation. This is primarily due to the highly segmented nature of the drilling industry where we must deal with multiple service companies, rig contractors, equipment manufacturers, etc. Apart from the digital infrastructure, the availability of proper instrumentation devices has also hindered progress. Special sensors and other devices are required in the drilling process because 1) the sensors are required to provide real-time data, and 2) many measurements are made in sub-surface environments (Cayeux, Daireaux, Dvergsnes, Florence 2014).

SPE and the International Association of Drilling Contractors (IADC) are working towards bringing automation in drilling to market in the near future. SPE has a specific technical section aimed at these advancements - termed the SPE DSATS (Drilling Systems Automation Technical Section). One of the group's focuses here is on standardizing communication protocol for the industry. The two current standards being considered are namely WITSML and OPC UA. IADC has also put together a committee working on comprehensive automation of the drilling process alongside the integration of surface and down-hole systems (Macpherson et al. 2013).

The next decade is likely to have even more exciting advancements in this area of drilling technology, especially with the current research going on. At this rate, it can safely be said that drilling automation is not a theory anymore and is fast becoming a reality.

3. MANAGED PRESSURE DRILLING

Managed Pressure Drilling is a technique used in the Oil & Gas industry to drill wells which have limitations concerning the pressures which can be applied to the wellbore. Although there is not a formal definition, MPD is defined by a subcommittee of the International Association of Drilling Contractors (IADC) as "An adaptive drilling process used to precisely control the annular pressure profile throughout the wellbore. The objectives are to ascertain the downhole-pressure-environment limits and to manage the annular hydraulic pressure profile accordingly. The intention of MPD is to avoid continuous influx of formation fluids to the surface. Any influx incidental to the operation will be safely contained using an appropriate process."

Not every well drilled requires MPD and it is only applied when required due to complexity and cost. However, if MPD is required, it becomes a vital part of the drilling process. This is due to its importance regarding factors such as wellbore stability as well as the fact it becomes a primary barrier in the well control process, preventing kicks and potentially blowouts.

The MPD process is particularly useful in drilling reservoirs where the pore pressure and fracture pressure gradient window is narrow. Any significant variation (typically loss of annular friction pressure caused due to mud pump shutdown etc.) in pressure causes the bottom-hole pressure (BHP) to go out of the pressure gradient window (or drilling window) resulting in situations like kick or lost circulation. It is not practically possible to balance the pressure variations with hydrostatic (mud) head. As can be seen in Fig. 1, the mud weight in the wellbore must be kept above or the right of the pore pressure gradient in order to avoid taking a kick or influx of hydrocarbons. However, the pressure must also be kept below or the left of the

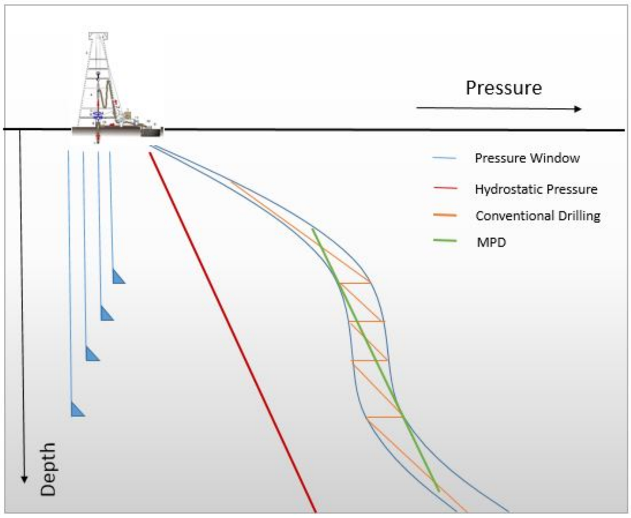

Fig. 1. Rough sketch of Managed Pressure Drilling using Constant Bottom-hole pressure technique

fracture gradient to avoid fracturing the formation and losing mud and wellbore integrity. While formation pressures are generally controlled with hydrostatic pressure, it is not practically possible to balance the pressure variations with hydrostatic (mud) head for the entire length of the wellbore. Therefore, the standard method is to set a new casing string anytime this is not possible. In areas with a narrow window between the two, such as in deepwater fields, this can result in much higher costs due to the number of casing strings required. MPD offers a solution to some of these problems. There are different techniques under the MPD umbrellas such as Constant Bottom-hole pressure (CBHP), Pressurized Mud-cap drilling, Dual gradient technique and others.

