**FUZZY LOGIC**

# Fuzzy logic for directional steering

**Rotary steerable tools open the door for true automated downhole steering. A critical feature is the downhole brain, which could use fuzzy logic to make directional steering decisions.**

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Currently, there is no commercial directional drilling system that offers true steering automation. Such a system would incorporate wellpath inclination, azimuth and Cartesian coordinates to command the controllable components automatically. Today's few auto-modes cater only to the much simpler cases of either inclination/azimuth control or pre-defined lateral tool force magnitude control. Attending to the 3-D location of the well bore still requires manual steering.

Removing human intelligence from the steering control loop – albeit temporarily – is far from simple. This is true whether the directional drilling system is controlled from the surface (bent housing assembly) or downhole (rotary steerable tools).

### Automation: Why and how?

The motivation for true automation is at least threefold. First, minimizing human expertise as the primary component for high-performance steering is desirable because the availability of such skill is always limited. Second, historical research and experience suggest imposing frequent, minor changes to operating conditions — the norm with a control system — produces a well bore with minimum dogleg severity (DLS) variance. A smooth well bore is less troublesome to drill and complete. A third motivation is to reduce in/out oscillations and thus, drill more pay zone.

A factor of critical importance for true steering automation is the algorithmic "brain" that governs the system. In general, a Fuzzy Logic controller defines a method by which observable system input is systematically mapped into controllable system output. In the 1980s, inaugural Fuzzy Logic controllers successfully removed full-time human dependency from the system's control loop. In multiple cases, the technology permitted automation for the first time. Commercial Fuzzy Logic applications include aircraft control, anti-lock brakes, cruise control and space shuttle docking.

A prerequisite for Fuzzy controller design is a human solution. For example, steering a vehicle is mentally rationalized with basic principles that are easily communicated with intuitive phrases and common sense (rules). With today's actively controlled directional drilling systems, this statement is similarly true for steering the direction in which a bit drills.

For rotary steerable systems, the system-specific mechanics of how lateral forces acting at or near the bit are controlled isn't vital to controller design. The consequence is the same in that lateral tool force magnitude and orientation (TFMO) is controllable for these systems.

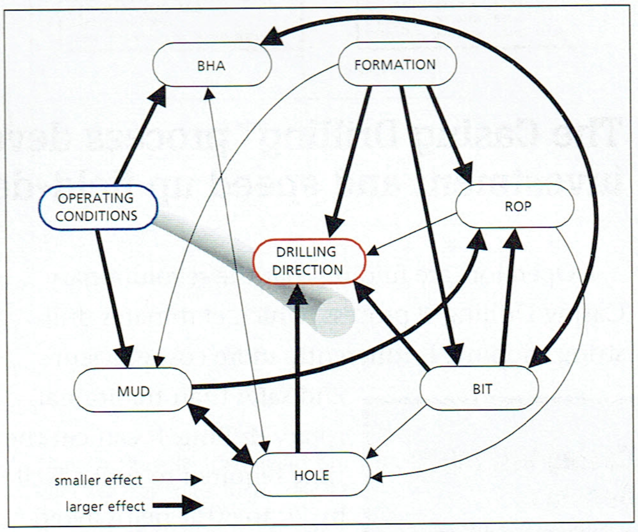


Figure 1. This cognitive map of drilling direction (CMDD) shows all the factors that influence bit direction.

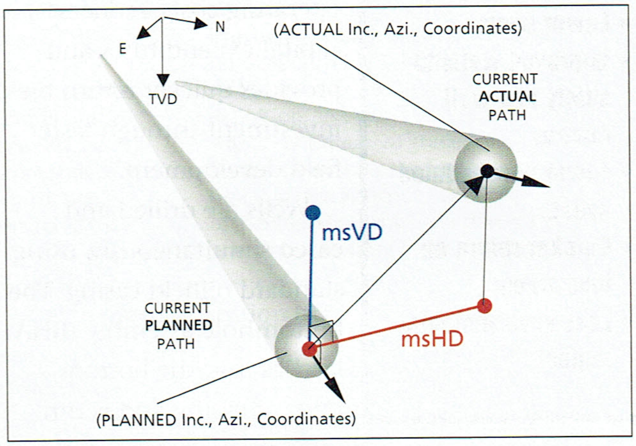


Figure 2. Vertical deviation (msVD) and horizontal deviation (msHD); two of eight components of THD. The sketch depicts "high and left" of plan.

