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Challenges of Modeling Drilling Systems For the Purposes of Automation and Control

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Abstract: To fully model every aspect of the process of drilling a borehole is still in the realms of research. Great strides are being made to develop high-fidelity models of well-defined domains such as the rig systems, drillstring, rock-bit interaction, fluid control systems and the Earth. Bringing all these models together in any unified manner and proposing a unified control solution to fully automate the whole process is still an exploratory venture. The uncertainty prevailing over the magnitude and spatio-temporal distribution of disturbances to be controlled or rejected by systems best described by non-linear partial differential equations rather than linear approximations, makes for a very challenging control problem. This uncertainty also raises interesting questions on how detailed the models need to be and how this might change our approach to modeling in the future. However technology is never static and certain developments are currently in play that will dramatically improve our capacity to model and control processes which are currently considered too complex to control.

Keywords: Drilling, modeling, control, delay, wired drill pipe

1. INTRODUCTION

Constructing a borehole in the ground for the recovery of a geological resource (hydrocarbon, heat) involves many interrelated steps. Great strides have been made to mechanize and automate the drilling equipment at the surface, Eustes (2007). The challenge for the control system community is to discover how the application of automation and control can be extended downhole to enable and enhance the process of well-construction. However, difficulties in monitoring in real-time what is taking place within the borehole and the surrounding rock during well-construction impose a fundamental constraint on the fidelity of control that can be delivered. This paper will discuss these challenges, involving the effects of spatio-temporal measurement delays, the limited number of measurements available, the low transmission speeds of the telemetry systems, the complexity of modeling these systems and the uncertainties in their boundary conditions.

2. DRILLING PARADIGM

Figure 1 shows the high-level system elements involved in drilling a well. The drilling-rig rotates and lowers the drillstring into the well. On the end of the drillpipe is the bottom hole assembly (BHA) which contains the drillbit, sensors and actuators needed to control the trajectory of the well. Telemetry links are established between the BHA, rig and the operations support centre(s) to allow measurement and control information to be exchanged between operators and machines.

If we unpack the drilling system a step further and identify the interaction-interfaces that separate the various technology and physics domains we arrive at Figure 2.

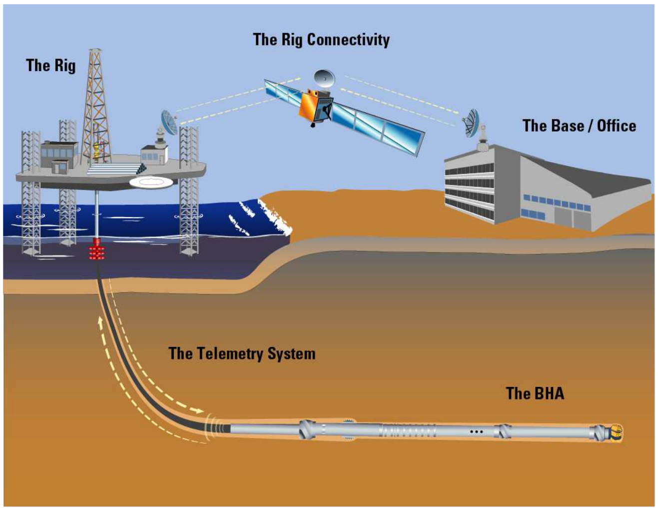

Fig. 1. Conventional drilling paradigm.

After many millions of years and for thousands of metres a borehole *surface* is propagated into the earth by rotating the drill bit attached to the lower end of the BHA. This removal of rock causes the stresses and fluids within the remaining formation to redistribute and achieve a new equilibrium subject to the support pressure provided by the fluid present within the borehole. The proximity of nearby wells can also influence this redistribution. The domain of Production control is concerned with controlling the pressure and flow regimes to optimize hydrocarbon production by virtue of the effects of redistribution.

The drillstring can consist of hundreds of tonnes of steel but the forces applied to the bit must be controlled to a small fraction of that potential load. The drawworks is used to lift and lower the drill string into the hole and controls the *weight on bit* (WOB). At the surface we also find the rig systems for handling the drillpipe sections and the rotary-drive used to rotate the drillstring at a given rate of *revolutions per minute* (RPM). Systems that control the *rate of penetration* (ROP) need to know how to modulate WOB, RPM and flow in order to achieve the set-point objective within the constraints set by other pieces of equipment, Dunlop et al. (2011).

Downhole drilling tools must operate at high temperatures and pressures for hundreds of hours without failure. Ever-challenging drilling conditions are requiring materials to operate beyond temperatures of 200 C (392 F) and pressures of 275 MPa (~40,000 psi). Modeling how systems degrade at extremes beyond design limits is challenging. Possibly the most significant contribution that control can make in this regard is with improved methods of controlling temperature and pressure fluctuations to keep the tools operating within their design limits.

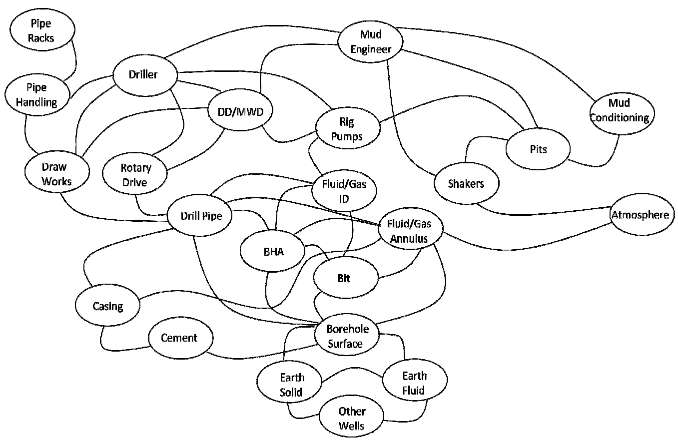

Fig. 2. Interfacial interaction between domains.

