Proceedings of the 12th International Conference on
Computational Fluid Dynamics in the Oil & Gas,
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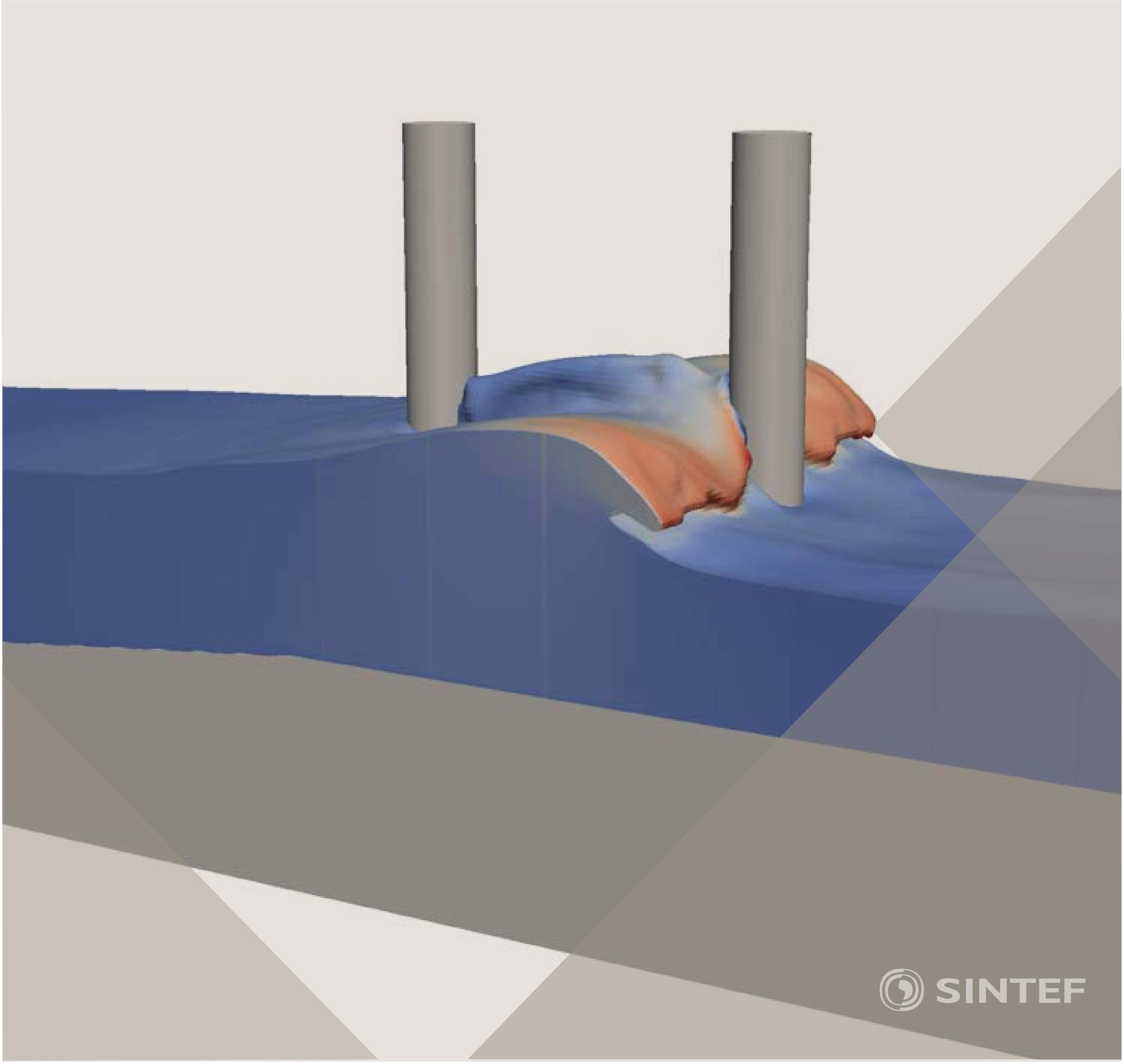
Progress in Applied CFD – CFD2017



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Editors:
Jan Erik Olsen and Stein Tore Johansen

Progress in Applied CFD – CFD2017

Proceedings of the 12th International Conference on Computational Fluid Dynamics in the Oil & Gas, Metallurgical and Process Industries

SINTEF Academic Press

SINTEF Proceedings no 2
Editors: Jan Erik Olsen and Stein Tore Johansen
Progress in Applied CFD – CFD2017
Selected papers from 10th International Conference on Computational Fluid
Dynamics in the Oil & Gas, Metallurgical and Process Industries

Key words:
CFD, Flow, Modelling

Cover, illustration: Arun Kamath

ISSN 2387-4295 (online)
ISBN 978-82-536-1544-8 (pdf)

SINTEF Academic Press
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PO Box 124 Blindern
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Fax: +47 22 96 55 08

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PREFACE

This book contains all manuscripts approved by the reviewers and the organizing committee of the 12th International Conference on Computational Fluid Dynamics in the Oil & Gas, Metallurgical and Process Industries. The conference was hosted by SINTEF in Trondheim in May/June 2017 and is also known as CFD2017 for short. The conference series was initiated by CSIRO and Phil Schwarz in 1997. So far the conference has been alternating between CSIRO in Melbourne and SINTEF in Trondheim. The conferences focuses on the application of CFD in the oil and gas industries, metal production, mineral processing, power generation, chemicals and other process industries. In addition pragmatic modelling concepts and bio-mechanical applications have become an important part of the conference. The papers in this book demonstrate the current progress in applied CFD.

The conference papers undergo a review process involving two experts. Only papers accepted by the reviewers are included in the proceedings. 108 contributions were presented at the conference together with six keynote presentations. A majority of these contributions are presented by their manuscript in this collection (a few were granted to present without an accompanying manuscript).