| System component | Elements of system component that affect drilling direction |
|---|---|
| Operating conditions* | Hook load; rotary speed; drilling fluid flowrate; tool face orientation (if applicable); adjustable directional tool settings (if applicable); drill fluid conditioning at pump intake. |
| Bottomhole assembly | Configuration of components; shape, type, size, hole clearance, length, and material strength of each component; transmission of forces to bit; vibrations. |
| Bit | Type; dullness; design; gauge profile; transmission of forces to BHA. |
| Formation | Dip; compressive strength; thickness; lithology; interfaces between different types; faults; fractures; compaction; in-situ stress fields; drillability. |
| Mud | Density; fluid properties; compatibility with formation. |
| Hole | Size; shape; profile above bit; curvature; inclination; changing curvature; frequency of survey data; survey errors. |
| Rate of penetration | Depends either directly or indirectly on all other system components |

* Controllable in real-time operations.

Table 1. System components regulate the direction in which a bit drills.

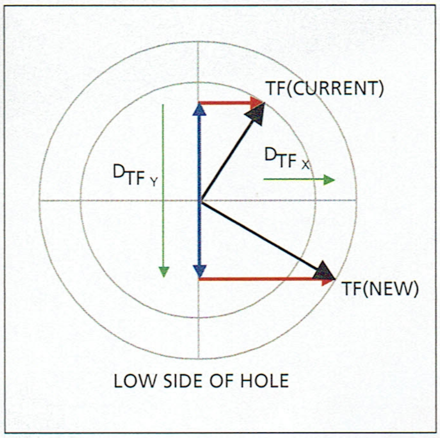


**Figure 3. The Fuzzy Drilling Direction Controller (FDDC) computes how to change tool settings that affect the lateral forces acting at the bit and thus the direction in which a bit drills. This is directly applicable to 3-D rotary steerable systems.**

## Cognitive map of drilling direction

Actual wellbore trajectory results from system component interactions that are complex to model. Gleaned from many researchers' published works, the most critical system components that affect drilling direction are listed in Table 1.

A cognitive map, the concept of which originated in psychology and political science during the 1970s[1], draws a causal picture of the association of components within a complex dynamic system. A cognitive map of drilling direction (CMDD) is presented in Figure 1.

The one-way and double-headed arrows show cause-and-effect relationships among the system components. The CMDD conveys in a simple snapshot the system complexity of directional wellbore steering. It also pictorially summarizes several decades worth of literature about the factors that affect drilling direction.

## Technical hole deviation (THD)

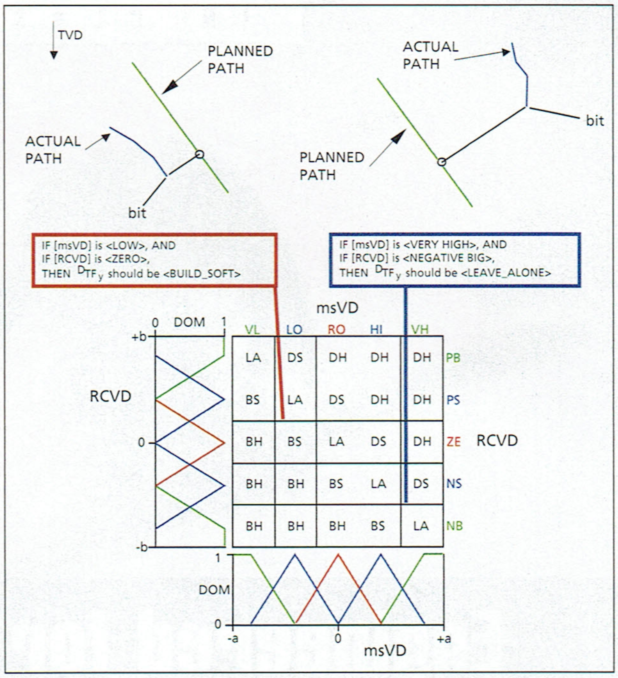
The CMDD is academic. It helps to explain why directional steering decisions made at the rig site are not driven by directional drilling simulators. For simulators, output-sensitive input parameters are unknown, and the system is too complex to compute directly the value of TFMO – or if applicable, tool face orientation (TFO) – and still possess a consistently reliable solution. Rather, like most spatial steering applications, such decisions are founded in geometries.

