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Demonstrating a New System for Integrated Drilling Control

F. Iversen, International Research Institute of Stavanger (IRIS); E. Cayeux, IRIS; E. W. Dvergsnes, IRIS; M. Welmer, National Oilwell Varco (NOV); A. Torsvoll, Statoil and A. Merlo, ENI S.p.A. E&P Division

Abstract

The application of calibrated models for optimizing oil and gas production has been standard procedure for some time now, and control of the drilling process with the aid of process models is also approaching common practice. The novelty of the system presented here is the application of automatic model parameter estimation in drilling process control.

Continuous optimization of operational parameters is performed using calibrated process models, safe operational windows are calculated, and operational sequences are automatically optimized through forward model simulations. The results are applied to machine control in real-time, providing process safe-guards and increasing process efficiency.

Drilling control automation with the new system has been successfully demonstrated on a full scale offshore type test rig. The following functionalities were demonstrated: tripping and reaming pressure and load control, automated friction test (pick up / slack off) for calculation of mechanical friction in the wellbore, automated pump start-up, and bit load optimization.

The results demonstrate that the incorporation of real time calibrated process models in drilling control can make the drilling process more reliable, increase efficiency, and improve safety for the drilling crew and with regards to well control.

Introduction

To date, automated control has only to a small extent been applied to the drilling process compared to other industries, although it could be of great value with regards to efficiency in drilling, reduced exposure to human error and enhanced ability to drill challenging wells.

The new system presented in this paper, combines existing hardware and software for monitoring and controlling the drilling process with continuously updated advanced mathematical process models in order to achieve enhanced drilling efficiency, safety and control.

Safe limits for the drilling operation are computed and enforced in real-time, according to existing process constraints, providing safe envelope protection. Optimized automation of operations within existing constraints is achieved through application of forward model calculations, providing a more efficient drilling process, and continuous diagnostic control and early detection of emerging problems is enabled through comparing model prediction with real time data, ensuring safe running of process automation.

The system concept may be seen as analogue to the concept of fly-by-wire electronically operated flight control, with automated optimised control such as the Airbus Brake-to-Vacate system for regulation of optimal landing speed and deceleration.

Adaptation of models for integrated system control is based on substantial research performed in previous projects, illustrated by the publications listed in the references. Comprehensive verification of developed process models has been obtained through testing and studies performed over a number of years. Development of calibration methodology has been a major research area, documented by Gravdal et al; 2005, Vefring et al; 2003 and Vefring et al; 2002. Further work has been performed in developing process control, illustrated in Iversen et al; 2006 and Vefring et al; 2004, and realtime applications and instrumentation has been further studied in Nygaard et al; 2005 and Lorentzen et al, 2001.

The main focus of the paper is presenting results from full-scale testing of the system on an on-shore test rig, demonstrating the control functionality of the system. Additionally, some results from passive monitoring of drilling operations on a North Sea rig are presented, providing verification of process models applied in automated control. The work described has been performed in preparation for an offshore Pilot demonstration of the new system.

System description

A brief system description is given below. For a more thorough description of system functionality see Iversen et al; 2006.

Components

The system is composed of 4 major elements:

- PLC controllers to steer the rig machineries, acquire sensor data and get commands from the driller;

- A database used to exchange data between the different components;
- A set of calculation modules which are continuously updated using real-time drilling data, providing input to and enforcing safety margins for machine control;
- A Graphical User Interface (GUI) monitoring drilling data and displaying model calculation results.

The calculation modules are run on a separate calculation-server. Otherwise all components are installed into the drilling control system, with system specific control algorithms programmed into the PLC controllers, the system specific database installed on the drilling control system database server, and the GUI made accessible through the drilling control system interface. The four software components described run on separate machines connected together via a local area network.

Data input and processing

The calculations modules make use of surface drilling data and time-based downhole drilling data. Depth based data is also applied, but for this data realtime streaming is not required. The surface drilling data is readily available from the drilling control system database, while the required time-based downhole drilling data is made available by interfacing with downhole measurements sources through the OPC client.

At least three types of pre-processing are performed on drilling data before being applied:

- Measured data from MWD/PWD is normally filtered by the provider.
- Pre-processing of data from surface sensors is performed in the drilling control system in order to supply applicable data.
- Further filtering of data is applied within system modules if required, to cancel noise and to avoid application of erroneous data.

These measures are to ensure reliable realtime data input to the calculation models.