The organizing committee would like to thank everyone who has helped with review of manuscripts, all those who helped to promote the conference and all authors who have submitted scientific contributions. We are also grateful for the support from the conference sponsors: ANSYS, SFI Metal Production and NanoSim.

Stein Tore Johansen & Jan Erik Olsen

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ON PRAGMATISM IN INDUSTRIAL MODELING
PART III: APPLICATION TO OPERATIONAL DRILLING

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ABSTRACT

In this paper, we will apply the concepts of pragmatic industrial modelling to the development of a real time drilling support tool. We develop requirements to such a modelling tool, regarding both input and output, model response times, and accuracy requirement.
The selected application will next be the subject to more theoretical discussions on analyses, standards, technologies, design of the database, and the interface for the modelling framework
On the selected pragmatic modelling case, we evaluate the proposed solutions and outline requirements for the realization of the described tool. We give a proposal of the architecture for such a system, and examples of analysis / modelling workflows, presented in pseudo-code.
We summarize the findings and discuss how this specific "pragmatism in industrial modelling" case should be concluded and prepared for further software/hardware implementation, reuse, sharing, and collaboration. Partial standardization of work processes (illustrated as workflows in pseudo-code), data, and metadata is a necessity for building more consistent and informative industrial models. It will answer to customer needs for relevant results, actual accuracy, and delivery speed, and will definitely pave a way towards a tool, which can enable an automated drilling process.

Keywords: Industrial modelling, pragmatism, drilling, real-time simulation, multiphase flow, hydraulics, robotized drilling operation

INTRODUCTION

Building industrially relevant models is handled in many text books, such as (Cameron, I. and Gani, R., 2011). From the software perspective, fields like software engineering and systems engineering has become highly developed over the last decades. However, how these areas can be exploited to build useful industrial applications does not have sufficient focus. A particular need is to arrive at standards for development and workflows that can help to improve the final quality. In the area of CFD we have seen attempts to develop standards, such as (Casey et al., 2000) and (Mendenhall et al., 2003). However, in many applications CFD will only be part of a larger picture.

At CFD2014 in Trondheim, Norway, a framework (FW) for pragmatic industrial modelling was suggested and demonstrated on industrial use cases with a process centric approach (Zoric et al., 2014). The framework was further elaborated (Zoric et al., 2015) at CFD2015 in Melbourne, Australia, with focus on metadata describing modelling and experimental data. Their organization, syntax, and semantics were exemplified on a use case related to drilling of oil & gas wells. In this paper, the objective is to apply previous principles of pragmatic industrial modelling to develop a drilling application for the oil & gas industry. The elements of such a development process are established knowledge, but how these elements are assembled into an application driven workflow is new.

In order to develop a successful application the pragmatic workflow can be seen as a procedure that can support quality of both the development work and the final application. The second element and success factor is the Solution Architect Team (SAT), as discussed in (Zoric et al., 2014). SAT will make numerous decisions on software engineering, model concepts, numerical methods and control strategies. In this way, the final solutions will reflect the level of knowledge in the SAT. This will become evident in the present paper, where we will decide on which concepts to work with, and at that point disregarded all other possible methods.

Well operations vary from operation to operation, and are tailored for each field. In this paper, we will focus specifically on the drilling processes. To date, several components for drilling operations pose phase specific challenges during each of the stages beginning from the initial planning phase to drill-stem testing. As services are provided by various vendors and, integrating multiple service interfaces into a single platform is often challenging. On several occasions, operators often receive un-scalable raw data with noise, replication, and missing values, instead of a comprehensive standardized format. Similarly, data storage poses a challenge due to heterogeneous database systems and analogue data. Hence, organizing inputs for modelling simulation studies has been inadequate, not precise, and time consuming. Data authenticity is often questionable as it is stored in several non-standardized formats, thereby escalating the uncertainty in the simulated results. The streaming of real-time data needs to be easily accessible and scaled in reliable and standard formats.

The literature reviewed is an integral and introductory part of the pragmatic analysis. As this paper merely demonstrates the pragmatic approach, we restrict the literature review accordingly. Over the last 60 years, a substantial amount of work on models and simulations of drilling operations has been published.

Examples of leading software for drilling are Drillbench® from Schlumberger and the software from eDrilling. Examples of publications on hydrodynamic models are (Bourgoyne Jr. et al., 1986) and (Hansen et al., 1999). Real time simulations are discussed in (Mathis and Thonhauser, 2007), (Cayeux et al., 2011a), (Cayeux et al., 2013b), (Cayeux et al., 2016) and (Rommetveit et al., 2017). Examples of mechanical models for the drill string are found in (Cayeux et al., 2011b) and (Cayeux and Skadsem, 2014). Tools for automated drilling and discussed in (Lohne et al., 2008), (Florence and Iversen, 2010), and (Cayeux et al., 2013a). The general impression is that the papers on real-time simulations are quite general and industrial, with limited scientific information. Information on modelling software design methods and design principles seems to be scarce. A major reason for limited information is that most of the work is confidential and thus not available to the public.

Based on the authors' knowledge existing application programs within drilling operations have several hardware and software limitations. The accuracy of physical models may in some cases be critical, and contribute to software limitations. In this paper, we primarily focus on the conceptual workflow: How do we (with above-mentioned challenges) develop a software, capable of delivering the required information and knowledge support?

