# Drilling Automation: Presenting a Framework for Automated Operations

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## Summary

This paper will present and discuss drilling automation on the basis of a "mode of automation" approach. Different modes of automation will be presented and explained. In particular, the paper will focus on how closed-loop control can enable higher modes of automation, which is essential to improve the operational and economic performance of drilling operations. Introducing a higher mode of automation may lead to optimal performance, but it also introduces new safety issues that need to be addressed in order to ensure safe conditions in the well. For each increased mode of automation, the work distribution between the automation system and the driller changes and a clear understanding of the human/machine interaction at each mode of automation is needed.

## Introduction

Automation in the drilling industry has been at a relatively low level compared to other industries, but research and development on automation solutions within the drilling community has increased significantly during the last decade. Automation of various aspects of the drilling process, such as ensuring mud properties, pipe handling, precise borehole-pressure control [managed-pressure drilling (MPD)], and automation of different drilling operations (tripping, directional drilling, pump startup), are now either commercially available or on the verge of becoming available (Strøm et al. 2008). The widespread acceptance of such systems is likely to increase as the technology matures and experience in its use grows.

In a broad sense, automation is the introduction of control systems and information technology to reduce the physical and/or mental workload of human operators in charge of running a process. Automation is a step beyond mechanization, which assists operators by replacing human power by mechanical. In general, process automation is motivated by a desire to increase economic and/or operational performance while making a process as safe as possible. Because automation has been slow to penetrate (no pun intended) the drilling industry, only to a relatively small extent, the economic benefits from introducing higher levels of automation in drilling may be significant. But to realize such benefits, automation systems must be carefully designed in order to ensure that the overall operational and economic issues are addressed. Rather than completely replacing humans, automation systems improve performance during normal operations while allowing the operator to intervene to varying degrees in case of abnormal events. An obvious requirement of automation is to ensure that it does not result in critical situations, detected or undetected, becoming worse than without the automation system in place.

Attempting to directly automate every single aspect of a relatively complex process, such as drilling, is highly challenging, if at all possible. Further complicating the situation is that there are already many different systems, software solutions, and service providers and vendors whose solutions address various aspects of drilling automation in isolation. Coordinating all of these and expanding them would be nontrivial.

The purpose of this paper is to put drilling automation into a general framework by using a "modes-of-automation" approach. Throughout the paper, the concept of automation modes will be explained, and some of the key terms and techniques will be further investigated and discussed [envelope protection, closed-loop control (feedback control, supervisory control, optimized control, and autonomy)]. In addition, the role of the driller in a highly automated environment and drilling automation in combination with poor down-hole conditions will be discussed. Finally, recommendations for future development will be made.

## Modes of Automation

Automation is a general term referring to a variety of automation strategies with different modes of human/machine interaction. In general, the role of both the human operator and the automation system will be affected by the chosen mode of automation. Today's mode of automation in the drilling industry is low, but increasing. Higher modes of automation are likely to be developed as long as the development is motivated by the desire to improve both the efficiency and safety of the drilling operation.

The role of both the driller and the automation system will be dependent on the chosen automation strategy. In **Table 1** the different modes of the modes-of-automation concept are presented, and both the actions and the tasks of the automation system and the driller's functions are discussed. The modes are listed from Mode 0 (lowest degree of automation) to Mode 6 (highest degree of automation). These presented modes are based on automation theory from the aviation industry (Billings 1996). Alternative automation modes for drilling operations can be found in Thorogood et al. (2009) and Ornaes (2010).

Mode 0: "direct manual control" mode. In this mode, the driller will receive no support at all from the automation system. The driller is presented with raw signals and simple alarms associated with topside hardware.

Mode 1: "assisted manual control" mode. The significant contribution of the automation system in this mode is the introduction of software that analyzes the current situation of the well and presents the information to the driller. This will improve the quality of the decision making of the driller.

Mode 2: "shared control" mode. This is the first mode at which the automation system will start to directly interfere with the operation of equipment. The main feature of this mode will be envelope protection. The philosophy of envelope protection systems is not to interfere as long as the conditions of the well are within a predefined range of acceptable values. If the system detects that the driller will violate these constraints, the system will limit the driller's actions.

Mode 3: "management by delegation" mode. In this mode some of the drilling crew's tasks are delegated to the automation system. This means that some of the tasks are fully automated by a closed-loop controller. Examples of automated modules are automatic pressure control in MPD operations using topside choke, fully automated tripping module, and pump startup module. The main reason for introducing closed-loop control is to improve the overall performance of the automation system.

Mode 4: "management by consent" mode. This mode of automation introduces supervisory control, which is a technique to efficiently coordinate several closed-loop controllers. To achieve such a mode of control, models describing the well and how the closed-loop controllers behave and interact are needed. Introduction of supervisory control will by nature result in autodriller functionality. The driller will be operating the system by choosing operational modes (drill one stand, trip out one stand, make a connection, start circulation), and defining key variables for the well.