Process models

A state of the art dynamic well flow model, calculating pressures and temperatures, and a string mechanics model, calculating torque and drag, are crucial elements in the system. These models are continuously updated through parameter estimation and form the basis of control and diagnostics functionality of the system, enabling model prediction of process behaviour and providing input to machine control algorithms.

The flow model performs dynamic calculations of pressure and temperature in the well, based on injected flow rate, drillstring movement and thermal boundary data, while the torque & drag model calculates the string torque, drag and mechanical friction factor, based on input from surface load and torque measurements and input from the flow model.

System Functionality

The following modules are implemented in the system

- Automation/control consisting of:
  - Automated friction test
  - Pump startup control
  - Tripping/back reaming control
  - Bit load optimisation
  - Stick slip prevention
- Diagnostics of active volume, pressure, cuttings, torque/drag, flow friction
- Monitoring function displaying key process parameters, trends and depth plots

Additionally a watchdog function detects any erroneous behaviour and automatically restarts malfunctioning modules.

A brief description of automation/control modules is given below. The stick slip prevention module was not tested during the demonstration and is not described here.

Tripping/reaming: The tripping module continuously calculates the optimal tripping velocity and acceleration/deceleration based on the current state of the well (taking into account surge/swab and gel effects), such that the pressure at the weakest point stays between the pore and fracture pressure. Reaming and back reaming calculations are also included in this module. If the calculated limits are less stringent than the machine limits (drawwork limitations), the machine limits will be used.

Automated friction test: The purpose of the automated friction test is to define a standard pick up/slack off test which can easily be performed and reproduced. Pick up/slack off may be with or without rotation. This test enables mechanical friction analysis through application of the torque & drag model. The user can choose among four pre-defined test types:

- Pick up, slack off
- Pick up, rotation off bottom, slack off
- Back reaming, rotation off bottom, reaming
- Pick up, slack off, back reaming, rotation off bottom, reaming

After choosing the test type, the necessary parameters such as velocity, rotational velocity and time for rotation off bottom can be set. If the requested velocity is above the maximum velocity calculated by the tripping module, the velocity will be restricted by the tripping limits. The defined test will be performed automatically through keypad activation.

Pump start-up: The pump start-up module optimises the flowrate buildup in two modes: Stepwise (unknown target flow rate) or resume mode (pre-defined target flow rate). An automatic fill-pipe sequence is also included. This module ensures that the pressure profile at any time and depth is within the pore and fracture pressure profiles. In stepwise mode, the flow rate is increased in constant steps, but the minimum time between successive steps is controlled by the module. When the maximum allowable flow rate is reached, it is no longer possible to trigger a flow rate step. Going beyond maximum calculated flow rate is only possible in manual mode. In resume mode, there are two possibilities, automatic and semi-automatic. In automatic mode, the pump is started as quickly as possible, according to the calculated start-up profile. In semi-automatic mode, the driller is in control of when each step should be performed, but the module controls the magnitude of each flow rate step is, and that the minimum time between successive steps is respected.

Bit load optimisation: The bit load optimisation module modulates the WOB and rotational velocity with a low frequency in order to calculate gain factors indicating the effect of changes in WOB or rotational velocity on rate of penetration.

Active System Demonstration

A demonstration of the active system components was performed on an onshore test rig. Additional computer hardware was installed to run the calculation modules of the system. Both the database and the PLC programs installed on the test rig were upgraded for compatibility with the new model integrated system control.

BHA

For the test, a slick BHA has was used (no stabilizers), with 12 drill collars 6 ½“ x 2 $^{13}/_{16}$“. A float sub has was placed on top the bit-sub in order to give a behaviour as similar as possible to real offshore operations (with a motor or a steerable rotary). A 8 ½” bit was used, with the rest of the drill-string composed of standard 5” drill-pipe at 19.5 lb/ft.

Drilling mud

A water-based bentonite mud was used during the test to obtain good cutting transport. The mud is made out of pre-hydrated bentonite, Soda Ash and N-Vis HI. No weighting materials were added.

Test well

Well TD was 1048 m at initiation of drilling. For a description of well profile see Appendix A.

Preparation of the drilling experiment

Due to upgrading of the draw-work software at the test facility prior to the demonstration of the system, extensive testing was necessary to assure that all safety mechanisms were performing correctly. Furthermore, the PLC software had to be adapted to the new draw-work software.