In order to develop applications for drilling, we need to understand the physical and operational challenges. The root causes of downhole problems are generally not well understood (Nazari et al., 2010). Typically, some downhole problems occur due to lack of implementation of lessons learned and best practices, but sometimes are also due to unforeseeable downhole mechanical failures. By developing a better understanding of root causes and using best practices, we could improve efficiency by 50 to 75%. Evaluation of daily drilling data should not only be accessed at the end of the well drilling operation, but should be reviewed regularly by competent personnel within drilling along with subsurface team members. Additionally, as drilling engineers during training and operations may need to better understand the effects of fluid properties, rotation and flow rate, an interpolation calculator tool may be used to interpolate between the set-up parameters. These parameters could be used to address pressure losses, thresholds for transferring cuttings from beds to suspension phase based on shear rate at surface, in a more complete simulation.

The autonomous solutions are not available for different activities in drilling. For example, the industry needs real-time characterization of the drilling fluids because as of today, insufficient sampling rate and volume correlations have incorrectly represented the true downhole mud properties. Similarly, standardized verification tools both in the laboratory and operations are not available to QC a cement's density and rheology prior to pumping downhole. We need instantaneous assessment of the mineralogy and morphology of drilling cuttings, cuttings cleaning and transport treatment and mechanistic hole cleaning models that could be applied to real-time advisory and decision-making systems.

Industrial solutions within enhanced kick and losses detection methods, particularly when using oil-based muds and in complex geological areas compromising of formations that are naturally faulted, have heterogeneous stress regimes and negative drilling window challenges yet to be determined. A real-time advisory system offers consistent results and this has been discussed in (Islam et al., 2016) and (Moi et al., 2017). The industry is also currently investigating more enhanced techniques towards monitoring and mitigating bottom hole drilling dysfunctions including buckling, vibrations, stuck pipe etc. An autonomous historical case-based digitalized database system should be applied from the laboratory testing phase up to field deployment, as this will help mitigate inconsistencies due to lack of competency.

Hence, a pragmatic approach to address the above-mentioned limitations can be roughly described by the following steps:

1. Accurately define *what each model should predict*. In addition, specify requirements addressing the computational speed (delivery time) and accuracy of the derived results, along with the key data input parameters. This includes the system configuration and field input data. This data can be accessed from various sources, e.g. adaptive real-time computations, stored experimental data, correlations, stored simulated data etc.

2. Provide integrated *conceptual design* approaches, which incorporate perceptive techniques for estimating model input parameters from different sources (and meet the case-specific requirements).

3. Decide and identify which *model framework* (e.g. 1D transient multiphase 3-phase model) and its sub models or elements should be included. Their orchestration during the drilling operation should be well defined, e.g. formalized by workflows and described in pseudo-code. This step must also resolve issues regarding standardization of data formats (obtained from multiple resources including experimental, field and simulated data).

4. The analysis workflow provides various parametric inputs at different *decision gate stages*. This process should be continuously evaluated, and verified to check if the current requirements meet the original data input criterion or the requirements need to be relaxed. If the bottlenecks in the modelling framework show up, the workflow should be corrected and new model elements (sometimes also including sub-models) developed.

5. The qualification of the *uncertainties* within the model framework is critical and hence needs a robust workflow wherein it is easy to adapt, implement, and increase accuracy.

This paper will investigate a case specific scenario wherein the drilling operation is carried out from a platform. During the drilling process, a drill bit is rotated at the end of a drill pipe. Non-Newtonian drilling fluid is pumped through the drill pipe and the bit, and is circulated back to the platform through the annular space to the surface. Should these cuttings accumulate in the annular space, this may lead to several problems eventually causing the drill pipe to be stuck if the necessary preventative actions are not taken. This could also be a result from caving collapsing within the newly drilled hole. When the mud flows through the annulus, some mud may be lost to the formation for various reasons. Sometimes this may lead to a kick wherein formation fluids enter the borehole and displace the mud, thereby reducing the bottom hole pressure. Should the losses be severe, this may lead to the hole collapse. In some cases drilling with a mud weight much lower than the formation pressure, also leads to the hole collapsing or induces a kick that could unfold into a blowout.

An application that addresses such challenges should handle all these possibilities.

Human intervention and responsiveness influences heavily drilling processes; hence, human errors tend to reduce the efficiency. Drilling operations are very expensive and the multi-dimensional challenges do occur, hence a more automated drilling approach should be advantageous.

By using the appropriate models, correctly interpreting the data, and providing appropriate remedial actions during operations, faster and more cost effective drilling operations will be possible.

PRAGMATISM - STEP 1: REQUIREMENTS FOR AUTOMATED DRILLING TOOL

The tool will be limited, but still designed to handle all drilling hydraulics, including gas kicks. Issues related to interaction between drill-bits, drilling fluids, and formation is included. The same goes for the tools and materials involved into the drilling operation (mud pump, motors, Bottom Hole Assembly, mechanics, and integrity of drill-string and drill-bits). Any failure of tools, risk for stuck pipe, and remediation of stuck pipe is part of what we will address. Prediction of the true drilling window is of major importance. The drilling window is the range of mud pressures, exposed to the formation, within which the operation is safe. If the mud pressure is too low, oils and gas may be produced into the drilling fluid (risk of blow out) and we have the possibility for rock collapse (have to give up well). At the other end (too high mud pressure), the drilling fluid may be lost to the formation. That will delay operation, block pores for future production, and trigger additional costs. On top of that, formation may be fractured and the well has to be abandoned.

A simplified example of a typical drilling scenario is illustrated in Figure 1. In Figure 2 we see the mud pump, supplying the drill pipe with high pressure drilling fluid.