Directional drillers mentally process tabular and graphical geometric data and rely on their experience to rationalize their steering decisions. Accordingly, an automated steering control system would require similar, relevant input.

THD is computed at each directional survey station with planned wellpath properties (inclination, azimuth and Cartesian coordinates) currently in effect and 3D-nearest to "current TD." THD is based on lineal and angular differences, and the relative changes thereof (summarized in Table 2). THD is collectively defined with eight components and is presented fully and graphically with two well logs.[2]

Four THD components address hole deviation in the vertical sense, and four do so in the horizontal sense. At non-90-degree wellpath inclinations, "vertical" relates to wellbore high side (HS) as viewed perpendicular/upward to the vector currently in effect and defined by planned inclination and azimuth. For example, an actual well bore termed high and left matches common directional-driller sense (Figure 2). The mathematics of THD are presented in Reference 2.

When one or more of the nodes in the CMDD acts to alter drilling direction, the significance is manifested empirically via THD. With respect to wellbore trajectory control, the associated perturbation is addressed by changing directional tool settings, if necessary.



IF [msVD] is <LOW>, AND
IF [RCVD] is <ZERO>,
THEN $D_{TF_y}$ should be <BUILD_SOFT>

IF [msVD] is <VERY HIGH>, AND
IF [RCVD] is <NEGATIVE BIG>,
THEN $D_{TF_y}$ should be <LEAVE_ALONE>

| | VL | LO | RO | HI | VH |
|---|---|---|---|---|---|
| PB | LA | DS | DH | DH | DH |
| PS | BS | LA | DS | DH | DH |
| ZE | BH | BS | LA | DS | DH |
| NS | BH | BH | BS | LA | DS |
| NB | BH | BH | BH | BS | LA |

**Figure 4. These sketches depict two steering scenarios addressed with two Fuzzy rules from a rule matrix.**

## Fuzzy sets and systems

While chair of the Electrical Engineering and Electronics Department at the University of California at Berkeley, Russian-born Lotfi A. Zadeh founded fuzzy set theory with the paper "Fuzzy Sets." His definition: "A Fuzzy Set is a class of objects with a continuum of grades of membership. Such a set is characterized by a membership function that assigns to each object a grade of membership ranging between zero and one. The notions of inclusion, union,

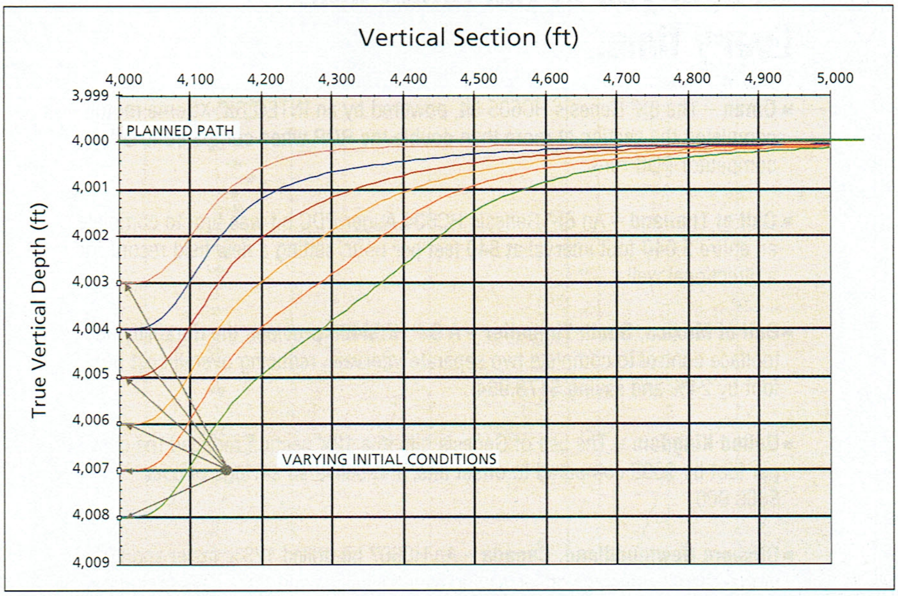


**Figure 5. Even with different initial conditions, the FDDC produced smooth well path trajectories, which demonstrates controller generality.**