The system was first tested with a short drillstring (one bit and four stands of 5’’ DP), and then with a complete drillstring. Based on experience from this test, some adaptations to the joystick functionality were made prior to the demonstration:

- Nudging the joystick to creep speed stops tripping, subsequently using the machine limits instead of the calculated limits (originally it was suggested to use the elmagco mode).
- Friction tests are performed without using the joystick but can be interrupted by nudging the joystick to creep speed (originally it was suggested to activate the friction test by setting the joystick in creep speed mode).

During the testing period, the watchdog functionality was extended to account for communication failure between the calculation sever and the database server and between the database server and the PLC. The resulting watchdog function is a distributed monitoring system which can inhibit the use of the system functionality if communication failure occurs between the calculation modules and their PLC companion function or if the calculation module itself is out of order. In addition, detection of discrepancies between the drilling condition used by the calculation module and the actual drilling condition can trigger a restart of a calculation module. For instance, if the pump start-up calculation were performed based on a long time since the last circulation, the pump startup module should be restarted when circulation is established (positive returned flow-rate) to account for breaking of gels.

An experienced crew was used during the demonstration. Based on feedback from the crew, the following adaptations were made:

- Interrupting a Friction test using creep speed should use the machine limits instead of the calculated limits. This is in accordance with the functionality for tripping with tripping limits.
- When tripping limits are on, under no circumstances, the tripping limits can be turned off by the software itself. Turning off the tripping limits should be made by the driller himself. If the tripping limits calculation has failed, it is not possible to move the block until the tripping limits manually are turned off.
- Automatic detection of unexpected hookload, surface torque or pump pressure fluctuation shall result in stopping the Friction test immediately using the machine limits, not the calculated limits.
- The fill pipe mode of the pump startup function shall always be used. In case no air gap exists, the fill pipe mode is aborting as soon as the SPP is above a minimum threshold.

No top-drive was installed at the test facility. It was therefore necessary to modify the block weight, friction test length and tripping limits heights during the experiment. No such modifications should not be necessary offshore, as a top-drive will always be used.

Since the formation around the test well is very hard, a narrow pressure window was simulated by entering artificial pore and fracture pressure profiles. This was done to demonstrate that the system would take this into account in tripping and pump startup control, maintaining the well pressure within the artificial pressure window.

Day One of the Demonstration

On the first day of the demonstration (May 11, 2006), the following features were demonstrated:

- Tripping limits for a 28 m pick-up and slack-off.
    - The system was able to control the acceleration, speed and deceleration

    - within the limits calculated by the tripping module.
- Friction test (pick-up and slack-off)
    - The pre-programmed parameters (length and speed) were used by the system.
- Interruption of tripping sequence by taking the joystick back to neutral position.
    - The calculated deceleration limits were used by the system.
- Interruption of tripping sequence by nudging the joystick to the right position (creep speed).
    - The machine limits were used.
- Friction test interruption using creep speed.
    - The machine limits, not the calculated limits were used.
- Tripping from 540 m to TD at 1048 m using the tripping limits.
    - The expected reduction in maximum tripping speed as the bit approached the casing shoe was observed (see Figure 1).
    - The acceleration/velocity/deceleration calculated by the tripping module was not violated.
    - Stopping of the block at the pre-defined tripping heights is very accurate (±1 cm).
    - The driller could only go beyond the tripping heights by using creep speed.

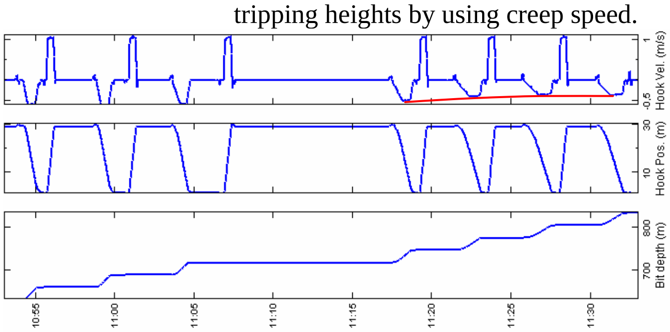

Figure 1: Tripping in velocity reduction around casing shoe. Reduction in maximum trip velocity indicated by red line.

- Fill pipe and Start pump with stepwise mode until max admissible flow rate (2200 l/min).
    - Drillstring contained 500 m of air. Flow rate reduced to minimum when SPP spike was detected (see Figure 2).
    - Driller could not perform next flow rate step until the calculated minimum time period was over.
    - Driller could not increase the flow rate further than the maximum calculated flow rate (2200 l/min).