Drilling fluid is used to lubricate and cool the drilling process, to transport the rock cutting to the surface and to balance the pressure of the fluids contained within the formation. High-power rig-pumps force the filtered and chemically conditioned drilling fluid down the drillpipe at hundreds of gallons per minute and at thousands of pounds per square inch pressure. The fluid ejects through the bit and impacts the rock with great force and flushes the rock cuttings away from the bit. The fluid and cuttings flow up the annulus formed between drillstring and borehole and are returned to surface at atmospheric pressure to flow over *shakers* that screen-out the rock cuttings and other debris. The fluid then flows to tanks (pit) where it is *conditioned* before being pumped back down the drillstring. In large-scale drilling operations this is a complex materials-handling control problem, which because of regulatory conditions must also deal with safe disposal of cuttings and contaminated fluids, Geehan (2010).

The interaction-interface between the drilling fluid and the rest of the drilling system is both extensive and complex, as shown in Fig. 2. It under goes change as it does work, as it is mixed with the fluids from the rock, as it undergoes pressure and temperature changes and as it cycles between down hole and the surface where chemicals are added and removed. It permeates the surrounding rock throughout the borehole and can change the fluid make-up of the near-bore fluid volume within the rock which can later impede the flow of oil. Depending on rock type there may be chemical changes that further alter the shape and structural integrity of the bore hole (swelling shales). The fast moving fluid can erode the borehole and change its cross-sectional shape with time. Many of the downhole systems are powered by this abundant source of fluid energy and undergo the effects of corrosion and erosion themselves. The whole of the drillstring is exposed to the effects of the mud internally and externally. To model and control any one of these effects involves a deep knowledge of the fluids involved and a great deal of experimental data to derive the key parameters concerned, Zamora (2005).

The effectiveness with which the cuttings reach the surface and do not accumulate within the borehole depends on the velocity and rheology of the fluid, the further size reduction (re-grinding) of the cuttings and the inclination and shape of the effective annulus. Failure to adequately control the removal of cuttings from the borehole may cause the drillstring to get irretrievably stuck in the hole. When trying to model the pressure regimes along the bore it is important to model the effects of cuttings loading within the fluid.

The role played by the fluid, particularly how its pressure is controlled throughout the borehole, is of the utmost importance. Failure to adequately control pressure can result in borehole collapse, a blow-out or uncontrollable fluid loss to the formation.

The upper sections of the borehole are mechanically-protected and pressure-sealed by concentrically nested steel tubes called *casing* and retained in place by cement. The drillstring rubs against the open-hole section (not protected by casing) of the borehole as it rotates the drill bit and both drillstring and borehole are abraded in complex ways. Trying to model and control the complex multibody abrasion and erosion process taking place between tools, fluid and borehole is a challenging research area.

The human operators of driller, directional driller, mud engineer, measurements while drilling engineer are important and difficult to model participants in the overall system. As will be described, drilling is a stop-and-go process. The switching from one process to the next is invariably initiated and controlled by one or more of these operators acting in unison. One of the challenges for any automated drilling system is to know *when* to move to the next stage. This requires as good method of automatically determining *what* is going on and *where* everything is. In effect it is important to be able to automatically model the context of what is happening.

3. DRILLING PROCESS MODELLING AND CONTROL

The key control objective for most drilling control loops is to maintain system response within an acceptably small neighbourhood of the desired set-point. Ideally the driller wants to achieve a smooth rate of penetration, a smooth variation of flow along the wellbore, a smooth borehole trajectory, a circular borehole and a smooth motion of the drillstring, etc.

Any spatio-temporal change which is saccadic, erratic, oscillating, pulsing, stepping or ramping rapidly is usually indicative of some dysfunction, inefficiency or inconsistency, or even a dangerous state. Knowing this greatly simplifies the definition of what is required. Putting right these undesirable situations largely consists of detecting when an unwarranted change is taking place, interpreting and diagnosing the cause of such change; and selecting the right corrective action.

However, the process of drilling is inherently saccadic. At regular depth intervals of approximately 10 to 30 m, drilling is stopped to add additional lengths of pipe. The borehole may be *back-reamed*, in which process the whole drillstring (kilometres in length) is raised and lowered whilst rotating to clear cutting accumulations or to machine away any formation swelling. The up-and-down motion can pressure damage the formation if done too rapidly. The bit is also unloaded and spinning with the drillstring and which can give rise to high levels of drillstring shock and vibration. Back-reaming is a good example of when multiple domains couple to interact in a strong manner. The rock-bit models produce the cuttings, the cuttings enter the fluid's model, the process model of drilling dictates that hole is back-reamed, the motion of the drillstring whilst back reaming is governed by the drillstring model, the damage done to the rock by the BHA's shock-and-vibration response involves the rock-bit model, the change in dynamic behaviour of the drillstring is altered by the hole being abraded by BHA impact and so on.

Before more drillpipe is added to drill deeper, rotation and flow are stopped. During this period rock cuttings can settle around the drillstring leading to a *stuck-pipe* situation. The downhole systems can start to heat up as the fluid flow is no longer removing the geothermal heat and give rise to performance issues if design limits are exceeded. The rheological properties of the mud can change to being more viscous (thixotropic) and can become less dense due to heating.