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TABLE 1—DIFFERENT MODES OF AUTOMATION AND THE RESULTING TASKS FOR THE AUTOMATION SYSTEM AND THE DRILLER ARE PRESENTED [MODES BASED ON AUTOMATION STRATEGIES FR OM THE AVIATION INDUSTRY (BILLINGS 1998)]

| Mode | Management Mode | Automation Functions | Drillers Functions |
|---|---|---|---|
| 6 | Autonomous Operation | Fully autonomous operation. | No particular function. Operations goals are self-defined. Monitoring is limited to fault detection. |
| 5 | Management by Exception | The automation system chooses operations and defines operation goals. Informs the driller, and monitors responses on critical decisions. | The driller is informed of the systems intent. Must consent to critical decisions. May intervene by reverting to lower mode of management. |
| 4 | Management by Consent | The automation provides coordinated control of multiple control loops. | The driller feeds the automation system with a chosen operation, operation goals, and desired values for key variables (e.g. circulation rate) |
| 3 | Management by Delegation | The automation system provides closed loop control of individual tasks. (E.g. Choke pressure control in an MPD system; automated tripping module) | The driller decides setpoints for the individual control loops. (E.g. setpoint for pressure in MPD operations). Some tasks are still performed manually (envelope protection active). |
| 2 | Shared Control | The automation system could interfere to prevent the driller from exceeding specified boundaries. Should predict the outcome of the driller's choices. | Envelope protection systems are enabled. Decision support/advisory systems are available. |
| 1 | Assisted Manual Control | Provides down-hole information trends, and detects abnormal conditions in the well. Does not intervene. | The driller has direct authority over all systems. Decision-making is computer-aided. |
| 0 | Direct Manual Control | Normal warnings and alarms. | The driller has direct authority over all systems. Unaided decision-making. |

Mode 5: "management by exception" mode. This mode of automation is separated from the preceding mode by additional logic that determines the next operational mode. This mode should be considered to be an autonomous mode where the driller has the authority to interfere if the system does not behave as expected.

Mode 6: "autonomous operation" mode. In a fully autonomous system the human does not play a significant role, and the only remaining task is to monitor or, if it is necessary, to reduce the chosen mode of automation in order to regain control of the system in abnormal situations.

It is important to note that the mode of automation does not need to be a permanently chosen mode; in fact, the driller should be able to move between different modes of automation during a single drilling operation. Even though a high mode of automation is used, the driller is still the absolute authority of the operation. This means that the driller must be given the means to override the automation system if it is necessary. Each mode of automation has a cost that must be balanced or overcome by its benefits.

## Envelope Protection

The basic idea of envelope protection systems **(Fig. 1)** is to prevent the driller from damaging either the topside equipment or the well. An envelope protection system is a system that does not interfere as long as the driller does not try to exceed the boundaries of the envelope. The challenge associated with development of such a system is the continuous calculation of the boundaries of the envelope. These boundaries should be dynamically calculated on the basis of the current state of the well and known topside machine limitations (which are static boundaries). Preventing the driller from damaging topside equipment is straightforward by setting constraints according to machine limitations (minimum and maximum values, in combination with acceleration and deceleration constraints).

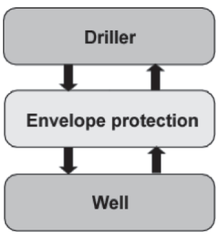

**Fig. 1—Level 2 "Shared Control" on the automation scale. Envelope protection systems are active.**

An envelope protection system that takes the well conditions into consideration when calculating the boundaries has been successfully implemented at an offshore installation (Iversen et al. 2009). Limitations on pump acceleration and pipe movement are calculated by analyzing the conditions of the well. One of the challenges associated with development of envelope protection is the requirement of a detailed model to estimate the current conditions of the well and to predict the outcome of the driller's actions (new circulation rate, tripping velocity). Dynamical calculations of the boundaries may result in a high computational cost.

Envelope protection systems have gained a widespread acceptance in the aviation industry, where the overall goal has been to develop systems that try to estimate the achievable flight envelope of the aircraft. In the aviation industry the term envelope refers to a set of states in which control actions exist to ensure that the vehicle can proceed to a safe landing from air, while constraints on flight path, landing point, and velocity are satisfied (Tang et al. 2009).

Both Billings (1996) (aviation) and Iversen et al. (2009) (drilling) raise an important issue related to envelope protection systems, which is how the system should work if a critical situation occurs. This issue is also prevalent in process industries where abnormal-situation management (namely, detection and mitigation) is of paramount importance for ensuring safe operations. **Fig. 2** shows the evolution of an abnormal situation into a more-severe catastrophic event.

The main motivation for the development of envelope protection systems is to prevent critical situations in general, but because of

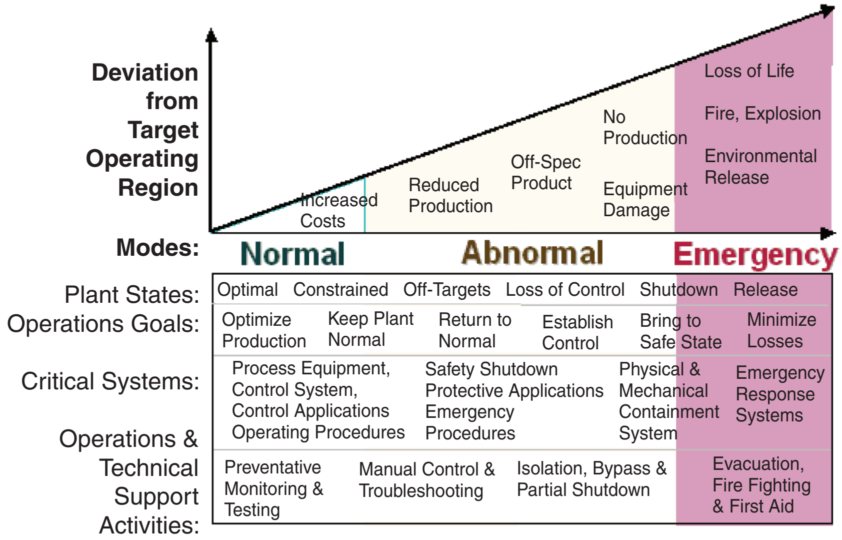

**Fig. 2—As the deviation from the operating region increases, so do the possible consequences of the deviation (courtesy of www.asmconsortium.net).**

