Current State 2019 / Future State 2025

This section of the DSA Roadmap report describes the current state in terms of industry initiatives, early adopters progress and outlook, the anticipated future state with a discussion on the transition to this future state.

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Introduction

The earliest specific description of an automated drilling rig is the 1970s National Automated drilling machine that was placed on a Walker-Neer Manufacturing Company Apache series Singles land rig (Figure 1). This drilling machine drilled a series of wells in Texas for Mobil. It did not become commercial because of difficulties maintaining the hydraulic fluid system after each rig move (quick connectors had not yet been developed) and the destruction of electronic valves, or tubes, during rig moves (pretransistor age) that involved lifts and drops of the computer cabin (Source: Bob Bloom, retired NOV CTO).

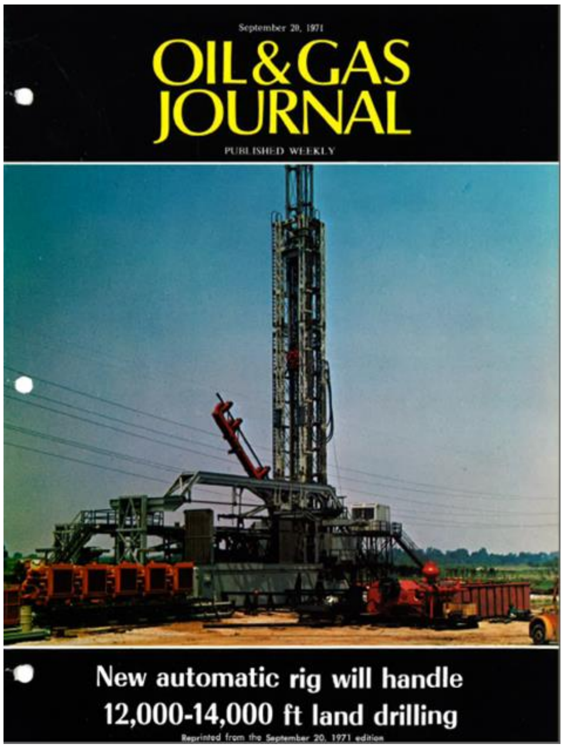

Figure 1: Oil and Gas Journal NADM 1971

Automation in drilling has advanced over the past 38 years but has not, until recently, been developed and adopted as systems automation that encompasses all the interconnected drilling systems. Initial applications of automation in the upstream oil and gas industry have been in Dynamic Positioning (DP) systems that maintain floating drilling units on station automatically. Automated DP systems have achieved extremely high reliability through technology, commissioning, and redundancy. This chapter contains examples of the current state of drilling systems automation at various companies and is not exhaustive. Companies are invited to submit short descriptions of their current state with graphics.

Current State Of Drilling Systems Automation

Drilling Rig Maturation

Drilling rigs have matured, from mechanical drives through Silicon Controlled Rectifier (SCR) DC electric drives, to AC electric Variable Frequency Drives (VFD). Variable Frequency Drive rig equipment has enabled a significant step forward in electronic control and thence automation.

Recent developments that have moved the industry toward systems automation include:

- Automated drillers that today electronically adjust the drill line feed rate from the drawworks based on variations in hook load and pump pressure, which equates to depth of cut. More advanced systems continuously compute the most appropriate weight on bit (WOB) and drill string RPM and feed these parameters to the drawworks and top drive VFD.

- Additional use of hard-wired drill pipe—drill pipe with wire incorporated throughout its length that transmits data at 56,000 bits per second— has realized further gains in closed loop control by using downhole measured parameters for WOB in place of the surface measurement, which is interpolated to WOB. The latter often results in significant errors in high-angle and horizontal wells in which along drill string friction is significant.
- Mud pump start-up rates may be pre-programmed into the pump controller when the rig is initially rigged up by the rig manufacturer. This ramp up can be revised in the controller for actual mud rheology and borehole conditions, although such changes are made infrequently.
- Specific downhole tools have developed remarkable control and automation capabilities, including autonomous rotary steerable systems (RSSs), which use closed loop control to steer the wellbore path in three-dimensional space.

SPE DSATS

The SPE Drilling Systems Automation Technical Section (DSATS) is an all-volunteer organization that develops recommended solutions for achieving interoperable drilling automation systems. Members from inside and outside the industry bring rich and diverse experiences, viewpoints, and requirements into a cooperative environment. This allows collaboration on guidelines and standards that are needed to advance the application of DSA while opening opportunities in the commercial arena for innovation and competition.

DSATS may be viewed as an incubator for drilling systems automation in which members benefit from open participation in symposiums, workshops, and webinars. Members develop and publish ideas and learnings that fuel further developments, which accelerate commercialization of those ideas in groups both inside and outside of DSATS.

Some DSATS accomplishments and work are described below. This is not an exhaustive list, but it does illustrate the tremendous strides in systems automation that are being made by enthusiastic volunteers.

Communications Standards

The first fruitful result of collaboration was the formation of a task force—the communications sub-committee—to research digital communications standards. The oilfield is composed of many individual companies, all with products and services and widgets, and systems automation is only possible if all those components use the same digital protocol to communicate.