Once the pipe connection has been made flow and rotation are re-established. If flow rate increases too quickly before the mud has *sheared* and its viscosity reduced, a formation damaging pressure spike can be generated. The kilometres of drill-pipe are spun up and the bit gradually lowered onto the rock to start drilling. A clumsy landing or overly rapid startup can cause the drillstring to enter destructive vibration modes requiring the whole process to be stopped, the energy drained away and the process restarted.

The control and automation challenge is to make all these processes flow in a smooth, bounded and controlled manner.

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2. MEASUREMENT AND CONTROL DELAYS

Drilling is a slow process with rates of penetration ranging from ~0.1 to ~500 m/hr. The curvature at which directional course changes can be imposed on the well-path made is also low; being much less than 15º deg for every 30 m drilled on average.

Real-time measurements of events taking place close to the BHA have improved greatly with the evolution of mud-pulse telemetry (Fig. 3), Hassler (1944), Turner (2004). The telemetry transmitting device is installed within the BHA and sends information to the surface by variously modulating the frequency, phase and amplitude of pressure waves in the mud column via a controlled process of flow interruption. The challenge for the industry has been to increase the channel capacity of this uplink as drilling depths have increased and more sensor measurements need to be monitored at the surface.

State-of-the-art mud pulse telemetry provides less than 100 bits/sec under the most favourable of conditions and little more than 1 bit/sec at extreme depths or noise levels.

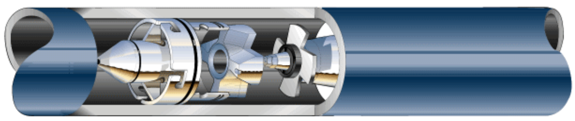

Fig. 3. Telemetry mud pulser.

Not only are these data rates low by normal external industry standards, there is considerable latency and jitter measured in seconds in the information arriving at the surface. For logging and monitoring purposes this is of no consequence as the data is time stamped and can be related to a defined time and place in the well.

The *delay* derives from numerous sources, which include the time taken to make the measurement and transmit it to the telemetry tool, the time needed to compress the data with other data channels from other tools, time spent waiting in the queue to be telemetered, time for the pulse to propagate through the drilling mud to the surface, the time taken by the surface systems to filter and decode and any communications delays between different surface systems.

Figure 4 is representative of many drilling situations. The rig is controlled to establish the required drilling parameters settings for flow, WOB and RPM. These drilling parameters can be used in two ways to influence downhole tool behaviour. The first and simplest class is where the modulation of parameters physically acts to change the state of the tool. For example, simple rotary drilling assemblies with no steering actuation can be directionally steered to a limited extent by varying WOB and drillstring RPM. The second and more advanced class is where the power modulations are decoded by downhole sensing systems into electrical or digital set-points for the downhole systems to achieve. For example, modulations in RPM or flow can be sensed by gyros or turbine alternators in the tools and the waveforms decoded. The class-one method supplies *the energy and the intent* to change the state of the tool; whereas the class-two method supplies the *intent* but relies on the receiver to have its own source of *energy* to change state.

There is also a delay on the downlink channel. Sources of delay include operator response times in selecting or approving the command to be transmitted; interconnect speeds between surface systems; operational constraints on modulating the drilling parameters given other rig activities; propagation delays in telemetry medium; and time taken to filter, decode and distribute information within the BHA.

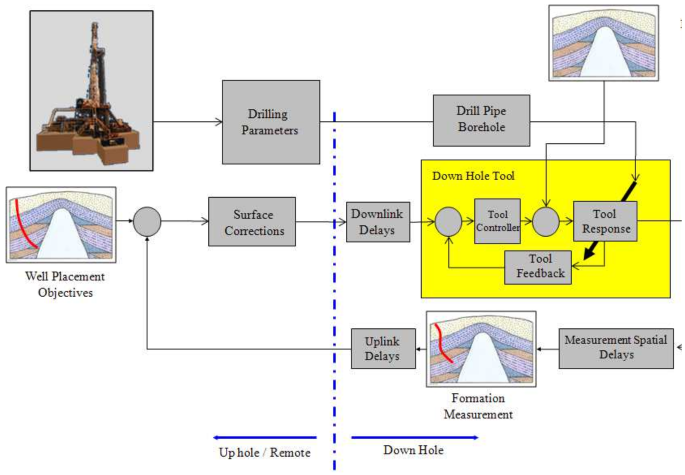

Fig. 4. Spatio-temporal delays.

The transient performance and stability of response of any loop closed between the surface and downhole is strongly influenced by the magnitude and variability of the telemetry delays, the spatial and temporal sampling frequency, and measurement noise, Barreto (2010). These effects must be included in any surface-to-downhole closed loop system and have impacted the underlying generic architecture of most drilling control systems. That is, the fast loops within any nested control hierarchy have had to be implemented downhole. This in turn has meant the models embedded in the downhole tools have had to be relatively simple, with the more complex aspects of the model installed at surface providing low-bandwidth set-points for the downhole fast loops.

5. BOREHOLE PROPAGATION MODELLING AND CONTROL

The rock surface in contact with the drill bit defines a complex ever-changing *wavefront* that propagates into the rock, (Fig. 5., right image). Drilling is clearly an irreversible process and can be modeled to a high degree of realism. The drill bit carries cutting elements made of polycrystalline diamond compact (PDC) that rotate with the bit and intersect the rock face to remove cuttings by gouging, shearing, chipping, crushing or abrading the rock. From a modelling perspective, tracking of the geometry of the rock as it is removed and shaped by the cutters is a memory-intensive calculation. Integration time steps of the order of ~1.0 msec or less are required depending on the bit's RPM. The loads required to remove a rock-element are determined by its size, shape, shear surface and rock type. Knowledge of the forces involved is derived from an extensive library of empirical "scratch" tests in which similar rocks have been cut using a similar single cutter under experimental conditions at realistic pressures and with representative fluids.