CBHP technique has been used in our model. It is a process in which the bottom-hole pressure is maintained at a constant pressure (pressure window in practice) specific to a depth, irrespective of pressure variations.

The application of MPD technique becomes vital in offshore wells which are some of the most difficult and most expensive wells to drill and complete. Most of the current offshore resources are difficult to drill economically using the conventional drilling methods. There are even cases where the pore pressure and fracture pressure gradient curves almost overlap making it extremely difficult to maintain wellbore integrity. Significant non-productive time (NPT) is caused by kicks, lost circulation and other problems in the high pressure, yet low strength formations. These issues can be resolved and other advantages like ROP enhancement and better well control can be achieved using MPD in the offshore wells (Noynaert 2014).

4. MATHEMATICAL MODEL - MPD

The MPD process is a closed loop mechanism as opposed to the open loop system in conventional drilling processes. A back pressure coupled with a choke manifold is used to compensate for the pressure variations in the wellbore. A simple mathematical model is developed for the setup using mass balance in the annulus (Godhavn 2010). To this end we write:

$$\frac{d\left(\rho V\right)}{dt} = \rho Q_{in} + \rho Q_{bp} - \rho Q_{out} \tag{1}$$

where Q_{in} indicates mud pump flow rate in to the drill pipe ; Q_{out} is mud flow rate out of the annulus ; Q_{bp} is flow rate due to the additional back pressure pump; ρ is mud density; V is annular volume

Assuming that changes in annular volume are negligible and the difference in density values along the borehole length are insignificant, we can derive the relation for the rate of change of density as:

$$\frac{d\rho}{dt} = \frac{\rho\left(Q_{in} + Q_{bp} - Q_{out}\right)}{V} \tag{2}$$

By introducing compressibility factor, the density rate changes can be expressed in terms of pressure rate changes as follows:

$$\beta = \frac{1}{\rho}\frac{\partial P}{\partial \rho} \Rightarrow \frac{d\rho}{dt} = \beta\rho\frac{dP}{dt} \tag{3}$$

$$\frac{dP}{dt} = \frac{Q_{in} + Q_{bp} + Q_{out}}{\beta V} \tag{4}$$

The system can be modeled as a closed-loop system by compensating for the pressure losses with a back pressure pump through a choke manifold. The flow rate out of the choke and pressure are related with choke characteristics. The choke opening (position), z is the control variable of the system.

$$Q_{out} = C_v(z)\sqrt{\frac{P}{\rho}} \tag{5}$$

A PID controller (control variable z) has been used in this model to control the choke pressure and track the set bottom-hole pressures (reference variable).

$$z = Ke + \frac{K}{T_i}\int e.dt + KT_d\frac{de}{dt} \tag{6}$$

The non-linearities in the system can be compensated by linearizing the model using nominal values (denoted by '0') and with careful tuning of the PID controller, it can be represented as a first order system.

$$P_0 = \rho_0\left(\frac{Q_{out0}}{C_v(z_0)}\right)^2 \tag{7}$$

$$\Delta P = \frac{a\Delta z + c\Delta q}{1 + T_p s} \tag{8}$$

$$a = \frac{\partial P}{\partial z}|_0; c = \frac{\partial P}{\partial Q_{out}}|_0; T_p = \frac{-1}{\frac{\partial \dot{P}}{\partial P}}|_0$$

The values of the unknowns can be found from field data. The work by Godhavn (2010) has detailed description of the model. This control system for automatic MPD was successfully implemented at the Kvitebjorn field in the North Sea.