| THD Component | Description | Deviation "Sense" | Unit | Order | Lineal Deviation | Angular Deviation | Verbal Descriptor |
|---|---|---|---|---|---|---|---|
| msVD | vertical deviation | Vertical | ft or m | 1st | X | | High/Low |
| RCVD | relative change in vertical deviation | Vertical | ft/1000ft or m/304.8m | 2nd | X | | Positive/Negative |
| msID | inclinational deviation | Vertical | deg | 1st | | X | High/Low |
| RCID | relative change in inclinational deviation | Vertical | deg/100ft or deg/30.48m | 2nd | | X | Positive/Negative |
| msHD | horizontal deviation | Horizontal | ft or m | 1st | X | | Left/Right |
| RCHD | relative change in horizontal deviation | Horizontal | ft/1000ft or m/304.8m | 2nd | X | | Positive/Negative |
| msAD | azimuthal deviation | Horizontal | deg | 1st | | X | High/Low |
| RCAD | relative change in azimuthal deviation | Horizontal | deg/100ft or deg/30.48m | 2nd | | X | Positive/Negative |

**Table 2. Components of Technical Hole Deviation (THD).**

intersection, complement, relation, convexity, etc., are extended to such sets."[3]

Zadeh's 1965 paper spawned a processing technology that is now a science. "Fuzzy" typically infers rule-based methodologies wherein Fuzzy Sets and Fuzzy Logic are employed. With Fuzzy Logic, human knowledge via rules may be assimilated into a numerical structure that can be exploited with a computer.

## Fuzzy drilling direction controller

A directional drilling simulator was developed to investigate a methodology for automated directional steering. The simulator was a 3-D finite element model and incorporated a drill-ahead model.[4] The modeled control feature was eccentricity settings (and thus, force settings) of a non-rotating, near-bit adjustable stabilizer. This work instigated the CMDD, created the necessity for THD, and produced a patent[5] related to using Fuzzy Logic for directional steering.

The Fuzzy Drilling Direction Controller (FDDC) systematically maps THD into change in TFMO (ΔTFMO). The vector ΔTFMO is determined by Fuzzy processing to compute the components $\Delta TF_y$ and $\Delta TF_x$, where positive y and x point to the hole high side and right side, respectively (Figure 3).

ΔTFMO has direct application to rotary steerable systems and auxiliary application to bent housing assemblies via TFO and drilling mode (rotary/slide). The FDDC could also serve as expert advisory software for directional drillers for either system type. Final "new" values of tool settings are computed by vector adding prior settings to the new Δ values.

The FDDC is comprised of numerous Fuzzy rules that are organized with multiple rule matrices. Each rule within a rule matrix addresses a basic steering scenario, such as those presented in Figure 4. Three rule matrices use msVD, RCVD, msID and RCID to systematically compute $\Delta TF_y$; identical symmetry is used to compute $\Delta TF_x$.

Six well paths generated with the simulator and with the FDDC in command are presented in Figure 5. The examples demonstrate a horizontal well with an immediate true-vertical-depth change in the planned path. Such applications occur frequently when directionally drilling thin pay zones in faulted reservoirs.

As observed in Figure 5, the FDDC "produced" desirable wellpath trajectories. Controller generality is suggested because in all examples the identical FDDC was employed. That is, the many parameters, functions and rules that comprise the FDDC were the same for all simulations, while initial conditions were varied. Simulations from kick-off-point through the toe of horizontal wells with a build gradient of 2° to 6°/100 ft were also conducted; equivalent performance and stability – with the identical controller – were observed.