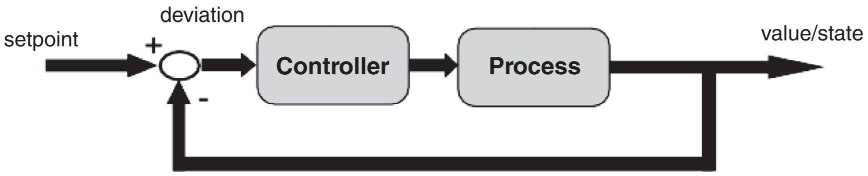

**Fig. 3—Illustration of the closed-loop control concept. The driller feeds the automation system with a setpoint, and the closed loop algorithm compensates for the deviation from this setpoint.**

the complexity of drilling operations and the uncertainty regarding downhole conditions, such systems are only likely to reduce the frequency of critical situations, not eliminate them entirely. A concern related to such systems is whether system limits intended to minimize wear and prolong equipment life interfere with the operator's flexibility in a critical situation. Indeed, the driller/operator may want the possibility of exceeding certain limits temporarily in order to handle a critical situation. While temporarily working outside the operating envelop may increase hardware wear and tear, it may prove beneficial for handling a critical situation, which is preferable.

## Closing the Loop

When moving upward on the automation ladder, closed-loop control becomes essential. Closed-loop control is a well-known concept from control engineering where the operator sets a desired value (setpoint) on a state of the process [e.g., the driller sets a desired bottomhole pressure (BHP) in an MPD operation]. The closed-loop algorithm compares the measurement with the desired value and uses the available input (same MPD example: the input may be a topside automated choke) to compensate for the deviation. The concept of closed-loop control is illustrated in **Fig. 3.** Of course, appropriate values for sepoints must be specified externally, and this can be done either manually or by an automated system that optimizes certain objective(s) and determines setpoint values as a result of this optimization. Continuing along the same lines, the objective(s) to be optimized can be selected either manually or automatically, subject to specific criteria. The entire activity creates a multilevel, multiscale decision-making and control structure. The multiple levels are distinguished by different time scales. The entire structure employs large amounts of data that are available in abundance from modern data-acquisition and control systems. Such systems have found widespread applicability in oil refineries and chemical plants.

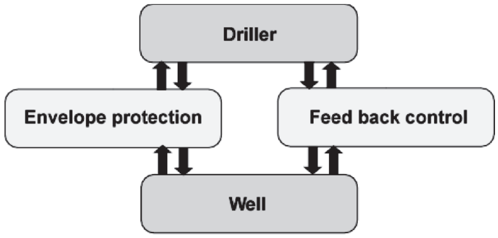

**Fig. 4—Level 3 ('Management by delegation') on the automation scale. Some tasks are performed manually (with envelope protection), and some tasks are delegated to the (closed loop) automation system. E.g. automatic pressure control in an MPD operation.**

In the following section, we present the hierarchy of the multilevel structure, which will enable the higher levels of automation and affect the working environment of the driller **(Figs. 4 and 5).**

## Multilevel Control Structures

In a hierarchical control structure, the higher levels coordinate lower levels to achieve the defined control goal. In a multilevel hierarchy, the control decisions are divided on the basis of different time scales [i.e., lengths of time horizons of optimization (Findeisen 1978; Lefkowitz 1975)]. Higher levels have longer horizons of optimization while maintaining fewer details of the system representation. Decisions passed to a lower level from an immediately higher level can be executed within a time length that is essentially zero for the upper level, though finite for the lower level because of the different time scales. As we descend in the hierarchy, we need an increasing level of understanding of the role of each process variable in each level. This is the key element that will lead to a more systematic procedure for deciding the type of hierarchical levels of control needed. However, in practice, selecting appropriate variables for control purposes can be a problem because of the vast number of variables involved in the process. The question of selecting the appropriate variables for control in chemical process

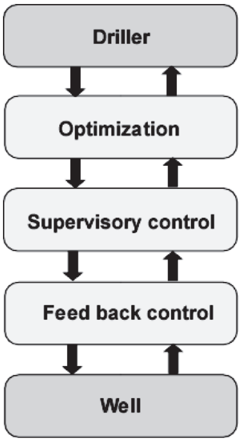

**Fig. 5—Levels 4 through 6 ("management by consent," "management by exception," and "autonomous operation," respectively) on the automation scale. The work process of the driller changes when the supervisory control level is introduced.**

industries has been addressed for several decades in the literature (Buckley 1966; Foss 1973; Skogestad and Postlethwaite 2005; van der Wal and de Jager 1995; Luyben et al. 1998). In a similar manner, Sigurd (2000a, 2000b, 2004) discusses the development of control hierarchies by addressing the fundamental questions of control-system design (Stephanopoulos 1984)—namely, selection of control objectives, measured and manipulated variables, interconnections among variables, and design of the control law. In that regard, the issue of control structure has to be resolved first before defining the right hierarchical tasks. This approach is commonly referred to as plantwide control. In this paper, we will use the term level to separate between different levels of hierarchical tasks within the control system, and the term levels to separate between different levels of automation (human/machine interaction level).