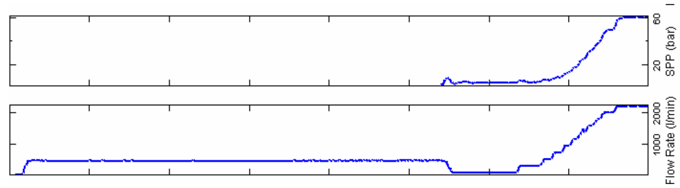

Figure 2: Fill pipe and stepwise pump start-up.

- Estimation of model parameters.
    - No downhole measurements available. The SPP was used to estimate drillstring frictional pressure loss coefficient.
    - After updating model parameters, the calculated and measured SPP matched very well.
- Friction tests with pump on (7 m using Kelly)
    - Pick up, ROB, Slack off with 0.1 m/s and 60 RPM
    - Back reaming, ROB, reaming with 0.1 m/s, 30 RPM and 30 s ROB.
    - Pick up, slack off with 0.2 m/s. Upward motion was limited by tripping limits to 0.15 m/s (see Figure 3).

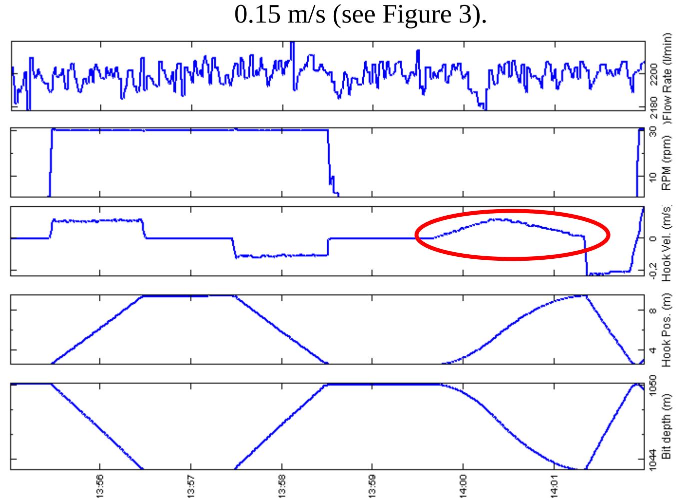

Figure 3: Upward motion limited by tripping limits.

- Friction test emergency stop based on hookload limits, torque limits and SPP increase.
    - To trigger violation of hookload and torque safety limits, the allowed window was reduced during the Friction test.
    - It was discovered that the calculated deceleration was used to stop the drillstring instead of the machine limit. This problem was fixed before the second day of the demonstration.
    - Violation of SPP safety limit was obtained by a manual increase in flow rate. Prior to this, the real-time calculation module had to be turned off, otherwise a non-steady state would be detected, and violation of safety limits

    would have been expected, thus the Friction test would not have been violated.
  - Flow rate increase demonstrated that manual increase beyond the calculated maximum flow rate is possible.
- Stop pump and restart using the semi-automatic resume mode.
  - Target flow rate obtained.
  - Driller was in control of when the steps should be performed as long as the minimum time period was obeyed.
- Start pump in fully automatic resume mode.
  - Target flow rate reached.
  - Each flow rate step was triggered automatically as soon as the system allowed it to be triggered.
- Drilled for 45 min. with auto-driller and bit load optimisation on.
  - RPM and WOB was controlled in sinusoidal variations, gain factors were calculated.

In Figure 4, from left to right, we display the bit position, hook position, hook velocity, hookload, WOB, RPM, surface torque, Flow rate and SPP data from the first day of the demonstration.

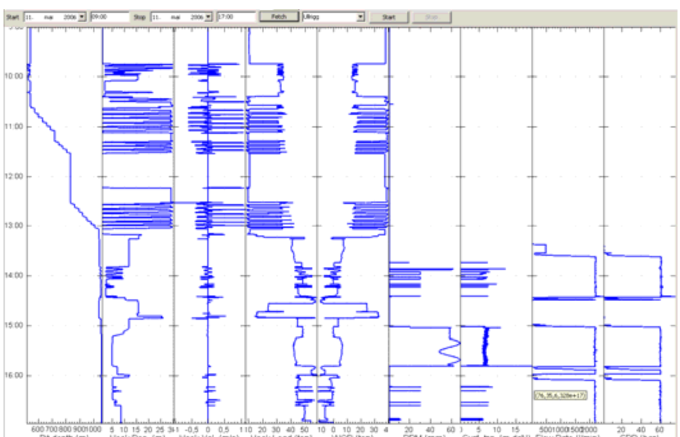

Figure 4: Data from day one of the demonstration.

