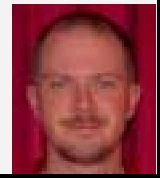
# Fuzzy Logic for Directional Steering



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***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.***

Currently, there is no commercial directional drilling system that offers true steering automation. Such a system would incorporate well path inclination, azimuth, *and* Cartesian coordinates to automatically command the controllable components. 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 (any type of 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 minimize oscillations, which create stationary water sumps in horizontals.

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. A cursory list of commercial Fuzzy Logic applications—spanning numerous industries—is presented in Table 1.

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.

## COGNITIVE MAP OF DRILLING DIRECTION

Actual well bore 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:

- Operating conditions;
- Bottomhole assembly (BHA);
- Bit;
- Formation;
- Mud;
- Hole; and
- Rate of penetration (ROP).

| COMMERCIAL FUZZY SYSTEMS |
|---|
| **Products** |
| air conditioner, aircraft control, anti-lock brakes, auto engine, auto transmission, cement kiln control, chemical mixer, copy machine, cruise control, factory control, handwriting recognition, health management system, humidifier, iron mill control, dishwasher, dryer, elevator control, kerosene heater, microwave oven, plasma etching, refrigerator, rice cooker, still camera, space shuttle docking, stock trading, subway control system, translator, toaster, traffic control system, television, vacuum cleaner, video camcorder, washing machine |
| **Companies** |
| Canon, Epson, Fuji Electric, Fujitec, Goldstar, Hitachi, Honda, Isuzu, Matsushita, Minolta, Mitsubishi, NASA, Nippon Steel, Nissan, Omron, Rockwell, Samsung, Sanyo, Saturn, Sharp, Sony, Subaru, Toshiba, Yamaichi |

**Table 1**: Commercial applications[1,2] that employed Fuzzy Logic made debuts in the 1980s.

| 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. |
| Bottom Hole 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 during real-time operations.