The committee developed a model for rig-site communications and selected OPC UA as the digital protocol for that model. In 2011, the committee demonstrated control of a top drive simulator of one organization, by the control software of another organization, using the model and OPC UA. Since that time, OPC UA has become the digital protocol of choice for drilling systems automation. Most recently Statoil selected it as its instrumentation and measurements systems connectivity protocol for all company assets.

Over the past seven years, as company roles in it have been further clarified, the underlying structural model systems automation has changed. During that period, there has also been a noticeable shift in perspective within DSATS. The original DSATS focus was heavily rig-oriented, while more recent focus has been broader. The rig is now viewed as the surface footprint of a systems engineering process that reaches from the formation, at or ahead of the drill bit, to enterprise transactional and planning systems.

Semantic Modeling

The communications committee next focused on how information could be transferred using OPC UA or, in essence, how to develop the semantics of the language for systems automation. For this task, called "Drill-A-Stand," the group focused on the events and information that must be communicated among all parties for the use case of drilling a single stand.

In 2014 two-day workshop in Halifax, Canada, the communications group managed to complete the task. This led to the realization of the undertaking's complexity and to the definition of sub-tasks: the roles of organizations in systems automation, semantic models for communications, and cybersecurity for communications and each is being pursued.

The roles task is evolving a new model for rig-site communications. The semantic task is being pursued by DSATS members working between standards bodies, OPC Foundation and Energistics, to map WITSML into the OPC UA semantic model. And DSATS actively supports the IADC ART group that has a sub-committee focused on Cybersecurity.

Development of a Collaborative Repository

Recently, Energistics has agreed to develop a repository for DSATS sub-committees, such as the Documentation and the Drilling State sub-committees. Not only does this provide a hierarchical repository in which versions can be tracked, it provides a means of transitioning DSATS guidelines into Energistics standards.

DSATS Sub-Committees

DSATS activities include various sub-committees. Past activities have been closed out and new ones formed. Subcommittees are formed to investigate and develop solutions to various issues that are hindering the rate of adoption of DSA, or that can accelerate uptake for universal benefit. Openings exist for new initiatives through which SPE DSATS could enable industry solutions and DSATS current committees, their objectives, and their progress can be viewed at https://connect.spe.org/dsats/home

DrillBotics

In 2013, DSATS launched a drilling automation competition for universities. Named DrillBotics®, this annual competition now attracts teams of undergraduate and graduate students from many universities around the globe. In the event's first phase, based upon their technical/design proposal, a select number of teams are selected to proceed to the annual competition. Each of these selected teams then construct a small drilling machine and apply sensors and control systems to automatically drill through a block of unknown composition that has been developed and constructed to cause drilling dysfunction. Judges evaluate the competitors and assess the winner. The annual winning team travels to the SPE Annual Technical Conference and Exhibition (ATCE) to present a paper on their accomplishments.

(See papers at https://drillbotics.com)

Education

DSATS runs regular webinars with invited speakers from outside and within the industry. It is not uncommon for these webinars to reach more than 100 online attendees, with additional viewers logging in for playbacks. In addition, DSATS organizes two symposia annually; one is held at the SPE/IADC Drilling Conference in conjunction with IADC ART, and the other at the SPE ATCE. Workshops, which usually cover two or three days, are periodically organized by DSATS. Attendees are experts from inside and outside the industry and the workshops generate discussion, and solutions of issues seen in both business and technical systems automation arenas.

Conclusions – The Way Forward

The SPE Drilling Systems Automation Technical Section (DSATS) is an energetic all-volunteer organization. Despite the significant industry downturn, by 2016 it had grown to 1,700 members. Members from inside and outside the industry bring rich and diverse experiences, viewpoints, and requirements into a cooperative environment. While DSATS now works on guidelines, the cooperative effort with Energistics is laying the foundation for future standards.

As envisioned, DSATS has become an incubator for drilling systems automation. Members work in collaborative subcommittees to develop and publish ideas and learnings that fuel further developments. This collaboration accelerates downstream competition and innovation, which leads to the commercialization of these ideas.

IADC Advanced Rig Technology Committee (ART)

This committee was formed by IADC to improve safety and efficiency through sound operating procedures, design of automated systems, and standardized automation. ART subcommittees include:

- BOP Controls Cybersecurity
- Drilling Control Systems
- Future Technology
-

Much of the work of these subcommittees is related to DSA.

http://www.iadc.org/advanced-rig-technology-committee/

The IADC ART committee is taking a lead industry role in developing cyber security plans to protect drilling rigs' control and automation systems.