Day Two of the Demonstration

On the second day of the demonstration (May 12, 2006), the following features were demonstrated.

- Pump startup in stepwise mode to 1700 l/min.
  - Not necessary to go to maximum flow rate when using stepwise mode.
- Performed several friction tests
  - Obtained good match when comparing calculated friction factors for tests with identical parameters
  - Crucial to have automated tests to provide the best possible basis for comparison.
- Friction test (pick up, slack off)
  - Maximum speed was limited by very tight tripping limits due to gelling effects.
- Pull out of hole (to 660 m)
  - For the given pore and fracture profiles, the tripping speed decreased when approaching the casing shoe, before it increased again after entering the casing
  - The tripping limits, which varied from stand to stand, were obeyed.

In Figure 5, from left to right, we display the bit position, hook position, hook velocity, hookload, WOB, RPM, surface torque, Flow rate and SPP data from the second day of the demonstration.

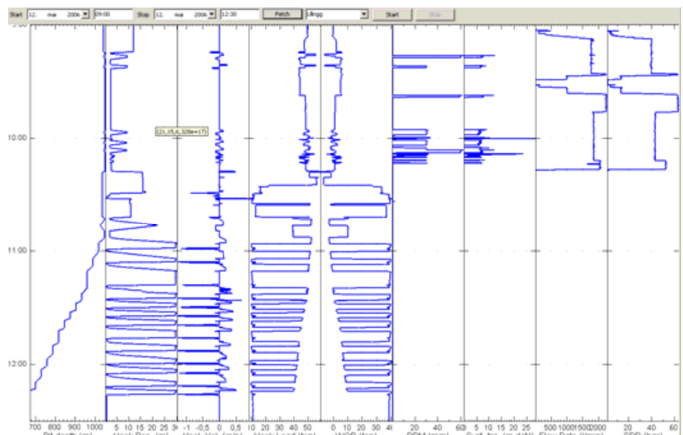

Figure 5: Data from day two of the demonstration.

Remaining challenges

The current in slips detection in the PLC is based on comparing the hookload to a threshold of the order of the travelling equipment weight. When the drillstring is released from slips, the hookload can be below this threshold for a few seconds. The PLC decides whether to use the tripping limits or the machine limits based on this in-slips detection mechanism. If the drillstring is detected to still be in slips when the tripping sequence starts, the machine limits will be used instead of the tripping limits. This problem occurred a few times, probably due to the test well being short, and the drillstring light. Nevertheless, a better in-slips detection mechanism would be preferable, and should be investigated prior to the pilot installation. One possibility could be to use the command signal to the slips.

Model verification

Extensive passive monitoring against offshore operations has been performed for model verification. Although model calibration is applied, it is essential that the flow and torque & drag models shall give good results without calibration as this will also provide good model predictability and diagnostic capabilities of the system.

Additionally, passive monitoring has enabled a very steep learning curve regarding drilling procedures and well behaviour, so that procedures and effects not normally accounted for in modelling of the drilling process may be taken into account enable good overall system behaviour.

Monitoring results

Some results from running the system remotely against offshore operations are presented to illustrate verification of process models.

Case 1: Figure 6 illustrates verification of calculated BHP, where the model produces good results after a period of low circulation with no BHP information to surface. Measured values are in blue. The pressure pulse tool, used for transmitting MWD measurements to surface, requires a minimum flowrate to function, and in this particular case the flowrate is below the required minimum for a duration in excess of 15hrs. As can be seen in the figure, the correspondence between calculated and measured values at restart of transmission of downhole BHP measurements is good.

It should be commented that the correspondence between calculated and measured standpipe pressure is not very good during the period of low circulation. As can be seen, the discrepancy is very much reduced after initial transients occurring after each pumprate change. Such discrepancies may be solved by applying smooth start in modelling initiation of circulation. See summary of verification below for further discussion.

The spike seen in measured SPP occurs when pipe is in slips and is not believed important for model verification.