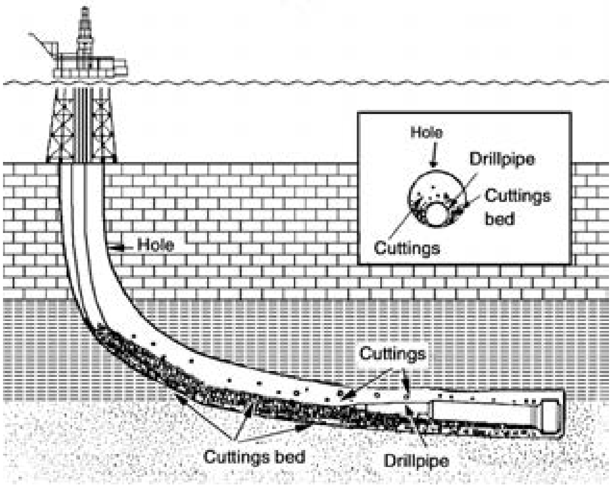

Figure 1 Typical scenario during drilling. Three types of rock is seen (from http://petrowiki.org/Hole_cleaning).

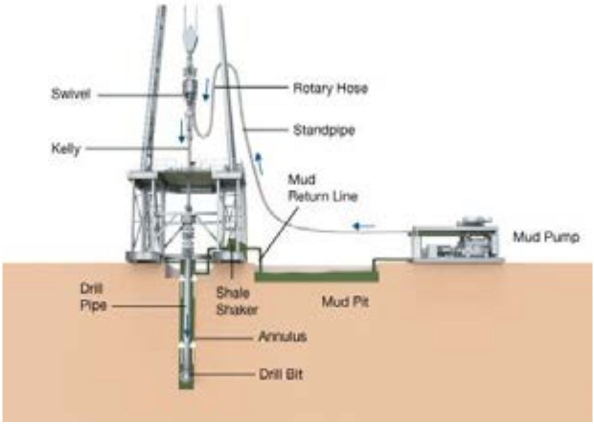

Figure 2 Drill platform with mud pump and shale shaker (from http://www.petroleumonline.com/)

The return flow of drilling fluid and cuttings is passed through the shale shaker where cuttings are separated from the drilling fluid. The drilling fluid is then circulated back to well bore through the mud pit.

The following considerations were shortlisted based on the current industrial requirements:

1. An automated tool capable of handling hydraulics during drilling operations from a platform or vessel.
2. Real-time assessment for drilling fluid characterization and rheological effects
3. A tool that mitigates uncertainty towards organising input parameters for the real-time drilling models during the drilling process, such as stuck-pipe events and wellbore breakout.

The tool will perform drilling process optimization – mostly monitoring critical parameters and their influences while drilling. The tool may comprise both software and hardware, and should integrate well into already existing database frameworks. As illustrated in Figure 5, the tool should support at least three distinctive modes of interaction: monitoring, predictions and recommendations.

The system must be a *real-time advisory system*. This includes full and transient predictions of hydraulics, adjustment of density and rheological mud properties, information on the interaction between drilling fluid and formation, torque and drag (T&D) on drill string. The drilling parameters, annular velocity, drill string rotation speed (RPM), Rate of Penetration (ROP), weight-on-bit (WOB), cuttings mineralogical and morphological info, particle transportation, well geometry, and drilling practices must be highlighted and made available to the user. In addition, online measurements must be made available and used by the system to improve predictions and analysis of the ongoing drilling operation.

Specific features that the model system should handle are:

- Enable ROP optimization. This includes prediction of T&D, effects of flow rate, WOB, effects of selection of bit type and size, and RPM.
- Interaction with the rock formation:
    - Predict rate of mudflow into the formation.
    - Predict rate of inflow of hydrocarbons from the formation.
    - Provide risk assessment for formation damage, and effects of the applied bits.
- Drilling window management: At any time, the model shall know the drilling window and be able to advice the best way to operate within the limits of formation pore and fracture pressure.
- Hole cleaning:
    - The tool should predict the amount of solids being laid up into sediments at any time and at any position in the annulus. In addition, the mass flux of cuttings being transported should be known at any time and location.
    - The tool should predict the cuttings size produced at the bit, including the particle shape factor and the mineral composition of the cuttings.
    - Included into the tool should be a device to perform on-the-fly fluid characterization of the drilling fluid. Both fluid density and viscosity shall be measured. The measured properties should be available at the latest 30 seconds after the fluid has been sampled.
    - The tool must make faster than real-time predictions, in order to assess the required mud-properties in advance. Based on the most favourable scenario for next near future drilling operations, the tool will instruct the mixing of the mud on the fly.
- Predict filter cake creation and properties of the filter cake (thickness, permeability).
- The tool shall assess enhanced Kick & Loss detection.
- The tool shall include an auto drill pipe handling system – accounting for fatigue and buckling. Based on the mechanical and thermal history of each drill pipe element, risk of failure shall be assessed and drill pipe elements with high failure risk will automatically be replaced by new elements.
- The model system should be integrated into a live data streaming system.

Prediction speed requirement:

The tool should be able to predict key parameters at least 20 times faster than real-time. This will allow look-ahead simulations that can be used to optimize the drilling strategy in the nearest future.

Requirement of spatial resolution of model:

The largest grid cells allowed is 100 m.

Model / operation input parameters:

- Borehole trajectory is available on digital format,
- Rock information (as this is not available in real time, we will use Mechanical Specific Energy (MSE) equations),
- Fluid rheology and fluid properties,
- Mud temperature out from mud pump,
- Formation temperature along borehole trajectory,
- Critical mud pressure for fracking of formation,
- Formation fluid pressure and permeability along borehole trajectory,
- Formation fluid properties along borehole trajectory,
- Dimensions and properties of tools, pipe, casings, cement, rock (mass of system elements, sound speed, thermal properties),
- Actual ROP (measured),
- Average cuttings size (measured),
- Pump pressure,
- Both applied torque and drill string rotation data is available,
- Hook load data is available in real time (hook load represents the force acting on the drill string at the platform),
- Block position is available in real time (block position versus time represents the axial velocity of the drill string at the platform end).

We note that uncertainty measures for all input parameters must be given. If uncertainty is unknown, the quantity must be labelled with *"Uncertainty unknown"*.