While the development of control hierarchies has been studied extensively and has resulted in successful industrial implementations in a number of industries, drilling processes in the petroleum industry have not benefited from this approach. However, a control-hierarchy design for production optimization in the oil industry has already been proposed (Saputelli et al. 2003). A natural extension is proposed here for drilling-automation operations. The multilevel control approach for a drilling-automation system will be based on a three-level approach:

1. Feedback control level
2. Supervisory control level
3. Optimization level

## Feedback Control

The purpose of the feedback control level is to ensure that controlled variables stay at their respective setpoints. Any control law can be applied in these loops, but the current industry practice is that these sorts of controllers are variations of the well-known proportional integral derivative (PID) controller. These PID controllers are by far the most widely used control technology in the industry, and such controllers use one input to control one output (single-input/single-output control). The total performance of the system is affected by controller tuning. Poorly tuned basic controllers may jeopardize the performance of the overall system because no matter how precisely the optimal values of setpoints have been calculated by upper levels, these setpoints will not be followed by controlled variables. Drilling dynamics are partly nonlinear, and other choices of controller technology may be better suited for some of the control loops. Nonlinear controllers increase the complexity of the system, and should be applied only if PID controllers or variations of this well-known technology are insufficient to meet the system requirements, or if the improvement it represents is greater than the cost associated with development, tuning, and maintenance of such an unconventional controller (Eker and Nikolaou 2002). These control loops are fast and should be implemented with a frequency range from 1 to 100 Hz. One of the key benefits of these low-level controllers is that the need for modeling in the superior control levels is reduced.

## Supervisory Control

A supervisory control level is proposed, and the main task of this level is to coordinate all the low-level-feedback controllers. The supervisory control level should calculate setpoints for low-level controllers. Multivariable centralized controllers can always outperform decomposed (decentralized) controllers, but this performance gain must be traded off against the cost of obtaining and maintaining a sufficiently detailed plant model and the additional hardware (Skogestad and Postlethwaite 2005). There are different control strategies for this level, and we are proposing to base the level on the "moving-horizon concept," which is known as model predictive control (MPC) on the control level. MPC is the only advanced control technique that has had a significant and widespread impact on industrial process control. The main reasons for its success are its ability to handle multivariable control problems naturally, take account of actuator limitations, and allow the process to operate closer to its constraints (Maciejowski 2002). MPC is a form of control in which the current control action is obtained by solving, at each sampling instant, a finite-horizon open-loop optimal control problem using the current state of the plant as the initial state. The models used in the MPC algorithm can be obtained through various methods (experimental step response models, mathematical models), and the models can be either linear or nonlinear. Nonlinear models increase the complexity of the calculations. Detailed description of supervisory control levels in drilling (MPD) operations are described in detail in Breyholtz et al. (2009). The main objectives of an MPC controller are in prioritized order as follows (Qin and Badgewell 2003):

1. Prevent violation of input and output constraints. Input constraints are caused by machine limitations. As an example, the topside choke cannot be closed further when it is completely closed and it cannot be more open than fully opened. Keeping the states of the well within its constraints (e.g., pressure constraints) is also given first priority.

2. Drive the CVs to their steady-state optimal values. A CV refers to the controlled (output) variables (e.g., pressure), and keeping them within its constraints is first priority. When this is accomplished, the system will try to bring the states to their desired values (setpoint). For example, the main intention for MPD is to maintain pressure within upper and lower bounds that guarantee safe operation.

3. Drive the MVs to their steady-state optimal values using remaining degrees of freedom. An MV refers to the manipulated (input) variables (e.g., choke opening, circulation rate). It takes one MV to bring one CV to its setpoint (e.g., the BHP can be controlled using the topside choke as long as the choke has not reached its constraints). If there are more MVs available than CVs, ideal resting values for the excessive MVs can be introduced. In Breyholtz et al. (2009), such a system is demonstrated with an ideal resting value for the circulation rate. It is important to note that the ideal resting values will be obtained only as long as the first and second priorities are accomplished. In certain MPC implementations, constraints and corresponding variables are prioritized, so that the most important constraints and variables are addressed first, with lesser ones addressed subsequently (Wojsznis et al. 2003).

4. Prevent excessive movement of MVs. An excessive movement of the MVs (choke opening, pumps) may damage the equipment and should be prevented. Corresponding penalty terms or upper and lower bounds can be included explicitly in the MPC formulation.

5. When signals and actuators fail, control as much of the process as possible. If one of the actuators fails (choke), the multivariable MPC controller will use the remaining actuators automatically, requiring human intervention for reconfiguration or retuning.

The MPC algorithm represents a possibility to coordinate rev/min, hook position, and circulation rate such that the weight on bit (WOB) can be controlled, and an optimal rate of penetration (ROP) is achieved. WOB poses significant control challenges (Nikolaou et al. 2005; Awasthi 2008), but if it is controlled it can be kept closer to an optimum, and an optimal ROP can be obtained.