These complex load patterns are summed across the bit surface and become stimuli to the rest of the drilling system. High-fidelity time-domain FEA models keep track of the bit's deflection in 6DOF as it transiently moves according to freedoms permitted by the BHA and borehole. The ability to include the motion of the fluid over the cutters can also be modeled using CFD techniques to determine if adequate flow is available to flush the cuttings away from the bit face, (Fig. 5., left image).

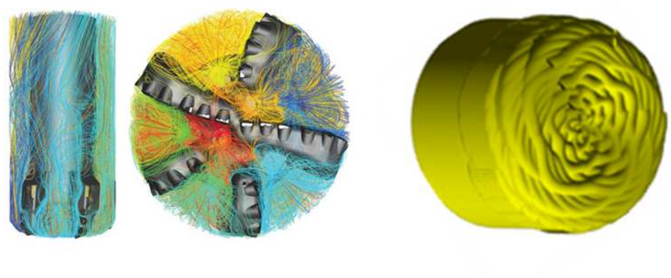

Fig. 5. Hydraulic bit-cleaning and rock-face propagation.

The complex shape of the borehole face and wall are stored within the simulation to determine how other touch points with the drillstring might influence response. And, it is even possible to simulate the subsequent change in borehole wall shape due to the passing of rotating stabilisers (pipe centralisers) over its surface.

Below this very high-fidelity bit model exists a wide spectrum of intermediate rock-bit models for the control engineer to select to suit particular purposes. We have everything from the full-time domain model to a simple gain term for ROP versus WOB. The question of which model is best is a recurrent issue. For example, it is possible to capture the essence of how a bit drills by generating an averaged set of modelling gains to describe its behaviour over a single or multiple revolutions? This massively reduces the time to compute how a BHA might directionally steer by permitting quasi-static techniques to be used to model borehole propagation. In so doing, a sacrifice is made concerning the modeling of high-frequency dynamics which may be critical to how the borehole diameter propagates and completely changes the borehole propagation predictions. From a control perspective ignoring these high-frequency effects in the design of the control loop may unwittingly create parasitic loops that destabilize the system.

The time is fast approaching when computer speeds will allow the high-fidelity system models to be run much faster than real-time, and it would seem that we would always want to use the best available model.

Creating models is the best means we have to capture and confirm our understanding of physical processes. Despite the undeniable theoretical complexities of some models there is *nothing more practical than a model that works!* However, because these models include everything we know, a large demand is placed on the user to supply accurate values for all the parameters, many of which vary with time, space and usage. The models also indicate that we are dealing with chaotic systems, meaning that the accuracy of any prediction critically depend on precise knowledge of the initial- and boundary-conditions, which are themselves complex and difficult to measure precisely, and thus usually have to be treated stochastically. Indeed, it is the role of the control engineer to make these systems less chaotic!

The interaction between the ever receding rock face and the drill bit is highly complex and moderated by the transient reactive loads and torques between rock and bit; the fluid flow patterns removing the cuttings from the bit-face; the propagation of fluid, particulate, fractures and fissures into the rock; and the general stress field around the borehole. All of these are complex matters.

There is always balance to be struck between the completeness of a model (its complexity), the extent of the period over which it is being asked to make a prediction, and the accuracy with which the input parameters need to be known. In the case of distributed media governed by partial differential equations, we can add the additional rider that *the distance of the edge of the space over which the prediction is being sought* is also weighed into the balance. With closed loop control we have a steady stream of additional information that can update the critical parameters so that they do not need to be totally specified in advance. The very nature of closed loop control obviates the influences of many parameters, making their estimation and modeling redundant. A point that repeatedly recurs in this field is that a simple model informed by high quality, fast and noise-free data can be extremely effective.

So whilst complex models are needed for the verification and validation of a control system it is not the case that they must always be incorporated into the fast loops of a real-time control system. But there is a good case for their incorporation into the supervisory levels of control where humans are better equipped to make judgements on how parameters can be changed and updated. However, what is a supervisory loop today will become a supervised loop tomorrow. It is a continual process of change. Deciding the comprehensiveness of the models to be used for the modeling and control of rock-bit interactions, drill string dynamics, borehole pressures and flow, mechanical model of the Earth etc. will be an ongoing challenge for the control engineer.

A rapidly developing area of drilling automation is that of ROP optimisation, Dunlop (2011). Great strides have been made to develop relatively simple models of the drilling process that can be updated in real time to provide a means of asking "what-if" questions regarding how the drilling parameters should be changed to increase the speed of drilling. This experience also serves to remind us that the process of drilling, especially when high performance is demanded, causes otherwise independent loops to start to be tightly coupled. For example, the drilling parameters corresponding to the optimal bit ROP may be unobtainable because they cause excessive drillstring vibration, or produce cuttings so fast that they choke the hole, or the rig drive systems cannot provide the power, or the directional drilling system cannot steer, or the bit dulls to quickly, etc.

Designing a single control loop in isolation is "relatively" safe. Designing multiple loops in isolation and hoping the interactions remain a simple matter is far from safe. It is in such situations that great value is found in the full high-fidelity model of the system where little concession has been made to simplicity, reduction or ignoring second-order effects.