Output parameters from prediction model

Primary prediction parameters:

- Transient flowrate at surface versus actual pump pressure
- Mass flow of cuttings to the surface versus time
- Mud temperature at shale shaker
- Hook load as function of measured or suggested block position.

The model should allow on-the-fly tuning of the model. However, tuning methods and selection of tuning parameters are not part of the present tool, but will be a future extension possibility.

The required prediction accuracy of the primary output parameters is assumed given. For the accuracy of the pressure, and mudflow rate predictions, a minimum accuracy of ± 10 bar is assumed required. The temperature of the mud should be critically assessed based on the climatic and field specific conditions.

Secondary prediction parameters:

- Dynamic updates of the drilling window,
- Optimal method selection to drill safely within drilling window,
- Based on primary output parameters, issue immediate warning if a kick is appearing,
- Information of where the cuttings are located in the system,
- Highlight differences between model and monitored data. Give interpretation of deviations and suggested actions.

At this point, proven accuracy in primary parameters prediction are sufficient for early kick detection. For example, this can be performed using existing multiphase flow codes such as LedaFlow® or OLGA®.

Monitor parameters, used to check the model, or to support, or to tune the model

- Hook load,
- Block position (hook load taken as input),
- ROP (input),
- Torque and RPM,
- Motor power,
- Mud temperature (both out from pump and for return flow into shale shaker),
- Cuttings mass flow into the shakers,
- Cuttings size (separated at the shakers),
- Mudflow rate out from pump (pump pressure as input),
- Mud pump pressure (mud flowrate as input),
- Return fluid flow rate,
- Density of fluid after the shaker.

Specification of requirements and the necessary information concludes Step 1. This pragmatic model approach closely resembles the use case specifications and scenarios, often adapted during software development. We recognize that some elements may be too generic and in a real project development, it would demand reiterating the above-mentioned specifications into further sub-classes .

STEP 2 CONCEPTUAL MODEL DESIGN

In Step 1 the process is led by Solution Architects Team (SAT), but is under strict control of the end user of the application. In this second step, the SAT will take a stronger lead. The team will now look at the specifications above and work out possible conceptual design possibilities. At this stage, it may be necessary to develop mock-ups, i.e. rudimentary and simple demonstration of sub-models, for assessing possible solutions. We will point to this possibility when necessary.

Based on the need to have a fast and accurate transient hydraulic calculation as part of the tool we realize that multidimensional Computational Fluid Dynamics (CFD) is out of the question for the system model. Presently, we realize two possible approaches for the system model:

A. **A transient 1D multiphase flow model, solving masse, momentum and energy conservation equations for the flow of liquid, gas (from kick), and solids.**
   The model is formulated by individual transient transport equations for the mass of mud, cuttings, and fluids entering from the formation (oil, gas). Similarly, we formulate individual transport equations for momentum of liquid, gas and cuttings, as well as mixture energy (temperature) of the fluids/solids and near well-bore region.

B. **A simplified transient 1D multiphase flow model, based on a mixture approach: The approach is computationally similar to a single-phase description. The phases are handled through a drift flux concept where phase slip velocity relations relative to mixture is known.**
   The model has mass conservation equations for mud, cuttings, reservoir fluids, and free gas. The velocity of free gas and cuttings is related to a mixture velocity by a slip relation. The slip relation may be obtained from existing data (lab, field, simulation). The prediction of temperature is the same as in **A.**

I.e., both flow simulation strategies are based on a 1D Eulerian-based flow code, and the system model should be able to represent pressure waves in the mud. This can be done by solving for the pressure waves directly in the model, or by using a characteristics methods (Skalle et al., 2014). This may be critical for prediction of pressure waves and enable early kick detection.

Use of pre-calculated data, field data or laboratory data

As we have decided that applying a 1D model is the only possibility to reach time requirements, we realize that such simplified models may need heavy support in order to give realistic predictions. Based on the current knowledge of non-Newtonian flows with particles, we see that it is possible to arrive at CFD models with acceptable accuracy in relatively short time. During drilling the drill-pipe is rotating, but also whirling. As a result, the transport rate of cuttings will depend on a balance between sedimentation, convection and dispersion effects (granular and turbulent dispersion), and where drill string position, RPM and whirling frequency are critical elements. Another important factor is inclination of the well trajectory.

Another option for simulating the transient drilling process is to use steady state data, coming from lab experiments or some steady state simulation tool. In this case the transient phenomena can be approximated by applying Succession-of-steady-states (SSS) solutions (Modisette et al., 2001). Such an approach is useful if the phenomena we want to model have a time scale that is significantly longer than the time scale of the transport processes in the system. E.g., formation and movement of cuttings bed is often orders of magnitude slower than the mudflow. Laboratory data are typically obtained at a much a smaller spatial scale than the field operation. I.e., such data need to be supported by either CFD of field data to ensure proper scaling of the model from laboratory to field conditions.

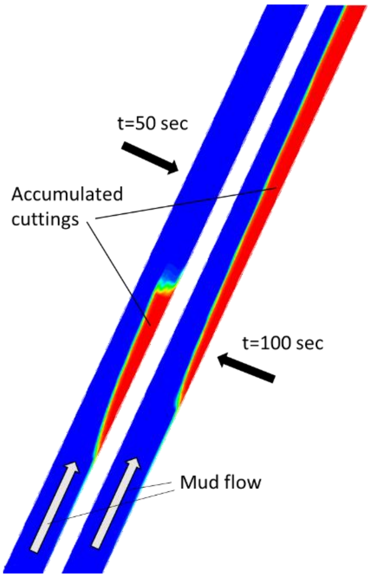

Figure 3 Flow of liquid and cuttings particles of 1.0 mm diameter. The red colour shows a compacted bed of cuttings.