From the there, it follows that the input the driller needs to give to the supervisory control level is constraints because of operational bounds and machine limitations. The machine limitations are most likely constant during the whole operation, but the constraints related to downhole conditions should be updated if new information becomes available (e.g., new information regarding pore and fracturing pressure). In addition to constraints, the driller needs to provide setpoints for crucial variables such that the CVs are brought to their desired values. Because the requirement to control one variable is one available manipulative input, and there are more available inputs than there are variables to be controlled, the remaining number of manipulated inputs is given by

$$N_{\mathrm{ss,free}} = N_{\mathrm{ss}} - N_{\mathrm{active}}, \quad \ldots\ldots (1)$$

where $N_{\mathrm{ss}}$ is the total number of available inputs, $N_{\mathrm{active}}$ is the number of manipulated inputs used to control the process during steady-state conditions, and $N_{\mathrm{ss,free}}$ is the excessive number of manipulative variables during steady-state conditions (Larsson and Skogestad 2000). In the next section, an alternative approach to finding the setpoints and ideal resting values is presented. The overall idea is that there are a large number of possible combinations of variables that will result in the process staying within these constraints, and that an optimal solution could be found.

Introducing this level in a way that integrates and coordinates surface equipment with downhole conditions will result in an autodriller system. Florence et al. (2009) describe such a decentralized multivariable control system for ROP control, and conclude that the introduction of the autodriller system increased the ROP by more than 30% while reducing the number of bits used by 7%.

## Optimization

This level is not essential in order to achieve the highest modes of automation in Table 1, but should be implemented to improve the performance of the overall drilling operation. The purpose of the level is to calculate the optimal operational (and economical) conditions of the well. This could be achieved by calculating optimal values for inputs to the supervisory control level (setpoints and ideal resting values: $N_{\mathrm{ss,free}}$). To calculate the true optimal conditions, operational and economic objective functions needs to be defined. As an example, the objective function could be:

$$J = J_u(u,d) = \int_0^T \phi(u,d)\,\mathrm{d}t, \quad \ldots\ldots (2)$$

where $u$ is the degree of freedom for optimization, $d$ is time-varying disturbances, and $T$ is the total operation time. The variables $u$ are the variables that can be manipulated by the automation system, but the variables $d$ cannot be manipulated. The resulting optimization problem will then be of the form

$$\min_u J_u\,(u,\, d), \quad \ldots\ldots (3)$$

which is minimized subject to the inequality constraints:

$$g(u,d) \le 0. \quad \ldots\ldots (4)$$

There is however a problem when trying to locate the true optimal solution because mathematical functions that describe the quality of the operations in a scalar term need to be defined. To find the true optimal solution, these models/functions need to be perfect, all disturbances ($d$) need to be measured, and the dynamic optimization problem needs to be solved online (Skogestad and Postlethwaite 2005). Self-optimizing control has been introduced as a concept where the goal of the optimization problem is to find a set of controlled variables that when kept at constant setpoints indirectly lead to near-optimal operation with acceptable loss (Skogestad 2000). This will reduce the cost associated with modeling because steady-state models can be used. A key idea of this multilevel strategy is that the low-level feedback controllers should be able to handle all the measured and unmeasured disturbances. This dramatically reduces the need to continuously re-optimize.

To illustrate this concept, a simplified example from an MPD operation will be presented. In an MPD operation, the focus is on controlling the pressure in the openhole section of the well. During a tripping operation, the pressure in the well will be affected and pressure fluctuations are induced. Because drilling operations are also associated with a cost related to the time spent, a secondary goal of the tripping operation will be to complete the operation as fast as possible (the primary goal being keeping the pressure within its boundaries). If a self-optimizing approach is used, the optimization level will calculate a constant semioptimal setpoint and rely on the lower-level-feedback controllers to maintain the pressure at this level. Because the lower-level-feedback controllers will not prevent the BHP from deviating from the setpoint to some degree, a safety margin is needed to prevent the pressure from exceeding the drilling window. If, on the contrary, a true optimal setpoint is continuously calculated, an optimal-pressure-setpoint curve could be calculated that will allow the pressure setpoint to be slightly increased while tripping out and slightly reduced while tripping in. The purpose of calculating such curves is to allow for faster tripping without violating the pressure boundaries. Finding the true optimal solution (curve for pressure setpoint) is dramatically more expensive regarding modeling cost and computer power needed, but it saves some operational time and may increase the economic output of the operation. Because required modeling is so much higher with dynamical optimization, and the modeling itself may be off, self-optimizing control is a more realistic approach that will result in a slightly lower value of the objective function than the truly optimal solution. The loss, $L$, can be defined as:

$$L = J - J_{\mathrm{opt}}, \quad \ldots\ldots (5)$$

where $J$ is the actual value of the objective function given the chosen control strategy (self-optimizing) and $J_{\mathrm{opt}}$ is the true optimal value. The presented example illustrates why self-optimizing can be a good strategy compared to true dynamical optimization, but because of the simplicity of the presented example, the full potential of the self-optimizing method has not been presented. The economic potential of the self-optimizing is more obvious when expanding the problem to include ROP optimization. Calculating the optimal performance when considering ROP, hole cleaning, and pressure in the openhole section using the available degrees of freedom (mud properties, circulation rate, WOB, rev/min) is a more complex problem, where optimization can reduce the economic cost of the operation. However, it is important to have a clear definition of what optimal performance is because there are multiple factors that will affect the overall economy of the chosen operation.