6. DRILL STRING DYNAMICS MODELING AND CONTROL

Unlike the situation in most industrial plants in a drilling system a vast section of the power transmission system is "hidden" from view in about every conceivable interpretation of that term. The expanse of drill-pipe and fluid between the rig and the BHA conveying thousands of kilowatts of mechanical and hydraulic energy is at the mercy of complex couplings and energy exchanges caused by uncertain contacts between rock, steel and fluid, Spanos (2003).

The thousands of kilowatts of power poured in at the surface by the rotary drive may, at the limits of drilling, be less than 10% of this energy by the time its reaches the bit. The spatiotemporal distribution of where and when this rotary energy is dissipated in its journey to the bit is highly complex and depends not only on the structural and flexural properties of the drillstring but also on the shape of the hole; the shape of the tools; the ever-changing pattern of touch-points between drill-string, borehole and casing; the coefficients of normal and tangential restitution, and contact friction; the complex multibody abrasion and erosion taking place between borehole, drillstring, fluid and cuttings, to mention an incomplete list.

Modern mechanised rigs have high-fidelity servo controls on pump speed (flow and pressure), drawworks (hoist speed and load) and topdrive/rotary table (drillstring RPM and torque at the surface). Controlling what goes *in* is not the problem, Eustes (2007). Changes at the surface take time to propagate down. Kilometres of steel grinding away at the borehole mean that whatever is propagated down is contaminated by the consequences of these touch-points with the hole. The drillstring, once rotating, contains huge angular momentum. This distributes itself in a non-uniform manner along its length reflected in the possibility that kilometres of pipe can come completely to rest whilst other parts can spin violently, Aldred (1992), Baird (1985), Dareing (1968), Richard (2007), Zifeng (1999 a).

In the localities experiencing back-wards whirl, energy becomes stored in the drillstring not only in the form of rotation but also in the velocity of the centre of mass of the pipe as it rolls around the borehole.

It is feasible to model the dynamic behaviour of a drillstring in great detail (Fig. 6) and be fairly confident that the resulting motion is representative of what should ensue if we could precisely know all the parameters describing the interfacial relationships between drillstring, rock and fluid. In practice, we can only know these parameters to within certain bounds. Within these bounds is possibly permitted a wide range of behaviours from benign to possibly catastrophic depending on the design of the drillstring. Consequently, all predictions are based on a comprehensive parameter sensitivity analysis.

For example, the transition from smooth drillstring rotation through vaguely named intermediate states to a well-defined and unmistakable backwards whirl is so complex and so dependent on the interfacial energy exchange parameters, which probably change on each impact, that it is unreasonable to expect the transition to be precisely modelled. Fortunately, backwards whirl can be regarded as a stable energy condition despite its destructive consequences on the drillstring, and a model of the susceptible system can usually find that stable state efficiently.

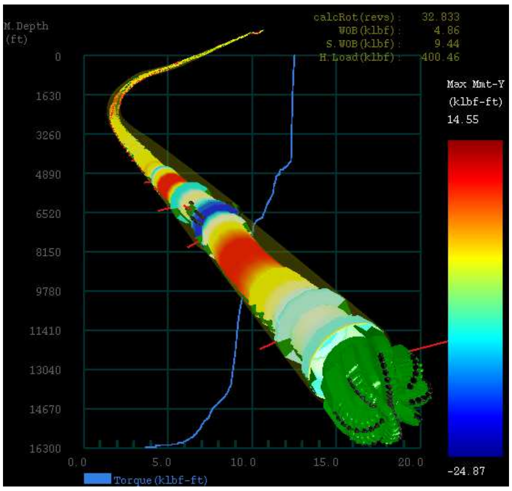

Fig. 6. BHA modelling.

The primary control input is *how* the drilling parameters are modulated from the surface. What happens below the rig is an uncontrolled action-reaction sequence of events. Knowledge of high-frequency events largely become apparent through what leaks-through to be detected at the upper or lower boundary conditions, including the ultimate *signal* of getting stuck or breaking into parts.

The primary method of *control* is to constantly adjust drilling parameters such that the drilling system *naturally* behaves in a passive manner, i.e., the right conditions are created to allow it to self-stabilize by virtue of the prevailing internal dampening conditions. As previously mentioned, there are many points of energy leakage throughout the system, and the challenge is to avoid this leakage aggravating any of the non-linear instability mechanisms.

Promising effects have been obtained simply by modifying the boundary conditions at the rig to condition the energy rebounding along the drillstring, Javanmardi (1992).

To *dynamically* control the behaviour of the drillstring as it transmits its mechanical energy to the bit, we need to associate its controller with a model of the drillstring. If the real world remains in line with our implicit or explicit model of the drill string then the rig inputs can be controlled to achieve a smooth response. The ability to measure local bending, twisting, lateral displacement, loads and torques at frequencies beyond 1 kHz at either end of the drillstring is not the real challenge. This can now be done to a very fine degree of resolution in time and measurement space. With large capacity memories, it is now possible to fit the recorded data to the drillstring model and make some assertions as to its form at the time of recording post-priori.

But the upward telemetry channel limitations present a challenge to any attempts to update or refine the model of the drillstring below a certain response time in real-time. The challenge for the control community is determine whether adequate control can be achieved through controlling the rig alone.