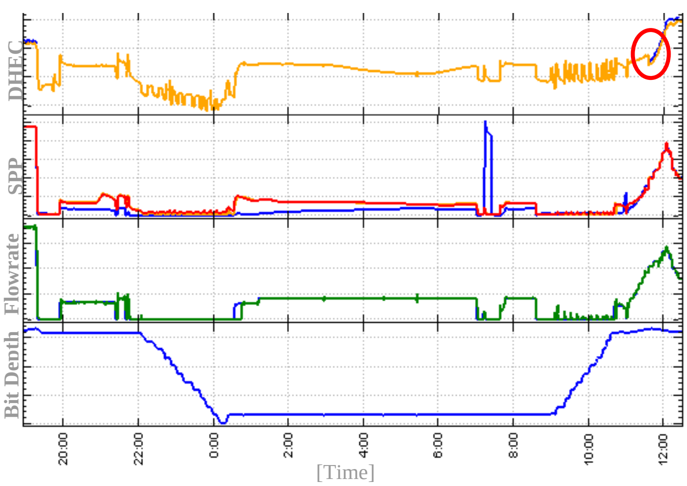

Figure 6: Period of low circulation during tripping up and down 10 stands. Measured values in blue.

Case 2: Below (Figure 7) we display the BHP, SPP and Bit Depth during the drilling of one stand. The flowrate is 1750 l/min while drilling and back reaming, but is reduced to 1550 l/min while reaming. The rotational velocity is of the order of 170 RPM, and the surface torque is roughly 20 kNm while drilling and back reaming. Corresponding parameters for reaming are 75 RPM and 15 kNm. The blue BHP and SPP curves are the real-time measurements for the downhole ECD and the SPP, whereas the yellow curve is the value calculated by the calibrated model. The calculated ECD seems to be shifted compared to the measurement, whereas the SPP matches very accurately. The reason is that it is the downhole pressure measurement, and not the downhole ECD which has been used when estimating model parameters. This indicates that different TVD's have been used when converting from pressure to ECD.

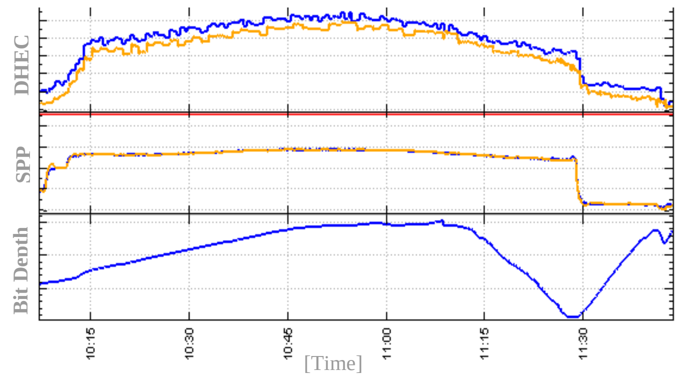

Figure 7: SPP and BHP calibration during the drilling of one stand

Case 3: In Figure 8 results from monitoring of tripping into open hole section is shown. Measured values are again in blue. The correspondence between measured and calculated values for SPP is good, even during large variations in pipe velocity, RPM and surface torque. A few spikes may be seen in the calculated flowrate out (green). Such pressure spikes may be detrimental to system control using models, as they may erroneously cause calculated downhole pressure to exceed the allowable pressure window. Eradicating pressure spikes is an important task in development of the system, in which both data quality control and modeling optimization play important parts. The problem of spikes at initiation of circulation has been solved though using a 'smooth start' modeling of pump startup. Smoothing out discontinuities in the data input to the models is crucial to system stability. It may be argued that such discontinuities will be dampened by the system, and that current state of the art process models are not complete with regard to total system response. This has been observed during system testing.

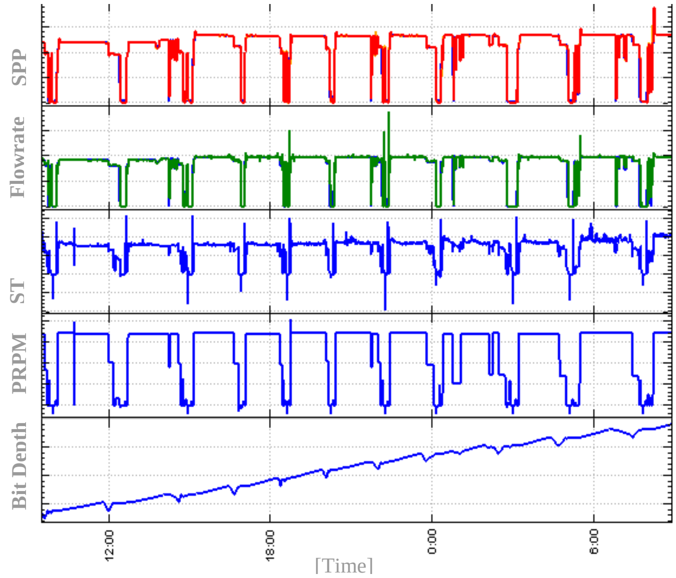

Figure 8: Tripping in 10 stands in open hole. Measured values in blue.