Operators Group on Data Quality (OGDQ)

A Chesapeake engineer explored the issue of data quality from rig sensors for current operations (not fully automated). Large sensor errors were found (Figure 13) that alerted the industry to a major systemic problem, which resulted in the formation of a stand-alone Operators Group for Data Quality (OGDQ). Link: http://ogdq.org

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	Rig A	Rig B	Rig C	Rig D	Rig E	Rig F
Rotary Torque	17%	17%	22%	24%	21%	18%
Makeup Torque	23%	11%	12%	17%	60%	13%
Rotary RPM	1%	1%	1%	1%	2%	1%
Block Position	6"	<0.5"	<0.5"	6ft	<0.5"	<0.5"
Hookload	11%		18%		12%	
Pit Volumes	15%	12%	18%	16%	15%	22%
Pump Rate	1%	32%	1%	1%	40%	1%
Pump Pressure	5%	4%	4%	4%	3%	5%

Figure 13: Drilling Data Error Matrix Errors Found Through Verification on Site

Key observations from collecting this data are:

- Every rig has had devices significantly out of calibration
- Most rigs have rig-ups or practices that will lead to device error or drift.
- Errors are common to all rigs and contractors

This group was formed to assess the extent of the problem and to develop calibration and maintenance processes to specify as required data qualities in drilling contracts. The initial program created a common contract specification, which these companies adopted. Later the group sought to develop industry standards for sensors to be included in contracts referenced through such bodies as IADC. This effort is an attempt to raise the quality and accuracy level of data being provided to the industry to a level that will ensure good and safe drilling practices. The first focus of this group is on surface measurements made on the drilling rig.

The ODQP determined that the impact of poor data quality:

- impairs our ability to measure, analyze, and improve our processes

- affects our ability to share knowledge and best practices
- may lead to or exacerbate safety issues like well control
- may negatively affect well deliverability and productivity
- will effectively prevent the development and implementation of automation (Figure 14).

Why it matters on the rig

Commonly Found Errors in Drilling Data and Corresponding Repercussions

Variable	Observed Errors in Field	Derivative Variable Errors	Small Error	Consequence	Large Error	Consequence	Worst Case Scenario
Torque	>100%	MSE Rig State	5%-10%	Sub-optimal drilling, analysis, planning.	>20%	Bit Failure, Motor Failure, MWD Failure, Tubular Failure, Vibrational Dysfunction, Poor Drilling Performance	**Loss of Drill String**
RPM	>100%	MSE, Rig State	2%-10%	Sub-optimal drilling	>20%	Bit Failure, Vibrational Dysfunction, MWD Failure, Poor Drilling Performance	**Loss of Drill String**
Block Position	>25% (cumulative >50%)	Bit Depth, ROP	1%-2%	Block Position Error is Cumulative. Incorrect MD/TVD/Survey Measurements.	>5%	Could lead to significant survey errors and TD compromise.	**Wellbore Intersection**
HookLoad	>100%	WOB, MSE, Bit Depth, Rig State	2%-5%	Sub-optimal drilling. Poor ROP or bit wear/damage.	>10%	This would represent ~50,000 lb for most sensors.	**Loss of Drill String**
Pit Volumes	>5% (100% delta)	ΔPit Volume, Kick Size /Density	1%-2%	Poor well control detection/performance.	>5%	5bbl error could be 100% error in well control calculations	**Well Control**
Pump Rate/ Pump Pressure	>100%	ΔP, MSE, Rig State	2%-5%	Sub-optimal drilling. Poor well control performance. Wear/damage to down-hole motors/turbines.	>10%	Potential damage to motors/turbines/MWD. Potential for kicks/fracturing when near pore pressure/frac gradient	**Well Control**

Source: SPE presentation – Chesapeake (The Role of Data in Drilling)

Figure 14: Quality Data Reasons

GCE Node

GCE Node is a funded Norwegian Global Center of Expertise (GCE) technology cluster composed of 76 companies located in southern Norway. It has several research, development, and innovation projects that are focused on topside drilling systems. These include common data gathering initiatives, offshore mechatronics, and robotics. The NorTex (Norway-Texas) data science cluster is an umbrella organization related to GCE Node. NorTex has played a key role in organizing workshops in Norway and in Houston focused on data science. GCE Node is primarily interested in fostering cooperation between companies in “noncompetitive” areas.

IRIS (NORCE)

IRIS, the International Research Institute of Stavanger is equally owned by the University of Stavanger and the regional foundation Rogaland Research and is a recognized research institute with a focus on applied research. Rogaland Research was established in 1973; IRIS was established in 2006. Today, IRIS remains an independent research institute with research and research-related activities in petroleum, new energy, marine environment, biotechnology, social science, and business development.

IRIS believes automated drilling has large potential and seeks to be among the lead research institutes within this area. The institute has developed methodologies and procedures focusing on automatic drilling procedures, such as automated drilling surveillance and systems for active failure prevention. IRIS will put further efforts into presentation and evaluation of algorithms for automated coordinated control of drilling machinery, pump rates, chokes, and drilling fluid properties.

The institute performs fundamental research into well flow and wellbore mechanics in the drilling process. The development of accurate process models is achieved through advanced physical and mathematical modelling combined with experiments and tests carried out in the laboratory, on the virtual rig, and at full-scale in the field and at the Ullrig Drilling Center.

In 2018, IRIS was absorbed into NORCE, a Norwegian Research Conglomerate.

Automated Drilling

IRIS has chosen to concentrate on automated drilling because many future oil and gas prospects will be highly complex and challenging and will be characterized by narrow geo-pressure margins that leave little room for human error. Researchers believe that increased levels of automation will result in more accurate pressure control and more rapid response to drilling anomalies, which will improve drilling efficiency and safety.