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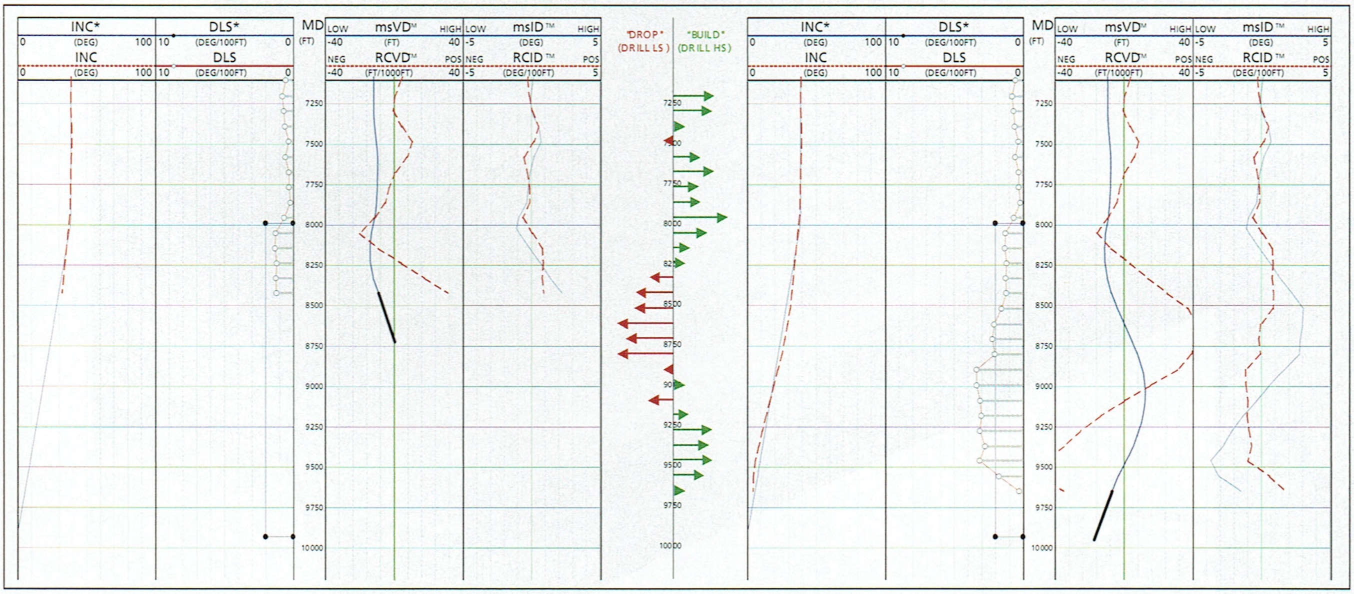

**Figure 6. Shown is a THD log in the vertical sense for a 2°/100-ft, 2-D drop section at 8,000 ft, drilled with a 3-D rotary steerable system. Qualitative FDDC output is presented in the center with green and red horizontal arrows. THD is the quantitative input to the FDDC.**

## NORTH AMERICA

**El Paso Corp.** sold its San Juan Basin assets in New Mexico to subsidiary **El Paso Energy** for US $782 million. Those assets include gas gathering, processing and treating operations, gas liquids transportation and treatment operations in south Texas and the deepwater Gulf of Mexico Typhoon pipeline. The Typhoon purchase meshes with the company's Marco Polo project.

Oklahoma's **Oneok Inc.** will sell some of its oil and gas producing leases to an unnamed buyer for US $300 million in cash. It plans to use the money to reduce debt. Those assets include interests in approximately 1,900 wells in Kansas, Oklahoma and Texas with net production of 43.5 MMcf/d of gas and 650 b/d of oil.

**Anadarko Petroleum Corp.** completed its US $258 million (including debt) acquisition of Houston-based **Howell Corp.** Howell properties will add some 50 million boe of reserves to Anadarko's total. Most of those reserves are in Wyoming's Salt Creek and Elk Basin fields. Anadarko will invest $200 million on Salt Creek field in the next 4 years to increase production by 150 million boe of reserves and raise production to 35,000 boe from 5,300 boe before 2007.

**BP** is checking out potential buyers for its shares in Kings Peak and Aspen fields in the Gulf of Mexico. It owns all of Kings Peak and 4% of Aspen with partner **Nexen** of Canada. Although Kings Peak produces 150 MMcf/d of gas, Aspen has yet come online with its estimated production of 30 MMcf/d of gas and 30,000 b/d of oil.

## ASIA

Russia has set a US $1.7 billion kickoff price for bidding for its 74.95% share of **Slavneft** oil company, and each additional bid must be at least $20 million higher than the previous offer. Only companies based in Russia were allowed to bid for the company.