7. DIRECTIONAL DRILLING SYSTEM MODELLING AND CONTROL

The ability to instrument control systems around some of the uncertain processes of drilling significantly improves system performance and consistency. Nowhere is this more apparent than for the most prevalent of downhole closed loop control systems - the directional drilling robots collectively known as rotary steerable systems (RSS), Warren (1998). A generalised directional drilling system is shown in Fig. 7 comprising multiple actuators to control the direction of borehole propagation; it also encompasses a wide range of the most important *passive* drilling assemblies, Downton et al. (2007, 2011).

Before the advent of RSS, modellers we were concerned with understanding why the borehole drilled by a *passive* rotary assembly built, dropped or turned the angle of the borehole to this or that extent, Birades (1986), Chandra (1986), Ho (1986), Lubinski (1955), Millheim (1978), Zifeng, (1999a, 1999 b). Small changes were seen to make a large difference particularly with regard to the complex rock-bit interaction, Ho (1987). Many parameters were never accurately known, and so the prediction had a fairly wide distribution of possible trajectories. However, when the error in *desired* direction of borehole propagation could be measured in real-time and fed back to the directional drilling system, a shift in modeling emphasis took place.

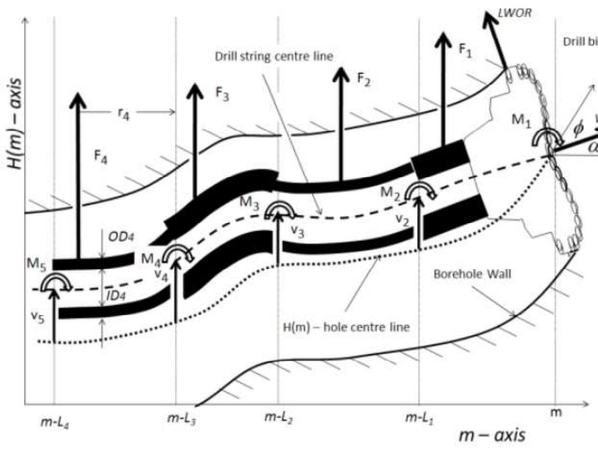

Fig. 7. Generalized directional drilling system.

Put in simple terms, the drillstring selection efforts shifted from trying to predict how each phenomenon would interact with the (open-loop) BHA, to determining the likely bound on each sources in order to select a big enough hammer (steering actuator force) to reliably crack all nuts (to steer the tool). This did not mean that the individual physical phenomena no longer needed to be understood, far from it. Instead, this was a reflection of the fact that certain effects are simply impossible to precisely predict far in advance other than their likely bounds. This is certainly true for drilling in regions that have never been drilled before.

Because of the benefits of closed loop control, we can steer a precise borehole trajectory without ever knowing the exact source or extent of a trajectory disturbance. Of no great surprise to a control's audience is the revelation that the greater the use of feedback and control, the greater our ability to manage the drilling system's response to a window much narrower than any open-loop prediction of system behaviour could ever reliably achieve. And, the greater is our ability to deal with bounded uncertainty.

The ability of closed loop RSS to automatically change state downhole has eliminated the expense of having to repeatedly retract and reconfigure the passive drilling assemblies of old. A similar story could also be told for how RSS have started to replace bent-housing mud-motors for high-value applications.

Although extensive high-fidelity modeling is performed to understand the behaviour of RSS, the models implicit within the RSS control systems are significantly less complex and detailed.

8. EARTH MODELS FOR CONTROL

Another *delay* shown in Fig. 4, which from a control perspective can swamp all the temporal delays combined, is the spatial separation between the *effective* measurement point, line, surface or volume of the measurement sensors and the bit. It is very difficult and expensive to *un-drill* a well, i.e., fill the *wrong* hole with cement and drill off in a better direction. The direction in which a well is steered is decided by what the measurements reveal about the stratigraphy of the rock formation, its contents and constituents and the stress field. The closer the effective measurement's location to the bit, the more "distance" is available to change to a more favourable course.

Prior knowledge of the layering of formation, its thickness and angular orientation, makes an Earth model (EM) invaluable in estimating where the borehole is being placed within the prospective reservoir. Even though the measurement point may be tens of metres behind the bit, knowledge of the equation of the centre line of the hole in the coordinate frame of the EM provides a useful control input to the steering system.

The EM can be constructed from data derived from drilling in the same locality or formation. For exploratory drilling, it is usually derived from seismic surveys which have a resolution of approximately ten metres, which is less than features such as a geological fault that need to be identified. In addition there is always a residual uncertainty on the location, thickness and type of formation in place beneath the surface. In complex formations, discontinuous geological faults can require a careful *lane-change* to be executed in order to maximize drain length within the reservoir (Fig. 8.).

The crossing of formation "tops", if they can be detected, is a useful guide to working out where the borehole is relative to the expected formation. Imaging of the borehole by use of resistivity measurements across small buttons in contact with the borehole can reveal how the formation layers are actually orientated. This *dip* information can be used to update the EMs representation of how the layers may be folding for example.

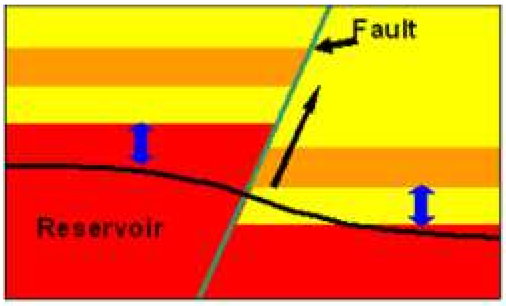

Fig. 8. Geologically faulted formation.