Case 4: An example of pump startup is shown in Figure 9. The initial erratic behavior is due to startup of models. As model parameters are adjustable through model parameter estimation the system adapts to the actual case. Subsequent modeled behavior corresponds well with measurements up until pipe rotation (PRPM) is turned on. At this point there occurs a discrepancy between modeled and measured downhole ECD. The effect of rotation on turbulence is included in the applied flow model, but results for this case indicate further coupling between drillstring mechanics and flow. However, one of the main tasks of calibration is adaptation of the applied model to changing well states, and as can be observed, the calibration results in good correspondence again between calculated and measured ECD.

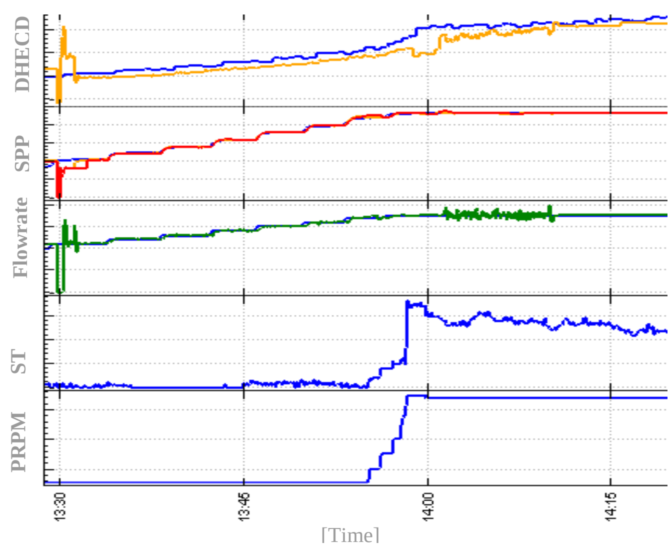

Figure 9: Pump startup with pipe rotation.

Summing up experiences from verification, it may be concluded that the flow model functions well even for long periods without calibration. However, some discrepancies occur during flow transients or other changes of state in well, and detrimental pressure spikes have been shown to occur. Further work has however shown that both pressure spikes and transient irregularities may be eradicated by smoothing input data. And model calibration will allow the system to adapt to the new well state.

Future possibilities

Required further development for optimization and possible new developments and enhancements are briefly discussed.

Research and development

Application of drilling data in current state of the art process models applied for model integrated system control is not straightforward. Substantial work has been performed to achieve efficient data quality control and control of transient behavior in the described system. A more comprehensive process model linking all current models together and taking into account more of the interaction between the different dynamic systems (mechanics, flow, energy) of the different drilling process components should be a focus for further research.

Other developments that will contribute to further optimization in system control are enhanced understanding of all phases of process operation, and incorporation of more detailed behavior of system components such as tool mechanics and sensor response.

More effort should also be put into data application and quality control. This area will become of increased importance as the amount of drilling data escalates through application of new technologies, as described below.

Through such development enhanced model integrated system control will be enabled and the full advantage of an automated system may be realized.

Emerging technology

There is a currently a lot of development within the area of integrated operations (IO) and related tools and technology which has an impact on the possible functionality of the type of system described here. Some examples are given below, including WITSML, wired pipe and other new equipment.

WITSML is a standard protocol for transfer of drilling data which is under development. This protocol is applicable for transfer of data input from a third party (such as survey, mud data, formation data, well profile, well plan, drilling plan etc.). It is not considered to be applicable for realtime data transfer, as the transfer rate with WITSML is too slow.

In its current state, the WITSML protocol is not enabled for transfer of all input data required for the new system. Further development of the protocol is required before it becomes fully applicable. This is an area for further development.

Application of transfer of WITSML drilling data from 3rd party should improve user friendliness of the system, as it should not be necessary to manually enter setup data. And updating of data such as mud properties and tally may be done automatically if such data is available through 3rd party WITSML sources.

Wired pipe will enable consistent transfer of downhole data measurements during all phases of the drilling process. In the future it should also be possible to place sensors along the drillstring to measure temperature and pressure along the annulus and have these measurements transmitted instantaneously to surface.

Not only will downhole measurements be available at all times with wired pipe, but the resolution will also be a lot better, as the resolution now is 30sec to 1min, while the resolution with wired pipe should be of the order of 1 sec.