Russia's **Lukoil** will sell its 10% share of giant Azeri-Chirag-Guneshli field offshore Azerbaijan to **Inpex Corp.** of Japan for $1.25 billion. According to Lukoil, it wants to stick with a project in which it has the majority interest. BP is the operator of the field, and ExxonMobil, Unocal, Statoil, TPAO (Turkish Pipeline), Itochu and Azerbaijan's Socar state oil company all have shares. Inpex is a 50% subsidiary of **Japan National Oil Corp.**

**CNPC (HK)** put up US $14.5 million to raise its position in the Salyan joint venture in Azerbaijan to 25% from 10%. At the same time, **China National Oil and Gas Exploration and Development Corp.**, another CNPC subsidiary bought another 10% of the project. Both shares came from the **Delta Hess** (**Amerada Hess** and Saudi Arabia's **Delta Oil**) 20% share in the field. CNPC (HK) had purchased a 15% share in the field for $26 million earlier in 2002 and its sister company matched that purchase, as well. CNPC entities now control half of Salyan Oil, which is developing the Kursangi-Karabagly onshore field south of Baku with 750 million bbl of oil reserves.

## EUROPE

Finland's **Fortum** has agreed to sell its **Fortum Petroleum AS** Norwegian exploration and production arm to Italy's **Eni** for approximately US $1.1 billion (including $658 million in debt) as the parent company seeks to focus on its core business areas. The acquisition gives Eni 210 million boe of additional reserves from shares of offshore Norway's Asgard, Brage, Heidrun, Mikkel and Goliath fields and other assets. The acquisition raises Eni's Norwegian production by 40%.

More than 91% of the shares of Norway's **Hydralift ASA** were tendered in response to **National-Oilwell Inc.**'s request to purchase at US $7.50 a share. Hydralift makes drilling equipment, cranes, pipe-handling systems, heave-compensation systems, riser-tensioning systems, mooring systems, handling equipment for cable-laying vessels and well-intervention systems. Regulatory authorities also approved the acquisition.

**Paladin** signed an agreement to buy **TotalFinaElf Exploration Norge AS**'s 18% share in Veslefrikk field offshore Norway for approximately US $15 million. The purchase increases Paladin's share of the field to 27%. The 1989 field currently produces 30,000 b/d of oil with 8,000 b/d net for a 27% interest from proven and probable remaining reserves of 15 million bbl.

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## *... FUZZY LOGIC CONTINUED FROM PAGE 65*

An example THD log and qualitative FDDC output using real data is presented in Figure 6. Again, the identical controller as that in Figure 5 was employed. Neither THD nor the FDDC were available while drilling this well, which was drilled with a rotary steerable system.

The vertical THD log presents a 2°/100 ft 2-D drop section at 8,000 ft measured depth. A snapshot at two different times in the progression of drilling is displayed. In the center between these snapshots, qualitative FDDC output is displayed. Green and red horizontal arrows at each survey station represent how to change settings with respect to borehole high side. Arrow lengths are directly proportionate to the ΔTFMO magnitude computed by the FDDC.

It appears as though the directional driller, who can directly affect RCID, didn't begin to lower msID (RCID made negative) until after 8,750 ft; this is after the overshoot was under way. Overcompensation follows as purposeful steering is enacted (excess DLS is the smoking gun) to attempt to regain control. The FDDC output was suggesting drilling low side hundreds of feet prior to the overshoot.

THD logs expose important details that are impossible to observe from standard directional plots. Even without focus on automation or advisory software, it is thought that THD can assist the directional driller to better assess the situation and make more-informed steering decisions.

If directional well bores are drilled that produce less drill string torque and drag because of less tortuosity and minimized DLS variance, then limits of reach can be extended, and running casing is more likely to be uneventful. If geo-driven changes in the planned path can be implemented smoothly and quickly, fewer sidetracks will be necessary. If technology (automated or not) can produce a better well bore for the operator, then eventually that technology will become standard.

### Other fuzzy control applications

Directional steering is one of the most obvious drilling control applications to warrant investigation of Fuzzy Logic control. Several other control applications within drilling operations exist:

- choke and mud pump control during well control operations;
- rotary speed and hook load control for minimum vibration or optimized ROP;
- flow rate control for air or underbalanced drilling operations;
- drilling diagnostics and alarm systems;
- liquid mixing systems for density control; and
- dynamic positioning for drillships. E&P

### Acknowledgments

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