A fast method to produce rheology online is critical. It is suggested to apply a number of pipe rheometers operating in parallel on the field, to obtain robust data with a good measure of uncertainty.

A task will be defined to clarify how lab data, possibly field data, and simulated data from 3D CFD can be saved, processed, and retrieved (to provide the input for the system model). The processed data may supply both pressure drop data (wall stresses) and slip data. The data is supposed to be steady state, and it is required that an uncertainty measure of the data is provided with the data.

Application of CFD to build database or to improve closures

It is fully possible to use CFD (Computational Fluid Dynamics) to provide useful data. CFD is slow, compared to online applications, but can be used, over time, to build a substantial database. It is therefore preferred that a case database be established initially, and is dynamically extended over the time to improve the prediction power of the system model. As an example we have used a previously developed granular flow model (Laux, 1998) to predict the flow of liquid (superficial velocity of 1.5 m/s, and solids fraction in the lower boundary inflow is 2%) and solids in a 65 degree inclined, 40 mm diameter, channel. The fluid is here water and the solids density is 2600 kg/m^3. As seen from Figure 3, the 2.0 mm solids separate in the lower wall and form rather quickly a thick deposit layer. The compacted bed is assumed to have an internal angle of friction (repose) of 30°. The cuttings accumulate fast and may build a large bed along the annulus (here a channel). If the mud pump is switched off, the shear stress from the fluid supporting the bed will disappear, and the cuttings will avalanche to the lowest possible point. In Figure 4, we see that a few seconds after the pump is shut off, an avalanche is taking place. Such avalanches may lead to pressure build-up of roughly 15 bar for each 100 m of open hole. This effect alone can lead to substantial pressure variations, and it must be considered in order to understand the drilling window.

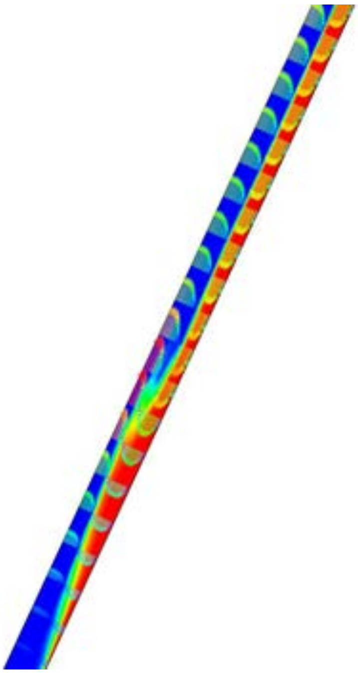

Figure 4 The blue colour shows liquid, red is the cuttings concentration and the vectors show the liquid flow. The maximum velocity is 5.8 m/s.

The mechanical model will apply a Lagrangian framework to handle drag and torque related phenomena. For the mechanical model, we have two overall approaches:

- **C. The mechanical model integrated into the flow model.**
- **D. The mechanical model computed independently, and the data exchanged between the flow model and the mechanical model.**

For the Pipe Auto handling system, this system will be designed based on that the mechanical model is keeping track of the temperature and stress history. I.e., the work to make such a system is separated from the overall model and can be handed over to a team with the necessary knowledge. As all teams delivering into the project, they will have a deadline for when their work is to be finished and well as necessary documentation of uncertainty in the actual sub-models input and prediction parameters.

All fluid and material properties is to be made available to the models through a database. These data will at the time of execution of the tool, be made available in a fast and efficient manner. Data from online monitoring may also be provided through the same database, or if very high transmission speed is needed, through an industrial API for data communication. However, a filter for validation of these data is needed in case the measuring equipment is failing. A strategy for handling this may be to continue with the latest data available. Depending on the variation in the recorded data, it can be decided if the drilling operation should be aborted or not.

STEP 3 SELECTION OF APPROACH

We are now at a point where we should choose between the sketched approaches. What we can say is that system model A: "A transient 1D multiphase flow model,

solving mass, momentum and energy conservation equations for the flow of liquid, gas (from kick), solids and energy" and mechanical model C: "The mechanical model is integrated into the flow model", is the set which is expected to give the most robust simulations. In addition, this set of coupled models will allow simulation of the most important physics involved.
On the other hand, the system model B: "A simplified transient 1D multiphase flow model, based on a mixture approach", together with mechanical model D: "The mechanical model is computed independently, and where data is exchanged between the flow and the mechanical model", may offer the fastest simulation strategy.

We will briefly give some design considerations and implementation techniques that will be part of the development. These methods and techniques are mostly well established, but have to be walked through in order to get an understanding of the pragmatic workflow.

Mock-up solutions

To select between the above-mentioned modelling options, it may be necessary to develop mock-up solutions to demonstrate and compare capabilities of the different modelling approaches. The mock-ups are good starting approach for concretization of such systems, and they should be constructed as sets of simplified collaborative functional modules and processes.

Workflows

To create realistic mock-ups one should specify well the overall operational drilling process. Good starting point can be describing them as workflows, modelled in pseudo-code (example given in Table 1). An information system usually supports many different workflows, representing various work and process situations and necessary actions. The system should support monitoring activities, give various predictions and operational information, and finally give recommendations for operational situations and actions (particularly in urgency situations). Formalization and modelling of the important (if possible) complete set of workflows is necessary if we want automatization of the operations and well-functioning reasoning engines (see Figure 5).
Based on the mock-up evaluation results and the overall judgement of the System Architects Team (see also (Zoric et al., 2014)), the application system design can be started. Of course, if new and critical information arrives, the selection of the basic methods and models may have to be changed.
Maybe not necessary to mention, but it is critical that the users and application owners are continuously involved into the development. Workflows, exemplified by pseudo-code in Table 1, with well-defined (inputs, outputs, transformation functions and activities), are a good tool for specifying both the user interactions and other design and implementation details.