The analysis of the rock cuttings, fluids or entrained gases can all help weight the estimates of relative position. The energy efficiency with which the bit is able to propagate the hole also provides useful clues on formation type. Interpretations from geologists on how the formation was deposited and contorted over time are highly critical, and geologists usually have the last word on how the EMs should be updated.

From a control perspective we have the interesting prospect of updating a predictive model of the Earth using a diverse range of inputs whilst making irreversible decisions on propagating a hole through it, not knowing for sure the consequences of those decisions until tens of metres of well have been drilled. This is generally called *geosteering*, Griffiths (2009).

9. FLUID MODELLING AND CONTROL

Of paramount importance is the need to prevent uncontrolled movement of drilling or formation fluid (oil, water, gas, etc.) between the rock and the borehole. If the pressure in the borehole is too high, it will fracture the formation, and the drilling fluid may leak away in an unexpected manner with consequences ranging from an unplanned cost to a catastrophic loss of the well. If the pressure is too low, the fluid in the rock can exude out into the borehole. If unchecked a "kick" can occur as the low-density fluid displaces the heavier mud and sets in motion a positive feedback system of ever-reducing hydrostatic head with ever increasing size of influx. If the kick fluid is a gas, then the lost of hydrostatic head is even more rapid as the gas expands out and therefore lightens the fluid in the column.

Information regarding the safe pressure window versus depth is provided by another type of EM that estimates the rock stresses and fluid pressures in the borehole.

Managed pressure drilling (MPD) is providing a rich source of problems and challenges for the control systems community, Breyholtz (2010), Fredericks (2008), Geehan (2010) and Stamnes (2011). The base-line objective is to control the bottom-hole pressure (BHP) in the face of all disturbances. Operationally, these include pressure spikes caused by rapid pipe movement and rapid pump start up, pressure drops caused by shutting down the pumps and removing the pressure contributions of dynamic head (friction), pressure build-up caused by cuttings accumulation and changes in mud density due to additives. Geologically, pressure disturbances can be caused by drilling into a high or low pressure zones requiring an update to the pressure window model and corresponding new BHP set-point. Should two rock layers connect with no overlap in pressure window a down hole blow-out can occur and is a most difficult situation to control because no one BHP pressure set-point will stem all flow.

Although the surface systems can be heavily instrumented to measure flow, pressure, temperature and mud properties the same is not common place when it comes to measuring the BHP. In many situations there is no direct measurement of BHP.

Normally the returning fluid from the well is at atmospheric pressure as it flows out of the well. An MPD control system (Fig. 9., left) uses a Rotating Circulating Device (RCD) (Fig. 9., right) to seal the annulus between drill pipe and borehole at the surface and to divert the flow through a variable choke. The variable choke in the return path is used to create a pressure greater than atmospheric. The pressure throughout the annulus, and most particularly the BHP, can thus be increased in a controlled manner. The density of mud is chosen such that the pressure versus depth slope follows (as best it can) the safe pressure window for each point in the well. The static head in such cases is not enough to stop the well from flowing; consequently, a delta-pressure increase is imposed by the variable choke.

Whilst adding or removing drill-pipe there can be no flow. The target BHP is therefore maintained by trapping pressure between the choke and a non-return valve in the drillstring. An auxiliary pump may also be used to adjust annulus pressure if required.

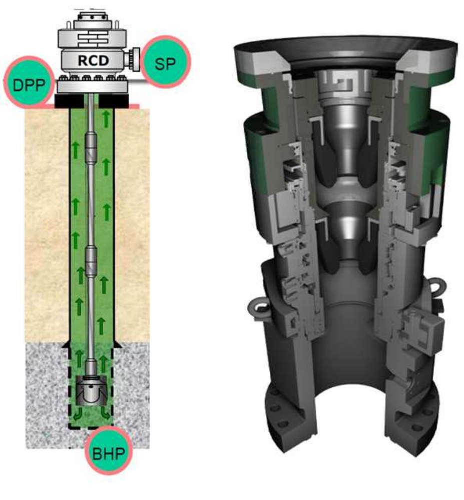

Fig. 9. Managed pressure drilling system and RCD.

It is of absolute necessity that the fluid circuit is modelled in real-time, using all available real-time surface measurements to infer an accurate and timely estimate of BHP. There is no more important task to befall drilling than to control BHP. The spatio-temporal validity and accuracy of this model is therefore paramount.

Although research attempts are being made to develop controllers that assume no apriori knowledge of the plant, we currently have to select a suitable model to proceed with any hope of achieving a workable implementation.

The situation improves if annulus pressure measurements on in the BHA can be telemetered to surface. Although impacted by telemetry delays, steady-state direct measurement of BHP can be used to update and correct the model. This improved model gives a better estimate of BHP when direct measurements are not available i.e., when making a drillpipe connection.

As in previous cases, the question arises regarding the complexity of the model required. The same patterns emerge. The more predicatively accurate the BHP model needs to be, the more it needs to be complete (thus complex), requiring access to reliable mud properties data, pump and drawworks transients, EM model, and phase of drilling operation. The accuracy of this model improves when the number of spatio-temporal sampling points is increased (i.e., by including BHP direct measurements), and this lessens the demands on having to accurately estimate parameter variations. The ability to close a tight loop via the surface is fundamentally limited by the telemetry data rates and time delays and the propagation of corrections through the media.