IRIS has contributed significantly to automated drilling through several research projects, two of which, DrillTronics and DrillScene, have resulted in commercial products marketed through Sekal. IRIS has participated in demonstrations and pilots to make this technology available to the market and has ongoing research projects aimed at taking new steps within automation, including:

- Adapt DrillTronics for Wired pipe
- Automated Drilling Fluid Processing
- Automation of Formation Integrity Tests, Leak-off Tests and Extended Leak-off Tests

- Advanced fluid transport modelling
- Instrumentation, measurements, and standards.

The primary focus for a DrillTronics installation is to enhance drilling operations and maximize productive time during drilling by:

- Applying operational safeguards to the drilling control system that ensure pressure inside the wellbore remains within the geopressure window, even during transient operations, such as starting the mud pump or tripping in or out of hole
- Providing automatic safety triggers that react to drilling incidents, such as pack-offs, and take corrective action to prevent problems from becoming more serious
- Enabling automatic sequences that offer greater efficiency and consistency across a range of drilling operations while ensuring that the well is protected by using safeguards and automatic safety mechanisms. These sequences allow the driller to focus on the most important information while executing standard operations. Predefined automatic functions implement the required operational sequences and manage associated parameters when operating the mud pumps, draw works, and top drive.

UT RAPID Program

The University of Texas at Austin launched a drilling research consortium named Rig Automation & Performance Improvement in Drilling, or RAPID. The objective of this program is to deliver automation well construction solutions from researchers from multiple engineering disciplines. Current research focus areas include:

- Automated drilling control
- Intelligent mechanization and automation
- Downhole modeling, simulation, and empirical validation
- Monitoring, data analytics, and 'Big Data'.

Research areas of interest include:

- Remote, directional drilling control, and geo-steering
- Automated control for adverse conditions (i.e. stick-slip, whirl, bit-bounce)
- Automated control for wellbore stability and lost circulation prevention
- Automated managed pressure and dual gradient drilling
- Automated completion, stimulation, fracturing, and intervention tasks
- Surface automation and mechanization (pipe handling, BHA assembly, drilling while circulating)

- Mechanization for rig move and transport, mob/demob, and skidding and rig walking
- Automated optimal control for tripping
- Rig design for automation
- Novel sensor design, new sensor integration, data quality, data analytics, and sensor standards
- High-frequency downhole and surface sensor analysis

SPE DSATS Assessment

The fractured nature of the digital backbone in drilling operations has led to three distinct islands of development: downhole, surface, and remote.[1]

Of the three, downhole systems have reached the highest levels of automation—including semi-autonomous systems—largely because until recently only low bandwidth, high latency MWD communications systems were available. Surface systems at the rig site have become highly mechanized, with automation of drilling components, such as soft-torque systems. Remote systems have flourished in recent years with the advent of digital surface communications but are employed primarily to monitor drilling operations.

The increasing availability and use of digital technology, in particular "bit-to-shore" communications backbones that make real-time modeling and simulation possible, coupled with strong technical drivers, such as increasingly complex and expensive wells and human data overload, has led to an increased interest in systems automation. Other drivers include health and safety, and retention and distribution of knowledge.

There is no apparent technical reason preventing the drilling industry from attaining high levels of drilling systems automation. While some areas, such as instrumentation and measurement, are in dire need of attention, there is a healthy "technology push" for drilling systems automation.

However, the "business pull," that is the financial case for investing in drilling systems automation, is currently weak (unorganized and unfocused). The reason for this lack of cohesion appears to be the highly diverse nature of the drilling industry, which is composed of four main segments—operators, service companies, rig contractors, and equipment suppliers. This diversity, combined with the performance moderation attitude that results from the multiplicity of day rate contracts, creates an environment that discourages the industry-wide coordination necessary to promote drilling automation.

However, certain recent industry collaborations have led to interoperability and standards initiatives, which have opened the automation space to all four drilling industry segments.

Existing companies within the industry are exploring the potential of drilling automation and new companies that directly address drilling systems automation are forming.

A dichotomy in automation objectives has developed. The first is the “well manufacturing” objective aimed at cost-restrained, highly repetitive wells having similar profiles. The second is the “complex well” objective driven by technically challenging, unique well profiles and large volumes of data.

An operator may control the well manufacturing objective using heavy rig automation, which has numerous analogs in other industries, such as mining and car manufacturing. A risk inherent in this approach is cost constraints that drive operators toward low-cost solutions, cheap sensors, and commoditized components that may prove detrimental to efficiency in the long term.

The complex well objective has yet to find a business champion, or integrator. It appears, however, that a business model change that clearly identifies the champion and provides financial benefits to those who deliver value through automation would be a solution. Initial steps within the complex well arena, by both service companies and equipment suppliers, have focused on drilling optimization and managed pressure drilling.

Regardless of the final business model, interesting days lie ahead for the industry as technology matures and reaches the field. While the industry may not have the time to adopt drilling automation in a strategically planned initiative, the application of technology in an open standards environment may ultimately tip the industry into drilling systems automation.

Finally, drilling systems automation is not pushing a button and drilling a well. It involves a blend of human and computer control that delivers an economically viable, safe, and fit-for-purpose borehole. This implies a sophisticated level of design that keeps the driller and engineers in the loop and always aware of the situation.