System design considerations

Software design and implementation technology, programming languages, database technology, and data communication technology require also careful evaluation (Zoric et al., 2015). However, for all of these choices it is likely that some legacy issues must be addressed. For the software design, it means that probably the existing codes might be modified and used. However, if the existing code does not satisfy critical requirements some parts may have to be redesigned or replaced. The choice of programming language to some extent will rely on developer's competence and preferences, as well as on the implementation of the existent systems that have to be interfaced with.

Information and data handling

Heterogeneous field data is collected in all major drilling operations today, and the most cost-effective solution will be to rely on the database and communication technology already in use, which requires respecting the existing and hopefully standardized interfaces, APIs and data handling protocols and formats. Some additional data/information processing might be involved to solve the aspects as, data formatting, data curation, enrichment with metadata and contextualization of data, as well as filtering of the data/information that is worth preserving.

One possible solution could be SOFT (SINTEF Open Framework and Tools (Hagelien et al, 2017)). This is a framework for semantic interoperability of scientific and industrial software, making it possible to make software data-exchange seamlessly, according to given semantic rules. Parts of the SOFT system is in industrial use in the commercial LedaFlow ™ software and is applied in the Porto software (Hagelien et al., 2015). Porto is designed to effectively exchange data between a number of different software, ranging from atomistic scale models, meso-scale models, CFD and system models. SOFT is based on a data-centric design, and can tap into numerous data-streams and collect the external data needed for given tasks. The application data could at the same time be available for external applications, with the granted access. For maintenance and further development of an application, established industrial standards should be preferred.
Detailed discussions and analyses of software frameworks are outside the scope of this paper, but we can conclude that a well-designed pragmatic modelling system should follow good SW engineering practices.

STEP 4 SUMMARY AND CONCLUSIONS

In this paper, we have investigated how a more automated drilling approach can be obtained. We have used principles of a workflow and a set of methods we have named "Pragmatic industrial modelling".
In Step 1, we discussed "Requirements for an automated drilling tool". Here we found it rather challenging to give the necessary acceptance level on input and prediction results. The numbers in the paper must be considered as suggestions. Within a technological development project, detailed work must be performed to quantify which uncertainties are acceptable. It is important that during this process we identify and explore critical components within automated drilling systems.
Furthermore, we have identified various possibilities to build simulation tools to cater to new requirements. As a

basis, we could build on existing models, current streams of monitored wellbore data, as well as historical data from laboratory and field applications.

As CFD is too slow to meet the requirements for system analyses, CFD will not fulfil the requirements. On the other hand, drilling operations include numerous complex flow situations, not represented or reproduced by current 1D-flow models. In this perspective, CFD would be capable to represent the flow physics, provided that: we understand the phenomena, have these cast into mathematical models, and correctly implemented and validated. The CFD results should be handled similar to the experimental data and field data. CFD results have their strength in that input is well defined, and models may scale well with geometries and fluid properties.

On the other hand, lab data and operational data is reflecting the reality, even if the conditions for the data may be poorly defined. It is clear that we have only succeeded when models supported by CFD and lab/operational data agree, and show similar qualitative and quantitative results.

CFD models, if validated in conjunction with lab/operational data, can be used to build lookup tables for the simulation tool, or it may serve as a sub-element applied to improve the closure laws for the system hydraulics code. As demonstrated above, CFD modelling has the capability to reveal poorly understood issues (e.g. cutting avalanches) that may be critical for successful operation of an automated drilling system. Other examples may be cuttings, which during tripping out of the hole, may result in cuttings pile-up in front of the Bottom Hole Assembly. Such a phenomenon may lead to unexpected and high-pressure losses, and possibly stuck pipe.

Based on the requirements and above indicated approaches it seems quite likely that it would be possible to produce an automated drilling system. Verification that a complete tool can be developed to meet the requirements ("Step 1: Requirements for automated drilling tool") is a staged process. As part of this process the different modelling solutions must be properly assessed, based on developed mock-ups when necessary. The described system was planned be able to operate without relying on advanced downhole monitoring systems. If this is actually possible, it can only be substantiated by suggested mock-ups or by making tests using available 1D-flow simulators.

Based on our preliminary assessments, the tool that would answer to the requirements could be a transient multiphase flow model, directly linked to a mechanical model. However, the necessary assessments described above (part of the pragmatic modelling workflow) could show that this combination of models may be too slow to meet the requirements. In that case a different overall solution may have to be selected.

A critical element in an automated system is that existing operational data streams are seamlessly interpreted and integrated into computations, with no additional costs.

At the current stage, the degree of user-interaction and control over the drilling process cannot be established. However, it seems clear that a much higher degree of automation than what is the case today will be possible. In order to get closer to a real recommendation for the actual components in an automated drilling system, a development project has to be initiated.

ACKNOWLEDGEMENTS

The project Advanced Wellbore transport Modelling (AdWell) with its sponsor, the Research Council of Norway and its partners Statoil, ENGIE E&P Norge AS, IRIS, UiS, NTNU and SINTEF are gratefully acknowledged for funding and supporting this work.