A specific optimization problem needs to be defined for each operational mode because the overall objectives of each mode will be distinct. If such a system is in place for each operation, the work tasks of the driller will be reduced to monitoring, fault detection, and mode selection. It is wise to consider if it is economically reasonable to define objective functions for all operational modes, or only for those that can be justified economically when comparing modeling cost with improved performance. In general, designers tend to automate everything that leads to an economic benefit and leave the operator to manage the resulting system (Parasuraman and Riley 1997).

## Autonomy

Autonomy is a term referring to the highest degrees of automation (Levels 5 and 6). An autonomous system is able to operate without human interaction. The term autonomy does not necessarily imply systems that are remotely operated. It is irrelevant whether the driller/operator is located at a remote location or at the drilling rig when deciding the level of automation of a system. A system in autonomous mode should be able to make decisions by itself and adapt to changing conditions. In **Fig. 6** a schematic of the intelligence flow for a drilling operation in an autonomous mode is presented. The major difference when considering automation Modes 5 and 6 is that the automation system will change operational mode

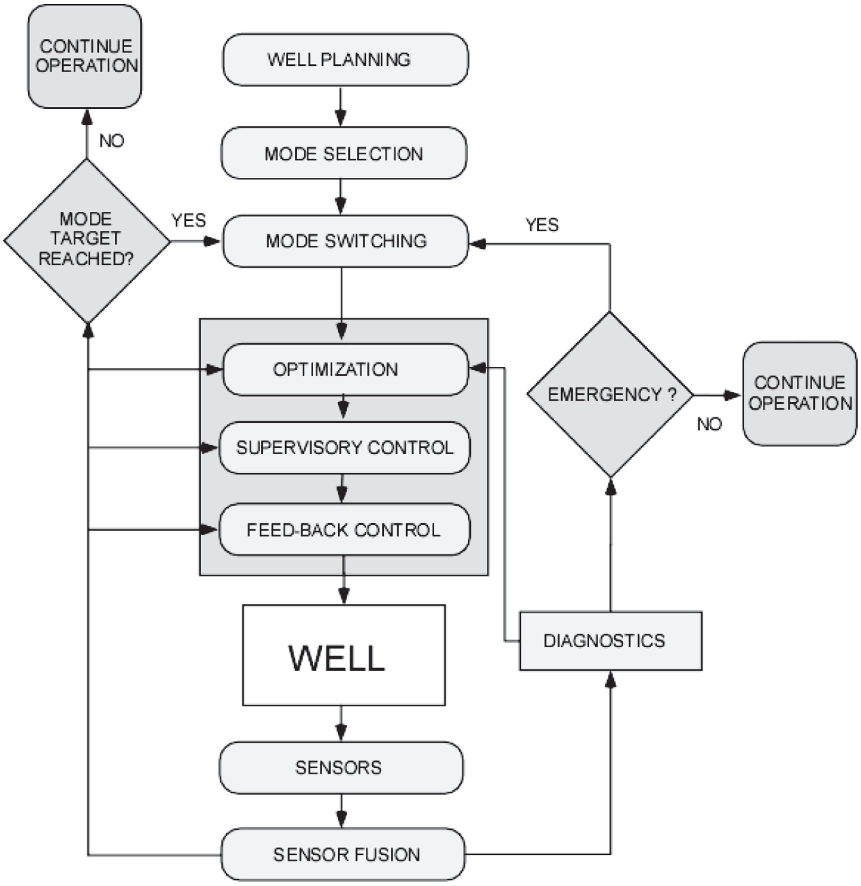

**Fig. 6—Intelligence flow in an autonomous operation.**

by itself. To achieve such a level of intelligence, goals for each mode need to be defined, and the system must be able to detect when the goals are achieved (e.g., drill one stand). Additional logic to determine the next appropriate mode also needs to be implemented. An autonomous system also needs to have a diagnostic module in order to be able to detect abnormal conditions in the well and hardware malfunctions, and it needs to be able to handle such events.

## Driller's Role in a Highly Automated Environment

In the modes-of-automation concept presented in Table 1, the major change to the driller's working environment happens when the automation level increases to "management by consent." As illustrated in **Fig. 7,** the driller will be supported by the automation system up to that level of automation, but from Mode 4 and upward the driller will be supporting the automation system. This is major change, and the result will be that the driller is no longer directly operating the equipment at all. In general, there are two categories of tasks left for an operator in an automated system (Bainbridge 1983). The driller may be expected to monitor that the automation systems perform and behave as expected, and if not the drillers should manually takeover the system or call for expert personnel to assist. In general, it is impossible for the designer of the automation system to foresee all possibilities in a complex environment, and if the system fails, the driller must have the authority to manually take over the operation.