System automation progress by some early adopters

Shell

A major operator, Shell, has developed a SCADADrill (Supervisory Control and Data Acquisition) system supported by RigME that has undertaken various drilling activities in automated mode. Shell now licenses the application of this system.

SCADADrill is Shell’s internal version of an autodriller. To extend the capabilities of the autodriller, additional information from the wellbore and from drilling instrumentation was required as input. RigMe was developed by Warrior Technology Services in conjunction with Shell as a calculation module-interface for SCADADrill. Directional drilling, torque and drag analysis, and wellbore hydraulics are the three main drilling engineering applications that comprise RigMe. Applications include:

- Directional Drilling:
  - Automatic steering performance analysis
  - Instantaneous directional drilling directives
  - Optimized trajectory and minimized tortuosity
  - "Project-to-bit" using slide history
- Torque and Drag:
  - Detecting imminent issues such as stuck pipe
  - Assisting hole cleaning practices
  - Facilitating getting casing to bottom
- Hydraulics:
  - Wellbore stability
  - Reservoir protection
  - Annular fluid velocity and pressure
  - Cuttings transport and hole cleaning
  - ECD

Recent additions include a view of the trajectory relative to the wellplan and geosteering, which is integrated with a 3D geo-model.

RigMe can now be found as the commercial product, Drill-It. Further information may be found at http://www.rigme.com/index.html .

Shell developed this system with a focus on drilling repeatable wells with average drillers across a fleet of various land rigs. But the oil price crash and the acreage Shell held in this type of operation drove them to reduce this activity. The drillers who were high-graded to remain active in these operations were the best drillers, which resulted in high performance across the reduced rig fleet. This high performance was difficult for the automated system to compete against to deliver value. As a result, Shell's automation project was required to turn its attention to one-off type wells in which significant performance gains are still an opportunity. This has changed the whole concept of the value delivery by automation from manufacturing style to project style deliverables (see section Systems Architecture).

The slide below (Figure 2), from David Blacklaw's presentation to the SPE GCS Annual Drilling Symposium held on 14 April 2016 in Houston, Texas shows that Shell proved that drilling automation can add value in terms of its original goals. However, as described above, the market for Shell's drilling automation shifted considerably.

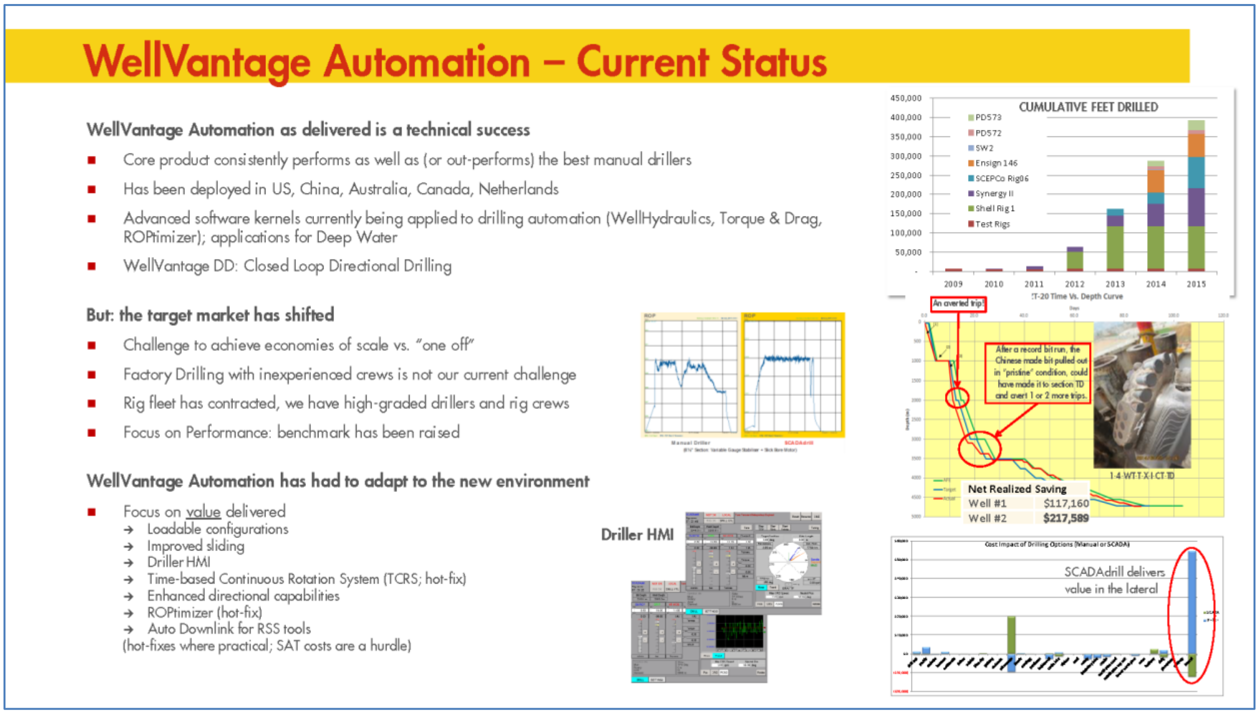

Figure 2: Shell's WellVantage Automation

Shell's outlook for the future is of interest to this discussion because it highlights the need for standards and interoperability to achieve broad adoption, which is the key avenue to general value delivery. It is also a key purpose of the SPE Drilling Systems Automation Technical Section and a key driver for this roadmap initiative to characterize solutions.