**Table 2**: System Components regulate the direction in which a bit drills.

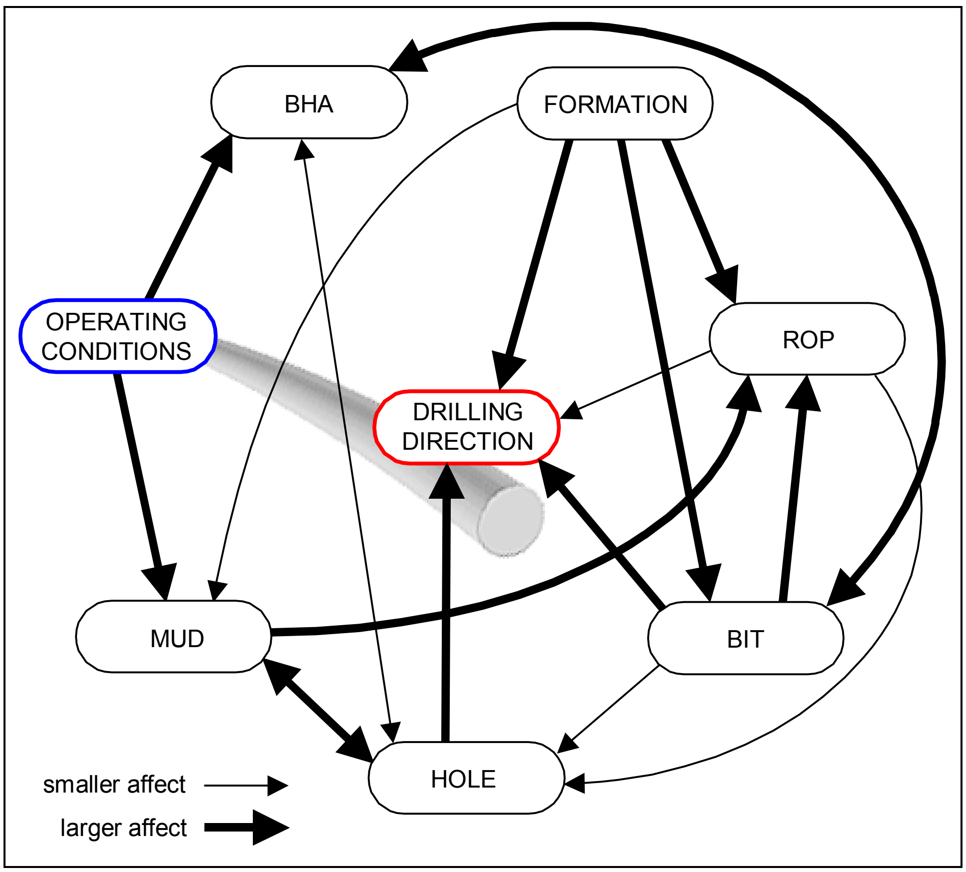


**Figure 1**: This Cognitive Map of Drilling Direction (CMDD) shows the association of System Components and how they influence the actual drilled well path.

The elements that comprise each of these components are presented in Table 2.

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.

Operating Conditions constitutes a node in the CMDD. People (or control systems) govern Operating Conditions. No arrows flow into the Formation node either, since deposition, sedimentation, and tectonics dictate it. All other CMDD nodes have dependent qualities.

Hook load directly affects how the BHA will deflect and transmit forces to the bit and to the wall of the hole. Hole enlargement alters how the BHA is constrained, and therefore the forces acting at the bit. When the hole changes shape, curvature, and/or orientation, the BHA and bit force characteristics also change. Hence, double-headed arrows connect the BHA and Hole nodes in the CMDD.

The vibrations induced at the bit from drilling are transmitted to the BHA. Because the BHA is the mechanism by which forces reach the bit, the BHA affects the rock cutting process. Thus, a double-headed arrow connects the BHA-Bit nodes in the CMDD.

The Formation node has a casual connection arrow into the Bit node. Formation characteristics—in conjunction with bit type and design—influence how rock is drilled.

The Bit node is connected to the ROP, Drilling Direction, and Hole nodes. The forces at the bit affect ROP. The forces at the bit and the bit design directly affect Drilling Direction. The bit design and condition, particularly the gauge profile and dullness, affect the shape of the drilled hole. The influence of the hole shape loops back around the system via the BHA-Hole connection.

Intrinsic formation characteristics, such as lithology and compressive strength, directly affect ROP. Formation properties such as dip and strike angles, and in-situ stress-field orientations, directly affect Drilling Direction. Hence, arrows connect the Formation node to the ROP and Drilling Direction nodes in the CMDD.

Because rock fragments and particles of the formation are carried in the mud, the formation affects the mud properties. Mud properties such as solids content and density directly affect ROP. Other mechanisms are the chemical and mechanical interactions that occur between the drill fluid and the exposed formations. These interactions change the near-wellbore stresses, the shape of the hole and the mud properties. This influence loops back through the system via a variety of possible paths to affect Drilling Direction.

Maintaining mud weight and various rheological properties act to pseudo-control mud properties. The mud flowrate into the drill pipe is directly controlled. Thus, a connection between the Operating Conditions and Mud nodes is drawn.

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 rigsite 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.

Technical Hole Deviation (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 3, THD is collectively defined with eight components and is presented fully and graphically with two well logs[3].

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 wellbore termed high and left matches common directional-driller sense (Figure 2). The mathematics of THD are presented in Reference 3.

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 well bore trajectory control, the associated perturbation is addressed by changing directional tool settings, if necessary.

| 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 3**: Components of Technical Hole Deviation (THD).

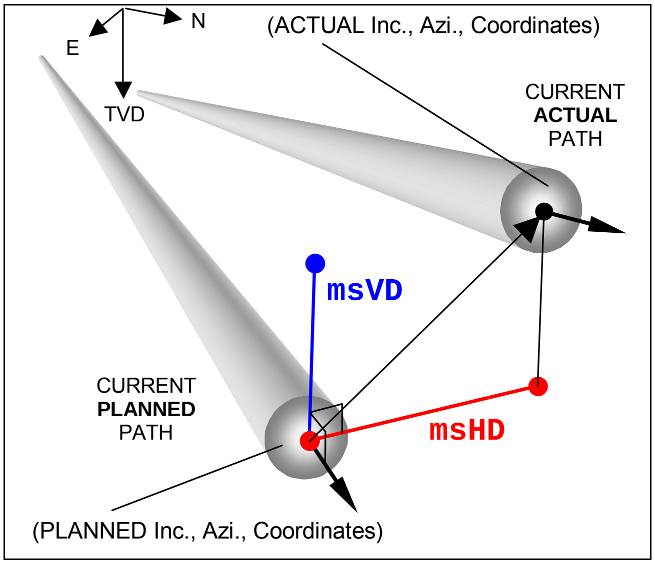


**Figure 2:** Vertical deviation (msVD) and horizontal deviation (msHD); two of eight components of THD. The sketch depicts "high and left" of plan.