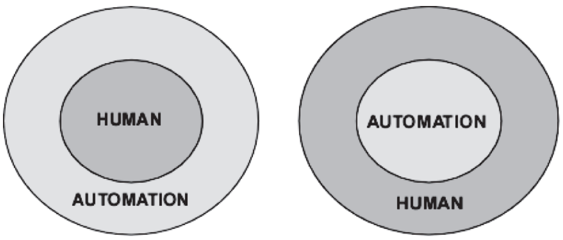

**Fig. 7—When the chosen management mode changes upward from "management by delegation" to "management by consent" the overall system changes nature; it is no longer the automation system supporting the human, it is the human supporting the automation system.**

Unfortunately, it is only after the automation system has misbehaved that the driller can detect its misbehavior. Because a manual takeover of the drilling process is likely to be motivated by an abnormal situation, and it requires both skill and experience to recognize both the reason for the abnormal situation and the correct counteraction to bring the well/system back to normal operational conditions. The time available to do both tasks is most likely limited, and an important question to ask is how the driller should know when to manually take over the process. Detection systems and decision-support systems may be of assistance, but in general the behavior of the driller will be based on experience. Drillers with experience from manual operations would most likely have a more intuitive understanding of when a manual takeover is needed than a future generation of drillers that may have limited experience with manual operations can be expected to have. This implies that training of the drillers/operators is essential. It is obvious that they require training when they will initially start using an automated drilling system, but it is as important that the training be continuous. Drillers should experience all possible failure scenarios in simulators in order to obtain and maintain crucial experience. If a highly automated environment becomes the norm, then the manual skills of the drillers will most likely decline, and that may reduce the probability of the driller safely handling a manual takeover.

Monitoring drilling operations is a task where a human may not excel routinely for long periods of time, unless nonoptimal, abnormal, or unwanted situations are indicated by an alarm system. Diagnostic and warning systems (expert systems) have been proposed as an appropriate strategy to increase the performance of human operators who have a monitoring role. Expert systems are often designed to give the operator a warning/alarm when the system fails, but for some critical situations this may be too late. An efficient strategy should be to analyze the current situations and try to predict if a failure is likely to occur in the immediate future. The higher the level of automation is, the more crucial the communication about the automation systems mode and intentions becomes (Parasuraman and Riley 1997).

There are possible issues related to trust when discussing expert systems. In general, such systems have prevented several possible dangerous situations (Billings 1996), but if these systems are extremely reliable, there is a possibility that the drilling crew will rely on them at all times, and when a rare failure occurs, the drilling crew may not detect the failure because of overreliance on the automation system. An opposite problem is expert systems that produce false alarms at a high frequency. In such cases, the drilling crew is likely to mistrust the alarms, and in extreme cases ignore or even switch off the alarms completely. If a real alarm is raised, the probability of the drilling crew trusting the alarm system decreases with the number of false alarms they have experienced. An important issue in monitoring is the communication between the automation system and the driller. It is of the utmost importance that the state of the automation system be communicated to the driller. The driller needs to be informed about the system's intentions in order to understand its behavior. In order to further improve the quality of the automation system, its behavior should be predictable. If both the mode/state of the system and its future actions (prediction) are communicated to the driller, it will prevent the driller from misunderstanding whether a critical situation has been detected, and whether or not it is being handled. To ensure that the quality of the expert system is high, the driller needs to monitor the data that are sent to the system (Parasuraman and Riley 1997). Sensor failures and sensor drifting may result in the expert system raising false alarms regarding downhole conditions.

Failures related to the automation system and the human/machine interaction have sometimes been claimed to be caused by "overautomation." Norman (1990) presents an alternative view and claims that such failures are not a result of overautomation, but of lack a of feedback, resulting in the operator not being sufficiently up-to-date with the current state of the system to diagnose them in reasonable time. Wiener (1993) illustrates this sort of problem with a real-case scenario from the aviation industry, where in 1985 a Chinese airline's Boeing 747 experienced a loss of power from its outer-right engine. The onboard automation system started compensating for this lack of engine power until it reached a point where it had used all of its compensatory abilities. The result was a failure to keep the plane stable, and when the flight crew became aware of the situation, they did not have enough time to analyze the situation and take action, which resulted in the plane going into a vertical dive of 31,500 ft before the pilots managed to get the plane under control. The aircraft was severely damaged. The state of the process/plane was not communicated to the operators but was masked by the feedback nature of the automation system. The increased compensation should have been communicated to the pilots, preferably as a warning being raised.

Even if the level of automation is increased, the overall workload on the drilling crew does not necessarily decrease, but the work task will change. Unfortunately, automation systems tend to increase the workload on the drilling crew at critical moments.

## Automation During Poor Downhole Conditions

A feedback control system (closed loop) will at all times try to compensate for undesired situations. The operator will not necessarily detect such a situation. Therefore the automation system should always include additional logic to detect if the feedback system has started compensating for an undesired state in the well. We illustrate this by a familiar example, and a known issue related to automatic pressure control in an MPD operation. If there is a sudden influx into the well, the pressure in the well will increase during an initial phase until there is equilibrium between the pressure in the reservoir and that the well. The response of a low-level automation will be to detect this as a deviation from the given setpoint and the measured value of this state. By nature, the closed-loop algorithm will try to reduce the pressure in the well to compensate for this deviation by slightly opening the topside choke opening to reduce the pressure. This will result in the system unintentionally trying to achieve a state of underpressure, which would be equivalent to underbalanced drilling if it were intentionally implement. If the driller is not observant and relies on the automation system, it may take several minutes until he/she is able to detect the condition of the well, and the pressure control system has probably made the situation worse than it would have been without such a system. A kick is a situation that the driller will eventually detect, but it is a situation that would be preferable to detect as soon as possible, and the feedback control system has actually detected that something has happened long before the driller will. But a low-level control system has only detected that something has happened that resulted in a deviation from setpoint that needed to be compensated for, it has not detected the reason for the deviation in pressure, which is an influx from the reservoir. To do the latter, a more advanced diagnostic system is needed, which takes pressure readings, flow rates, choke opening, and other factors into account. In this particular case, two different choke openings result in the same BHP only seconds/minutes apart when everything else is kept constant. This might be an indication that the conditions of the well have changed, but as previously stated, an advanced diagnostic system should be in place to assist the driller/automation interaction. If the feedback system only masks the situation without raising a warning, the situation may escalate to a more severe situation than if there were no automation system in place. An equivalent scenario is if the automatic MPD system for some reason fractures the well and a loss situation occurs. Again, the automation system will try to maintain an undesired pressure in the openhole section.