To provide real-time measurements of bottom-hole pressure for the feedback system in the simulation, the BHP is calculated as a sum of all the annular pressures including hydrostatic pressure (due to mud column), annular friction pressure losses (due to circulation), surge, swab pressures as well as any surface pressures. API Power Law model has been used to model the friction pressure losses.

$$BHP = Hyd + AFP + BPP$$
$$AFP = \Delta P_{DP} + \Delta P_{DC} + \Delta P_{Nozzle}$$
$$+\Delta P_{DC-Ann} + \Delta P_{DP-Ann}$$
$$+\Delta P_{surge} + \Delta P_{swab}$$

*Other pressure losses are neglected.

where BHP is Bottom-Hole Pressure; Hyd is Hydrostatic pressure due to mud column; BPP is Pressure due to back pressure pump; AFP is Annular Friction Pressure losses

5. DRILLING SIMULATOR IN LABVIEW

LabVIEW (Laboratory Virtual Instrument Engineering Workbench) is a National Instruments' software development environment. It has wide variety of industrial applications with major application areas such as Automation, Control and Data Acquisition. As its name suggests, LabVIEW provides an environment in which engineers can design their own laboratory instruments quickly and easily. These personally-designed laboratory instruments are called Virtual Instruments (VIs). LabVIEW's simple interface and easy-to-learn programming language make it a perfect choice for developing control applications (Bishop 2007). Data acquisition (DAQ) is handled easily with predefined block functions. Signals read from DAQ components are manipulated with standard block functions and the results of the program can be easily sent to an output board, which in turn sends signals to the plant.

In this work, LabVIEW has been used to develop a simulation environment for experimental purposes. Automated models can be developed for various stages of the drilling process and the models can be simulated and tested on this LabVIEW simulator. The system parameters or control algorithms can be modified and changes in performance of the system can be studied. This means the process are simulated and tested in a safe, no-cost environment on the LabVIEW simulator before implementation in real-world systems.

The simulator serves as a tool in wide range of applications for students, drillers and operators. Students can use the simulator to implement any type of control architecture for different operations. If virtual modules in the program are replaced with data acquisition devices, the simulator can be used by driller/ operator to control an actual drilling operation.

5.1 Why LabVIEW?

Interactive GUI - A simple, user-friendly interface (called 'Front panel') with graphics can be developed on this platform such that even non-technical people (Rig men in

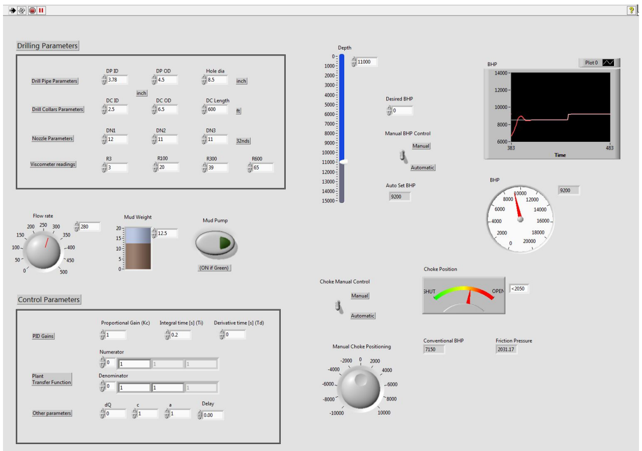

Fig. 2. Front Panel of Drilling Simulator

our case) can operate the program. Even the programming is intuitive with drag and drop graphical icons instead of writing several lines of text.

Hardware integration - Data acquisition tools that can acquire data from almost any type of device are available. With the help of these tools, it is possible to use the same simulated program developed for mathematical automated models for real-world implementation on field as well just by replacing few blocks in the program. This deployability feature in LabVIEW i.e. the deployment of Virtual Instrument (VI) directly into the field allowing HIL/SIL applications is one of the main advantages of building simulator in LabVIEW.

Advanced Control - There are several in-built functions (such as PID Autotuning, MPC controller among others) in the software, Control Design and Simulation toolkit in particular which is of high relevance to the drilling automation applications. Any control algorithm from basic PID to non-linear control can be used directly in the program. There are provisions to execute multiple parallel loops also at high speeds on FPGAs and real-time processors.