## FUZZY SETS AND SYSTEMS

A set is a collection of definite and distinguishable objects of our intuition or intellect. Prime numbers, large dogleg severities, and very busy streets are each examples of a set. While chair of the Electrical Engineering and Electronics Department at the University of California at Berkeley, the Russian-born American immigrant 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, intersection, complement, relation, convexity, etc., are extended to such sets."[4]

Zadeh's 1965 paper, and the subsequent efforts of many, spawned a processing technology that is now a science. A keyword search with "Fuzzy Logic" at Amazon.com yields more than 250 books. "Fuzzy" typically infers rule-based methodologies wherein Fuzzy sets and Fuzzy Logic are employed. The logic is not at all vague. 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 (FDDC)

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[5]. 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[6] 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 wellpaths 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 build gradients of 2º to 6º/100 ft were also conducted; equivalent performance and stability—with the identical controller—were observed.

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.

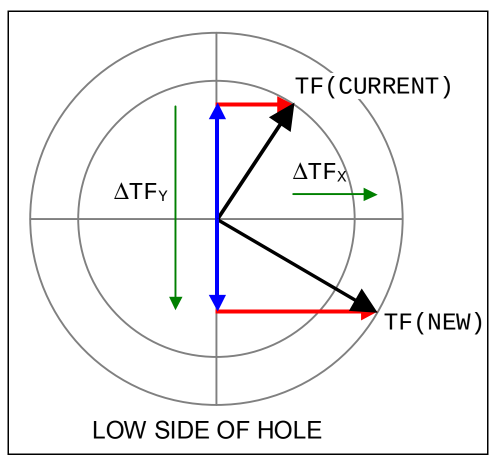


**Figure 3:** The FDDC computes how to change tool settings that affect the lateral forces acting at the bit and thus the direction in which a bit drills. The FDDC is directly applicable to rotary steerable systems.