10. OPERATORS AND AUTOMATION

Probably the most complex part of the whole system to model is the human community of surface operators, Parasuraman (2000), du Castel (2012). As control system technology is introduced, operators move away from hands-on control to more supervisory roles. No longer are we so interested in their speed of physical response as part of a teleoperated control system. Instead, our interest concerns their "situational awareness" of what is going on, in particular, what mental models of the process and plant do they have when giving commands, taking instructions or trying to recover from an unrehearsed or uncertain failure event. As technology becomes more proficient at instrumenting the lower-level control systems to reduce uncertainties in the process, so automation of the process grows in complexity and the need increases to understand the type of interactions that can take place between the different parts of the drilling system and its operators.

The key control objective for most drilling control loops is to maintain system response within an acceptably small neighbourhood of the desired set-point. This greatly simplifies the definition of what is required. It also means that detecting these undesirable conditions consists of detecting when a change is taking place, diagnosing the cause of such change and selecting the right corrective action, Aldred (2008). Consequently, an interesting synergy is developing between Bayesian signal processing techniques to identify state changes and ontological models of the drilling process to reason about subsequent corrective actions. The computed output is close to human language and therefore very relevant to improving the interface between human and the automated machine.

11. CONCLUSIONS

Anyone unfamiliar with the drilling industry must by now be asking: "Why labour under the communications constraint imposed by the telemetry systems?" Figure 10 shows the status-quo. Control and actuation exist as information-islands at the surface and down hole, bridged by a low-bandwidth communications link.

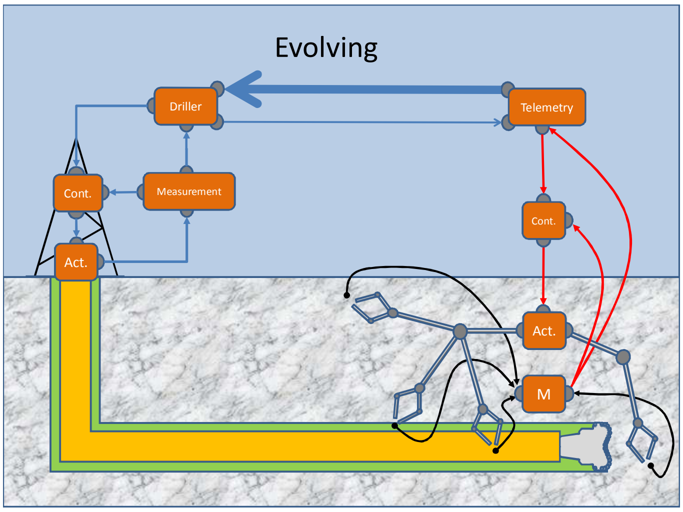

Fig. 10. Current communication and control architecture.

Every aspect of modeling and controlling rock-bit interaction, drillstring dynamics, ROP optimisation, trajectory path following, borehole fluid pressure control, geosteering and general state awareness would be made so much easier to instrument if standard industry communication speeds were available at multiple points along the well-bore and the whole system networked together as in Fig. 11.

If high-bandwidth, low-latency measurements can be made at regular intervals along the wellbore of the fluid, mechanical and formation system states then the complexity of the models filling in the *line*, *surface and volume* voids between these measurement nodes should be simpler and able to achieve an accuracy to compete with more complex models spanning more widely spaced points. The same argument applies to control. A network of actuators distributed throughout the well bore will be more effective at rejecting disturbances than actuators placed more widely apart.

An evolutionary path, S0 to S4, is discernable for the measurement and control of current and future drilling processes:

- S0 = A drilling system with surface measurements and surface control
- S1=S0 + BHA measurements
- S2=S1+ BHA control
- S3= S2+along-drillstring measurements
- S4=S3+along-drillstring control

It need not be a high-bandwidth system; the above is true for any network. However, the propagation speeds of waveforms through steel, fluid and rock media probably mean the network should be faster to achieve the highest fidelity of control.

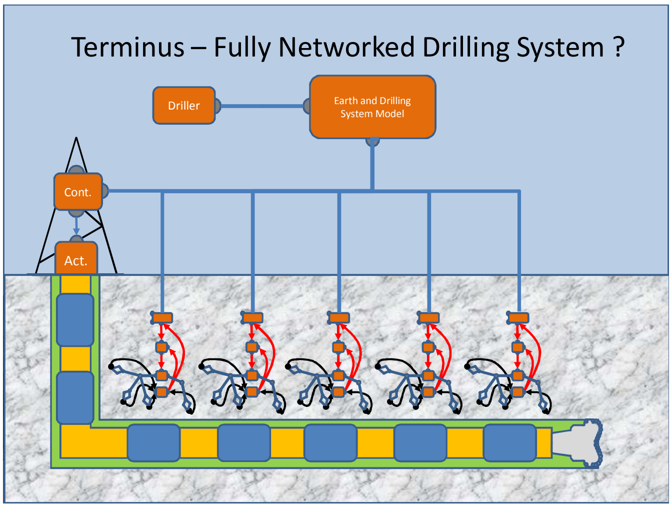

Fig. 11. Fully-networked communication and control.

A unification of models will probably be necessitated as the progressive automation of drilling demands ever higher performance. Put simply, in squeezing the last vestiges of performance out of the system the need to control erstwhile second-order effects and cross-domain (cross-model) couplings will be exacerbated. In the same way that a high bandwidth network of closely spaced sensors can simplify the models *within in a domain*, so it holds the promise to simplify the more challenging *cross domains* models. With tractable models come tractable control and thence a unified approach to drilling automation.

This kind of high-speed sensor-network functionality is becoming available through wired drillpipe, Jellison (2003) and Wolter (2007). It is a new and highly disruptive technology that is firing the imagination of control engineers to innovate solutions that currently might be regarded as science fiction. The book is far from written on this area of control endeavour.

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