High speed downhole-to-surface date transmission, along with distributed sensing in the drill string, is perceived to add further value. This leads to the conclusion that as drilling systems automation advances hard-wired drillpipe or a replacement technology will be required. Advancement in data analytics and the impact it can have on performance and value in well delivery is also a key target; this is a very challenging area that can adapt quickly to drilling if expertise is imported from outside the oil and gas industry. The additional opportunities Shell lists (Figure 3) include multiple technology advancements envisaged in this DSA Roadmap.

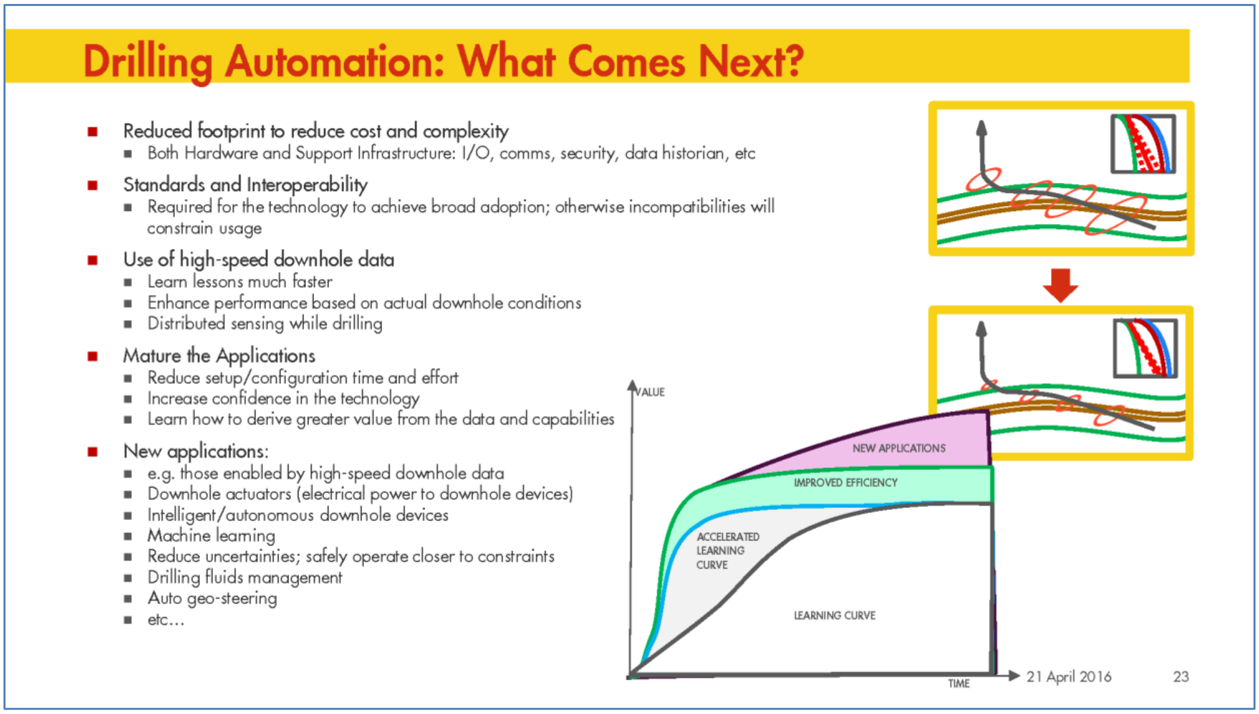

Figure 3: Shell's Outlook on DSA

Apache

Apache embarked on a drilling systems automation project around 2010. They contracted a Huisman LOC land rig, which included a fully integrated control system. The operator applied automation programs to a drilling project in West Texas and the project succeeded in operating the rig remotely from a standoff of 50 yards.

Apache developed several patented automation technologies, the ownership of which were transferred to rig startup company, Canyon Oak Energy. The Canyon Oak design leverages hydraulic systems, intelligent rig controls, pipe handling systems, and rig mobilization capabilities. As of early 2017, Canyon Oak Energy had not built any rigs incorporating their new designs or the Apache-generated automation.

Apache continues to develop a foundation for drilling systems automation by deploying aggregators that access and compile data for learning and drilling improvements on their rigs. This new data aggregation platform acquires data from all available sources via communication protocols (OPC-UA to 4/20 ma signals) and data digital file formats (csv to LAS). The new platform incorporates:

- Time-managed like similar to data
- Instituted key rig site sensor calibration validation effort

- 100 hz data, 1,000 tags, 7-day storage onsite capability
- Streaming of rig state, modeling, and executable algorithms
- Data quality control through comparison at sensor and through Bayesian network modeling
- Read/write capability onsite and daily reporting database that comprises important metadata
- Historical, database, and open executable layers
- Future full traceability and transparency on all data from sensor measurement to storage to analytics.