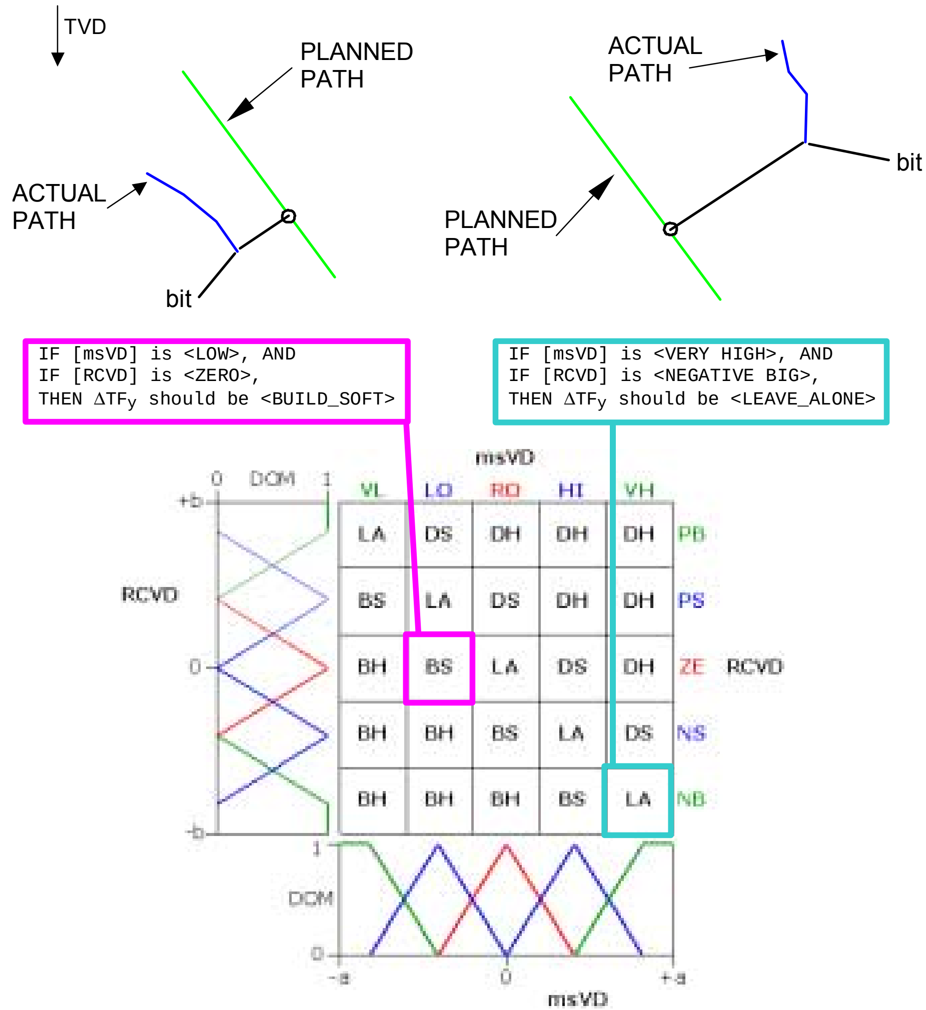


**Figure 4:** These sketches depict two steering scenarios addressed with two Fuzzy rules from a rule matrix.

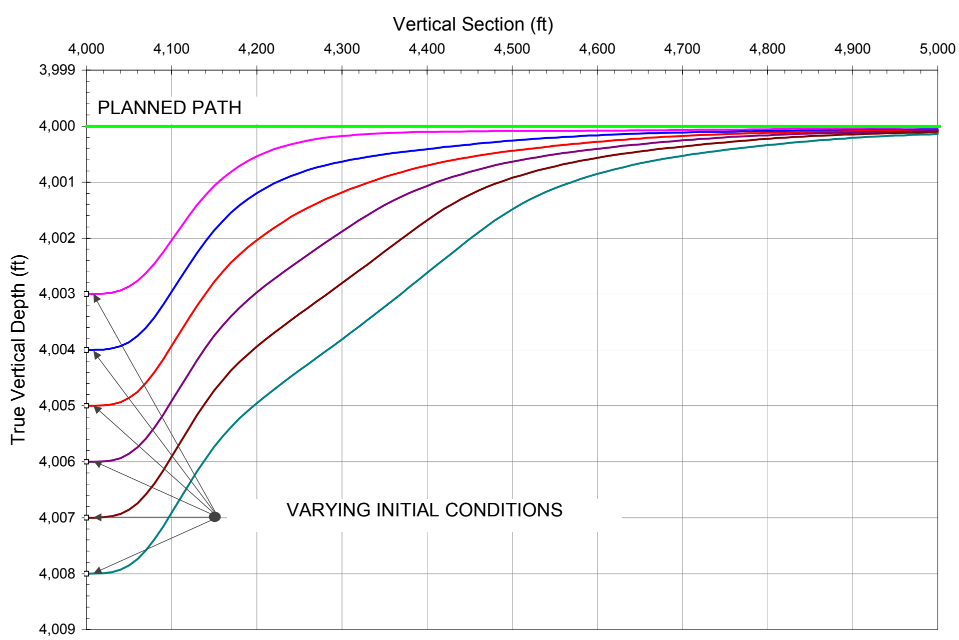


**Figure 5:** Even with different initial conditions, the FDDC produced smooth wellpath trajectories, which demonstrates controller generality.