An important question to ask is how a higher level of automation (supervisory control) would affect the situation. Again under the assumption of the situation being undetected, how would supervisory control behave? As stated before, supervisory control uses a priority hierarchy and is able to use every possible manipulated input to achieve the first-priority task if it is needed. If the highest priority is to maintain the pressure in the well within its boundaries, a supervisory control system has more freedom to try to maintain the pressure at its setpoint (primary: choke opening, flow rates; secondary: mud properties) and therefore can worsen the situation even further than if a lower level of automation were used. The important lesson to learn is that the higher the degree of automation, the higher the consequences of a failure might be. The highest risk in drilling automation is associated with poor downhole conditions not being detected. To improve the reliability of any level of automation, a reliable diagnostic system should be in place, and to even further increase the reliability, high-quality downhole data should be provided.

## Discussion

It is important to find ways to improve both the error resistance and the error tolerance of a drilling-automation system. The overall goal when designing such a system should be to prevent occurrence of all possible errors, including those of the human operator. This is an unrealistic goal because both the driller and the automation system are likely to make random errors with some frequency. It is highly unlikely that the overall system designer will be able to model all automation-failure scenarios, combinations of several errors, well responses, and the behavior of the driller. The interaction between the automation system and the driller is complex, and when discussing how to reduce the number of possible failure scenarios that can occur, a decision on the appropriate level of automation must also be included. The overall automation discussion will determine the appropriate level of interference by the automation system when the driller is making an error. There is a list of alternative approaches ranging from envelope protection to prevent the driller from exceeding a predefined range of legal values to the automation system denying the driller the ability to take choices that are not legal, and as an extreme alternative, the automation system goes into an autonomous state and takes control of the process and brings it to a safe state before returning control. Envelope protection systems are on the verge of becoming commercial products. One important factor to keep in mind is that the human is the absolute authority even when the automation system is in an autonomous mode. This means that the driller must be given the means to override the automation system if it is necessary.

Sequential approaches have not been addressed in this paper. A sequential procedure is a preprogrammed sequence, and as an example it might be a calculated (nonoptimal) velocity slope for tripping out a stand. Such an approach could be considered too be open-loop in contrast to closed-loop. This implies that the response from the well when applying the sequence is ignored. As a result of not considering the well response in the logic, the safety margin for such approaches needs to be significant to ensure that the sequence does not in any way damage the well. Sequential logic could be placed in the "levels of automation" hierarchy in Table 1 in the "management by delegation" mode, but because the gain from introducing closed-loop control will be superior to sequential approaches, we have ignored such approaches in the hierarchy. Sequential approaches are implemented on rigs today; but under the assumption of closed-loop approaches being superior, why do sequential approaches still exist? The answer lies in the lack of continuous high-quality downhole data. Wired pipe has been introduced as a solution to dramatically increase the rate, quality, and amount of downhole data becoming available topside in real time; but if such technology is not used, the downhole conditions need to be calculated (e.g., using a hydraulic model in combination with an adaptation/calibration technique). The uncertainty regarding downhole conditions increases the safety margins needed, which again will reduce the potential of closed-loop control. It is, however, possible to improve the performance of sequential approaches by introducing closed-loop control (e.g., automated choke control in MPD operations has started to replace MPD operators who manually adjust the choke opening), but the full potential of closed-loop control will become apparent when continuous, high-quality downhole measurements become available topside.

It is likely that if high-quality downhole data through wired pipe (or competitive technology) become available at a large number of wells/operations, the demand for closed-loop control will grow rapidly. To fully use the higher levels of automation to improve the performance of the overall drilling operations, high-quality reliable downhole data will be the key to allow the drilling operation to operate closer to the boundaries of the operation while taking safety issues into consideration.

## Conclusion

Experience from other industries indicates that increasing the current level of automation is likely to increase the overall operational and economic performance of drilling operations. A clear understanding of the impact such systems will have on the driller's working environment is needed, and it is important to have exact knowledge of how the automation system will behave during abnormal well conditions, both detected and undetected.. If the behavior of certain levels of automation during undetected downhole conditions increases the overall risk of the operation either (a) such levels (or automation in general) should be avoided or (b) steps to reduce the risk should be implemented to compensate for the increased risk (e.g., wired pipe to increase detection abilities through high-quality downhole data). Consideration of the communication between the human operator and the automation system is crucial to avoid misunderstandings when implementing higher levels of automation.

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