National Oilwell Varco (NOV)

Major OEM, NOV, has developed an automated system (NOVOS) focused on improving drilling performance in openhole sections, particularly with hard wire drill pipe that provides a high data rate and low latency communication between downhole and surface. This system provides the opportunity to capture lessons learned from well-to-well, apply improved processes and drilling parameters, and reduce the potential for human inconsistency in drilling operations. NOVOS has been operated repeatedly in the Eagle Ford, the Williston, Permian, and Utica Basins on land in the USA and its adoption is expanding rapidly in the North Sea.

In these operations, downhole data was fed through the wired pipe into the rig's control system. The data was then shared with a set of applications that analyzed it and sent set points to the rig's control system, which allowed the rig to drill ahead using the downhole data. Also, a surface automated stick-slip prevention system was run, which mitigated torsional vibration.

Using this system, the driller experienced 30% to 40% time reductions in openhole sections. Benefits were seen in all hole sections, but particularly in the lateral sections of the wells where significant WOB loss occurs between the surface and the bottomhole measurement. This is significant because surface measurements alone provide a poor indication of downhole drilling parameters, especially WOB, and the drilling dynamics environment.

Recently NOV developed a device to capture data while tripping (DWT). Mounted on the elevators, this machine captures live data while tripping in or out of the hole that can be used to provide real-time swab surge data and envelope protection.

Closed loop downhole automation (CLDA) is particularly effective at improving on bottom ROP, bit run lengths, and at reducing the number of trips that occur as a result of downhole tool failure.[2] On its own, CLDA has limitations: it requires sophisticated optimization engineers to be on the rig site managing the system, it has no impact on the manual connection processes, the driller must continue as the machine operator, and it is very difficult to capture lessons learned for further optimization of later wells.

NOV developed Process Automation System (PAS). PAS is a software platform that transforms a standard 1500-HP AC rig into an automated drilling rig. The software enables the driller to complete many common drilling procedures automatically, with little or no direct interaction with the rig control system itself. The driller is then free to turn attention to more important things, such as safety, personnel, planning, and resource management, instead of the menial task of sequenced button pushing.

The PAS automatic processes, which are configured during system commissioning, are easily adjusted on the fly. As drillers learn more about how it is reacting to the formation and the drilling environment, they can adjust the system to improve the process or make it safer or more efficient.

One of PAS's automatic processes is tagging bottom after a connection and many control points in the system allow the driller to specify how the bit engages the formation. Examples of these control points include changing the bit RPM before and after formation engagement and changing flow rate before and after bit engagement. The system also includes applications to provide third-party control of the drilling process, thus allowing any service company, operator, or contractor to impart their specific process to any rig in the world that has this system.

Finally, a key component of the system is a well program that describes the drilling environment. Through the well program, the system knows type of formation by depth, hole size being drilled, and hanger depth of last casing or liner. All this information provides a framework for drilling experts to prescribe automated behavior through drilling parameters assigned to specific parts of the wellbore.

NOVOS is readily applicable to NOV's Amphion and HiTech control systems.

Schlumberger

Schlumberger has embarked on a major project to develop their 'rig of the future,' which incorporates numerous automation features and rig redesign. Schlumberger has accumulated a broad spectrum of technologies related to drilling systems automation through acquisitions and JVs. This is a truly integrated approach under the direction of a single integrator, who directly owns or has access to all the technologies and equipment required for a fully automated drilling system. Paal Kibsgard, Chairman and CEO, presented the rig (Figure 4) to a conference in September 2015. Notable aspects of the rig of the future are:

- The use of the Petrel platform that indicates a tie-in between subsurface data, models, and drilling systems automation

- Cloud computing will enable 'big data' processing along with remote expert and algorithm input
- Rig design shows leveraging flat time activities through mechanization with automation, such as pipe stand racking.