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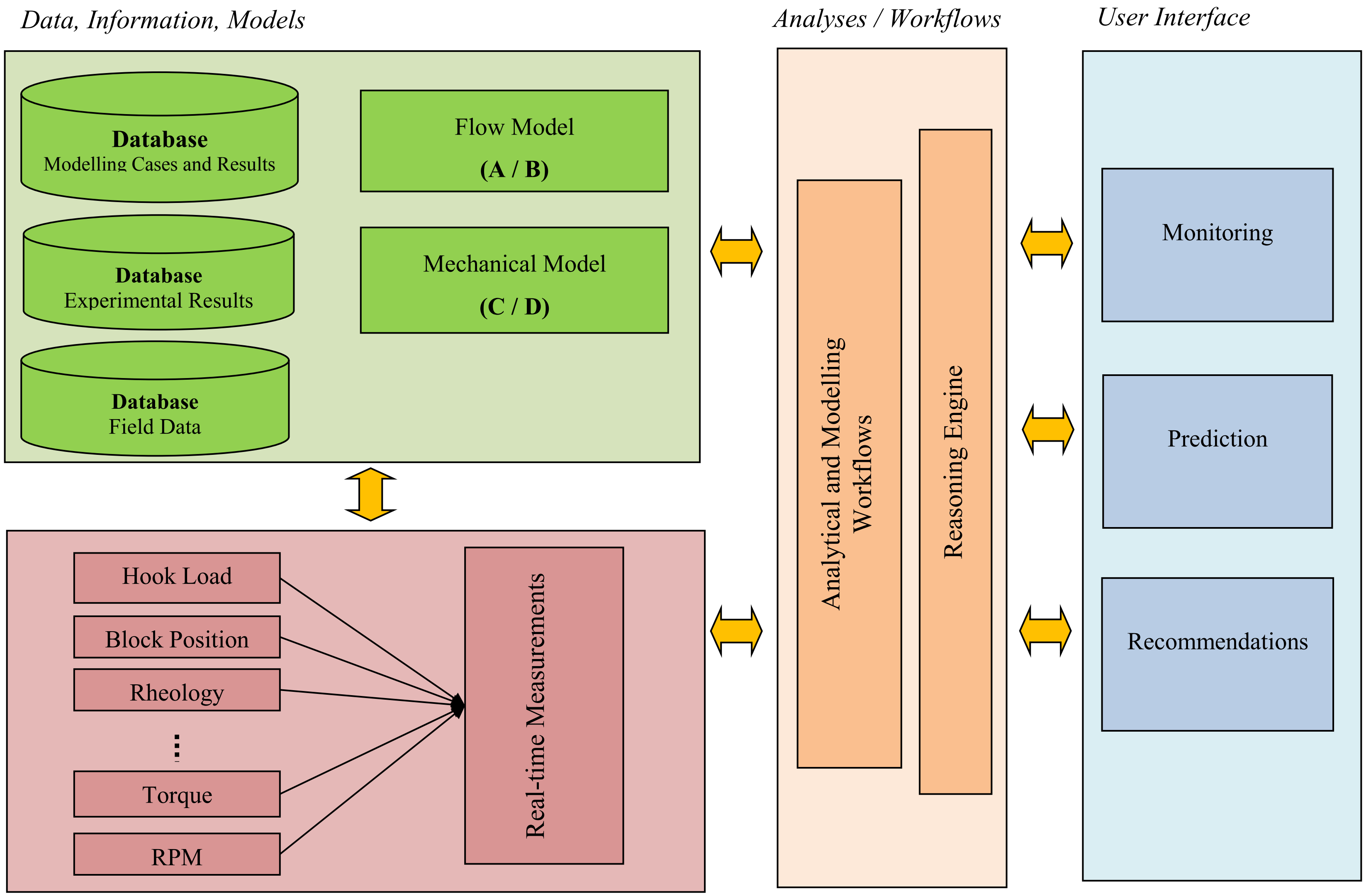

Figure 5 Architecture of the Conceptual Model - Operational Drilling Decision Support System. Four possible combinations of modelling approaches for flow and mechanical models (AC, AD, BC and BD) are discussed in the section "STEP 2 CONCEPTUAL MODEL DESIGN".

Table 1. Workflow / Pseudo-code for one of the analyses (modelling combination A-D), which supports drilling operations discussed above. Mechanical and flow model may be run in parallel.

OPERATION	COMMENT
INITIALIZE	
Prepare for drilling operation	
Check that input data for simulation is available	
Initialize simulation software: i) Flow model ii) Mechanical model iii) All other models	Ensure that monitoring systems are OK Read initial and boundary conditions for all models
BEGIN	
Start drilling operation	
Simulation software starts	
WHILE drilling in operation DO	
Continuous update on drilling operational parameters from monitoring system	Pump pressure, Hook load, Block position, Torque, RPM etc.
Continuous update of boundary conditions for mechanical model	Based on current position of the drill string, and monitored flow conditions.
Continuous update of boundary conditions, geometry and fluid properties for the flow model	Based on previous model runs and on monitor data.
Communicate coupling set-up between mechanical and flow model.	Ensure that the models are consistent with each other at all stages of operation
Run mechanical and flow models in parallel	Many look-ahead simulations may be run simultaneously, each with variations of initial and boundary conditions, and variation of other parameters. Communication between the models will happen also on a per time step basis, e.g., exchanging gradients for numerical stability.
Monitoring activity	Data is continuously retrieved from the monitoring system.
Collect simulation results into database	Database will contain all data needed to identify a drilling operation, and will be an asset for historical learning (some information may be added post-operation)
Analyse accuracy of simulation results	Compare with monitor data and estimate uncertainties.
IF mismatch between model and monitor data THEN	
Identify most likely sources of errors	Mismatch is defined as deviations larger than what is acceptable, based on uncertainty in input and simulation results.
Determine if deviation must lead to operational action or/and correction of model parameters	
Tuning of model input parameters and/or adjusting the model set-up parameters	Conditional; depending on the previous step
ENDIF	
Update borehole model geometry.	The modelling geometry essentially is the borehole angle and hole size as a function of length along the borehole. This information must be updated as the drilling progresses. Setting of casings: Update on thermal data
Analyse simulation results and monitor data	Find recommendation for settings of operation parameters. Identify eventual issues, e.g., risk for gas kick, etc.
Update status and result in operator view	Includes updating history server.
Provide adjusted settings to the drilling robot	Settings may be adjusted automatically, or overridden by a human operator.
END WHILE	
Stop drilling operation	
END	