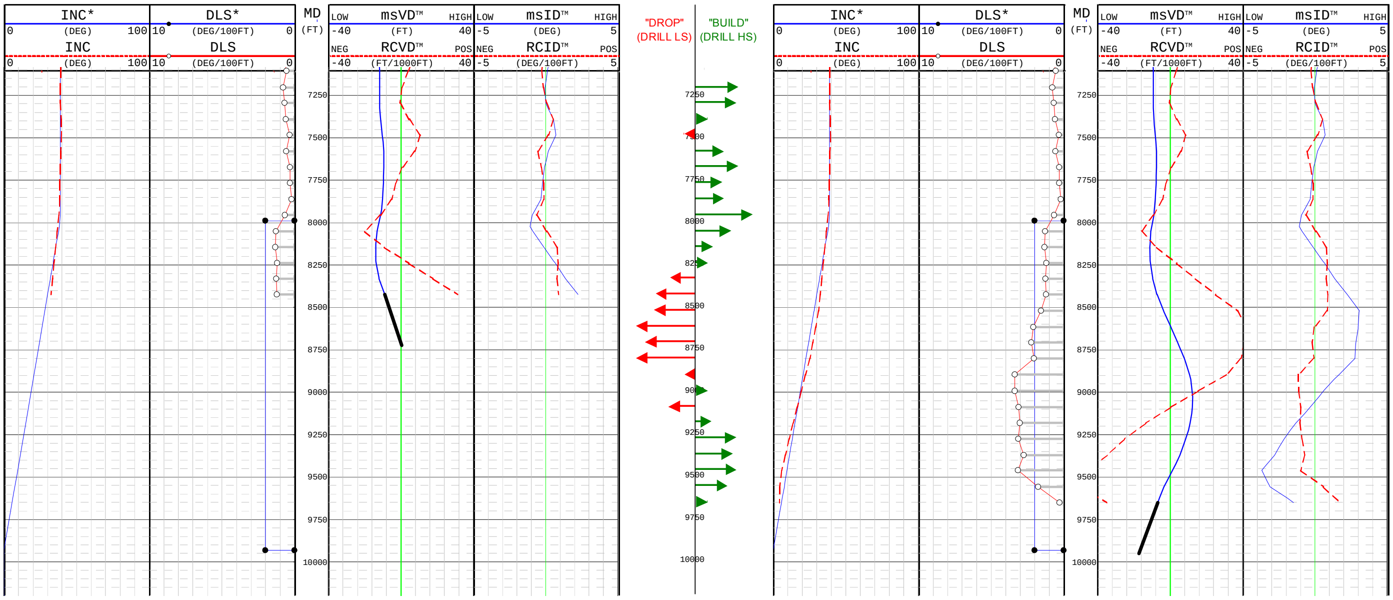


**Figure 6:** Shown is a THD log in the vertical sense for a 2º/100 ft 2D drop section at 8,000 ft, drilled with a rotary steerable system. From quantitative input (THD), qualitative FDDC output is presented in the center with green/red horizontal arrows.

The vertical THD log above presents a 2º/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. That is, 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 $\Delta TF_y$, which is 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 underway. 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—the mechanics model-free FDDC input—can assist the directional driller to better assess the situation and make more-informed steering decisions.

If directional wellbores 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 wellbore for the operator, then eventually that technology will become standard.

## OTHER FUZZY CONTROL APPLICATIONS FOR DRILLING

Directional steering is one of most obvious drilling control applications to warrant investigation of Fuzzy Logic control. Several other control applications within drilling operations exist. Many potentially could be automated or otherwise improved with Fuzzy Logic control technology:

- Choke and mud pump control during well control operations;
- Rotary speed and hook load control for minimum vibratory stresses 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.

## ACKNOWLEDGMENTS

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[1] Kosko, Bart. 1993. *Fuzzy Thinking: The New Science of Fuzzy Logic*. New York, New York: Hyperion.
[2] McNeill, Daniel, and Paul Freiberger. 1994. *Fuzzy Logic. The Revolutionary Computer Technology That Is Changing Our World*. New York, New York: Simon & Schuster Inc.
[3] Stoner, Michael S. 1999. Deviation log, new formulae aids directional drillers. *Oil & Gas Journal* (9 August): 64-70.
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[5] Stoner, Michael S. 1997. *A Fuzzy Logic Controller for Drilling Directionally*. T-4667. Colorado School of Mines, Golden, Colorado.
[6] Stoner, Michael S. 2000 (8 August). Numerical control unit for wellbore drilling. United States Patent #6,101,444.