5.2 Drilling Simulator

A Drilling Simulator has been designed in LabVIEW to serve as a basic simulation environment for testing and simulation purposes. The performance of the model and the designed control system can be studied from the simulation results. A PID controller is designed and simulated for MPD operations in the drilling simulator. Other control methodologies like MPC (Breyholtz, Nygaard, Nikolaou, 2011) can also be modeled and implemented in the simulator. The model is a simplistic one with several limitations. The model is based on the assumption that bottom-hole pressure reading is available in real-time. In this paper, we assume an ideal model such that the bottom-hole pressure reading is available in eral-time. This imposes some limitations that can be easily fixed in real scenarios. The structure of the simulator is described below.

5.3 Front Panel

This is the face of the (virtual) instrument. The front panel of the drilling simulator is a user-friendly GUI that depicts the control room at the drilling rig site. The user has option to select the type of formation to be drilled. The user has to input various drilling parameters being used in the drilling operation such as drill pipe dimensions, drill collar dimensions and bit nozzle sizes (these are used to calculate annular friction pressure losses). In addition, the user has to input control parameters viz. plant model variables calculated based on the field data. Once all the inputs are given as shown in Fig. 2, the simulation can be started.

The drilling operation can be started by lowering the pipe either by increasing depth manually, using a slider or by using a joystick to control the movement of drill pipe. As the simulation is running, the user has control over parameters like mud pump operation - ON/OFF, mud flow rate and mud weight that causes variations in the BHP. There are display options for pressure gauges, choke position monitor, BHP variation chart window and any other information needed by the operator. There are also options for manual control of equipment that are automated in the simulator viz. choke opening or set point of BHP. (The simulator runs by default in automatic mode).

5.4 Block Diagram

This part of the simulator runs in the background, which is where the actual programming is done. LabVIEW has an exclusive toolkit for design of control systems called "Control Design & Simulation" Tookit. The drilling simulator was developed using many of the in-built functions of the toolkit.

The main part of the program is built inside the Simulation loop function. Some important functions used are PID Controller, PID Autotuning, Construct Transfer Function, Simulation Timing and Feedback node among others. (shown in Fig. 3). These functions were used in the program to track reference bottom-hole pressures at various depths. These reference points are set using a lookup table function. Data acquisition functions are used to read values from joystick. Graphics functions like 3-D picture control were used to display 3-D animations of the formation and drill pipe as the process of drilling in the formation was carried out.

5.5 Highlights

Remote Control - The drilling simulator can be accessed by other users from any other location over internet. LabVIEW has different tools to accomplish this. In real-world application, the drilling program can be hosted by a driller at the drill rig site and the program can be shared with other users (can be supervisor at office, contractors and others). The users have the provision to monitor the drilling activity as well as control the drilling operations from their locations through a web browser. We have used a simple web publishing tool in LabVIEW to share the drilling simulator with other users. This application is useful in situations where frequent access to the rig site is not possible.

3-D Graphics - The drilling activity can be seen as a 3-D animation (with 360 degree camera control) on front panel in real-time as the simulation is running. The movement of the drill-pipe (including rotation) and the formation being drilled are shown in the animation. Other equipment like mud pump, back pressure pump, choke manifold can be included in the animation further.

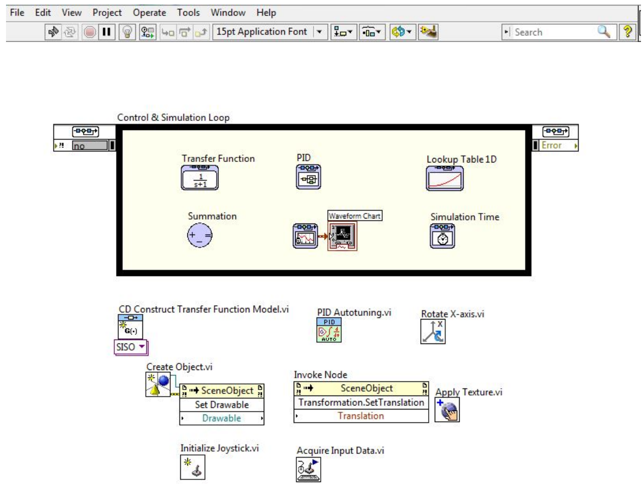

Fig. 3. Major function blocks used in Block Diagram of Drilling Simulator

Fig. 4. Joystick Control of the Drilling Simulator

Manual Over-rides - It is important to have manual override controls for all the operations that are automated. This is to have a better control in case unpredictable incidents occur. In the drilling simulator, there are manual controls for choke operation and setting bottom-hole pressure.