With application of the continuous flow of high resolution downhole measured data, system diagnostics and control will be greatly improved, as models may be updated (calibrated) at all times, and uncertainty in calculations will be greatly reduced due to the high resolution. With multiple measurements along the wellbore the model uncertainty will be even further reduced, and reliability of diagnostics and control improved.

The increased amount of data available through wired pipe measurements should also enable model improvements, as more data will be available for model verification.

Even though future developments may provide a wired pipe with multiple measurements along the wellbore, application of realtime calibrated process models will still be essential, both for diagnostics and for control. In diagnostics it is essential to compare predicted behavior with actual behavior, and for this models are required. The accuracy of current manual diagnostics such as fingerprinting will also be improved, but such diagnostics does not account for variation in state of drilling parameters, as an automated system can.

Regarding process control, increased resolution and continuous measured data will make control without models, such as PID (Proportional, Integral, Derivative) regulation, possible, but the use of models will still give more reliable control. And process optimization through predictive modeling is of course not possible without models.

New equipment may influence process behavior and needs to be taken into account in modeling and system control. As an example, an anti stall tool newly taken into use in the North Sea may be mentioned. Application of such a tool should have an impact on string mechanics, and must be taken into account in string dynamics control.

Conclusions

A new system using model integrated system control of drilling operations has been demonstrated. The new system enables automated control and safer drilling through applied operational constraints based on results from continuously updated process models.

The system showed good stability during testing on an on-shore test rig, where active control with the new system was demonstrated successfully. Based on the testing it was concluded by the experienced crew that the new system was useful and easy to use.

Verification of process models applied in the new system has been performed through running the system in realtime against drilling operations on a North Sea rig. It may be concluded from verification results that the state of the art models applied together with model calibration are adequate for safe implementation of model integrated system control.

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- Per Bu, UBBS

Nomenclature

TD = *Total Depth*
DP = *Drill Pipe*
PLC = *Programmable Logic Controller*
SPP = *Stand Pipe Pressure*
GUI = *Graphical User Interface*
ECD = *Equivalent Circulating Density*
DHECD = *Down Hole Equivalent Circulating Density*
RPM = *Revolutions Per Minute*
ST = *Surface Torque*
PRPM = *Pipe Revolutions Per Minute*

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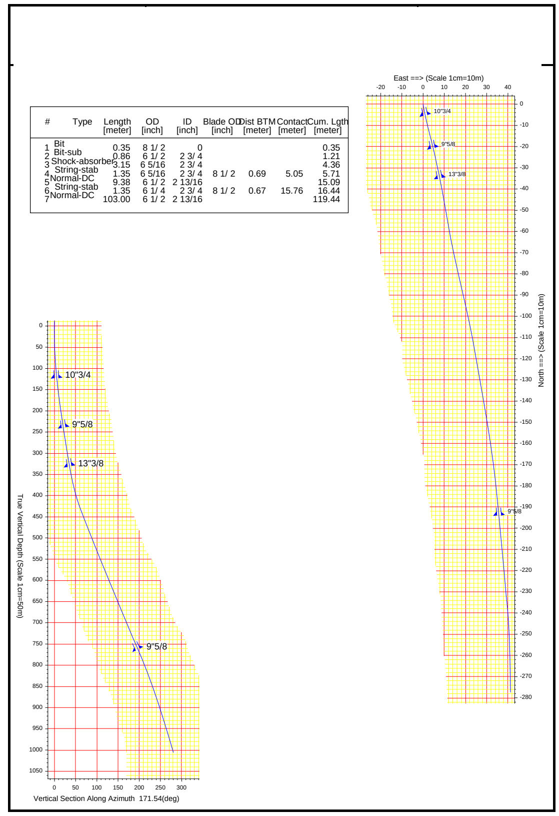
Appendix A: Test rig demonstration well projection plot



#	Type	Length [meter]	OD [inch]	ID [inch]	Blade OD [inch]	Dist BTM [meter]	Contact [meter]	Cum. Lgth [meter]
1	Bit	0.35	8 1/ 2	0				0.35
2	Bit-sub	0.86	6 1/ 2	2 3/ 4				1.21
3	Shock-absorber	3.15	6 5/16	2 3/ 4				4.36
4	String-stab	1.35	6 5/16	2 3/ 4	8 1/ 2	0.69	5.05	5.71
5	Normal-DC	9.38	6 1/ 2	2 13/16				15.09
6	String-stab	1.35	6 1/ 4	2 3/ 4	8 1/ 2	0.67	15.76	16.44
7	Normal-DC	103.00	6 1/ 2	2 13/16				119.44

Figure 10: Well projection plot for the test facility.