Realistic simulation - To provide a feel of the real-world drilling operation, control of the movement of drill pipe (up and down the borehole) is done using a joystick (Windows Xbox 360 controller in this case). The joystick is treated as an input device and data is acquired in to the program. Other parameters that can be controlled using the joystick are mud pump ON/OFF operation, manual over-ride toggle switches etc. as shown in Fig. 4. A vibration feedback can also be included in the program to indicate when the drill pipe is on-bottom for example.

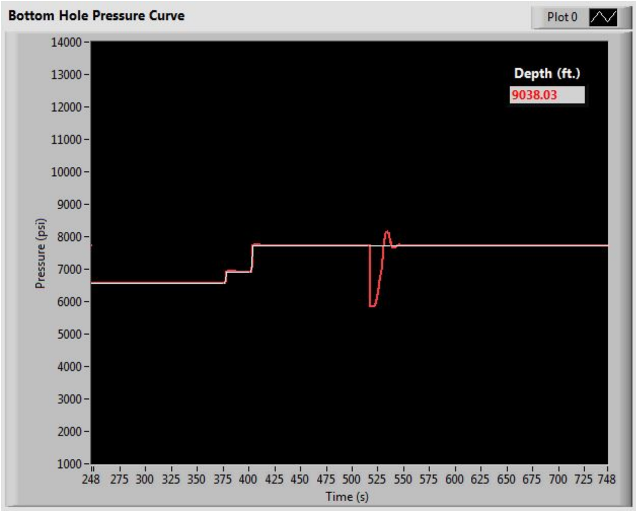

Fig. 5. BHP is maintained with set-point tracking

6. EXPERIMENTS IN THE LABVIEW DRILLING SIMULATOR

The Drilling Simulator developed in LabVIEW was tested on synthetic field data. Plant parameters are chosen arbirtarily. There is provision to manually adjust PID gains. However, a LabVIEW in-built function 'PID Auto-tuning' can be incorporated instead. With this setup, the simulation is run over a depth of 0 - 14,000 ft. Several test cases as mentioned below are applied to test proper functioning of automatic MPD operation in the simulator.

(1) Normal drilling operation with mud circulation - Constant BHP is maintained
(2) Mud Pump is switched OFF - BHP adjusted by the back pressure (choke operation)
(3) Manual BHP control - Desired BHP can be maintained at a depth
(4) Manual Choke control - choke opening to adjust pressure variations
(5) Changes in drilling parameters like mud weight, flow rate etc.

The objective of the control system is to track the set pressure values such that bottom-hole pressure is maintained constant in any case. As shown in Fig. 5, the required BHP (represented by white line) is efficiently tracked (red line represents measured BHP) by the controller. At around 525 seconds (not real time) mud pump is switched OFF which led to a drop in BHP (as there is no annular friction pressure now). It can be seen from the figure that the required BHP is achieved (after transients) at around 550 seconds. The set-point tracking can also be seen when the reference BHP value is increased at 375 seconds.

As mentioned, the simulation is performed with fabricated data. The well profile is not described exclusively here because the example is very general and the simulator allows the user to change the well model seamlessly to explore any other formulations. The novelty here is that the simulator can be used as a platform for implementing any kind of control technique. Other test cases are not described due to lack of space. More examples will be explored in a forthcoming paper.

7. CONCLUSION

In this paper we developed a simulation environment for drilling automation. In particular we developed an automatic control for a managed pressure drilling (MPD) operation using PID control techniques. Although the level of realism in the drilling process was not the main focus of the paper, the simulation environment allows us to replace the controller with modern techniques such as model predictive control (MPC) and nonlinear/robust robust control techniques.

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