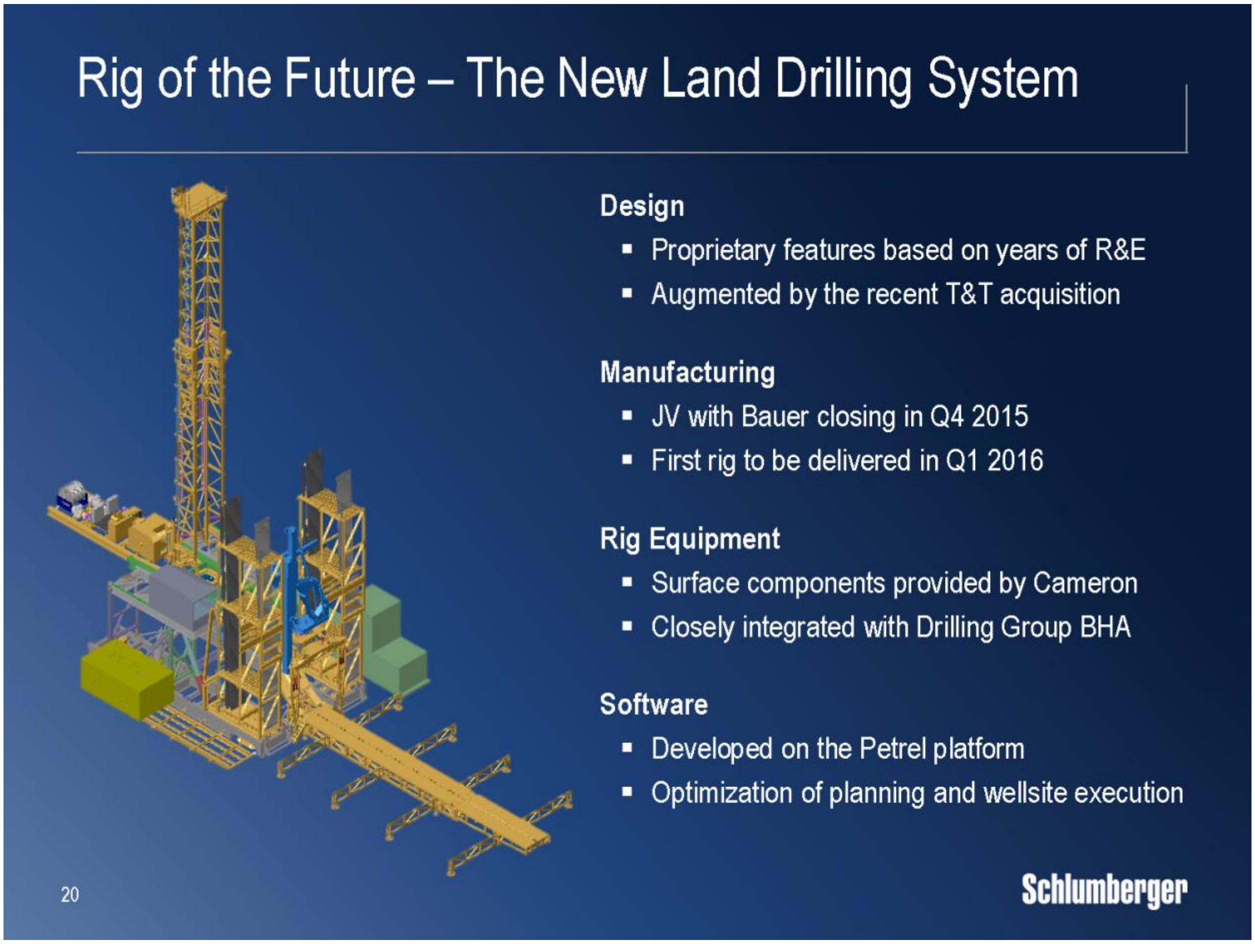

Figure 4: Schlumberger's New Land Drilling System

A financial analyst's late 2016 view of Schlumberger's Rig of the Future provided the following insights:

- Schlumberger had deployed two prototypes of its 'rig of the future' in the U.S. market with 3 more expected to follow soon.
- 'Rig of the future' is a strategic initiative for Schlumberger and over time may become a disruptive service offering that creates a serious competitive threat to established drilling contractors.

Specifically for this project, Schlumberger acquired T&T Engineering, a Houston-based rig engineering company, to help develop the new rig's design. Schlumberger also acquired the drilling controls company, Omron Oilfield and Marine, which is used by numerous leading USA land drilling contractors, including Patterson, Ensign, and H&P. Rigs are being manufactured by a joint venture, NEORig, based in Texas, which Schlumberger created with BAUER Maschinen GmbH, a leading German machinery manufacturer for construction, mining, and oil and gas industries (Figure 5).

The new rig will receive top-drives, pipe handling modules and blow-out preventers from Cameron's drilling equipment portfolio that includes TT Sense in Norway with rack and pinon drive rigs utilized extensively by Schlumberger's drilling contractor Saxon Energy Services, and LeTourneau's land drilling rig manufacturing. The drilling system will also integrate Schlumberger's suite of downhole tools and reservoir characterization technologies.

Figure 5: Bauer Drilling Machine

Schlumberger's description that "starting with concurrent well engineering based on subsurface modeling, the resulting well program is used to drive closed loop workflows and dynamic scheduling of rig operations, breaking down the traditional siloed approach to service execution on a rig today," strongly suggests the first application of drilling systems automation on bespoke equipment.

Industry analysis suggests that it would be incorrect to think of the "rig of the future" as an attempt by Schlumberger to capture a share of the highly competitive and commoditized North American land drilling market. Instead, it is an attempt to capture a share of the entire oil services market by moving from selling a Schlumberger downhole tool or a Schlumberger reservoir characterization service, to selling a Schlumberger well, and extrapolating a Schlumberger full field development. In many ways, the "rig of the future" is a logical extension of the company's integrated project management philosophy and should be viewed in that context. Commercially, this appears to be the first application of a total drilling system automation designed to gain market share. Essentially, drilling systems automation is being used as a potential competitive advantage.

David Rowatt presented key insights on Schlumberger's 'Rig of the Future' (Figures 6 and 7).[3] The objective of the rig is to integrate digitized planning with well construction in such a manner that the digitized drilling program can be executed by automated machines. This model intends to drive major value from data sensing, analysis, and digitization as instruction to the machines, leveraging the potential value above automated machines alone.

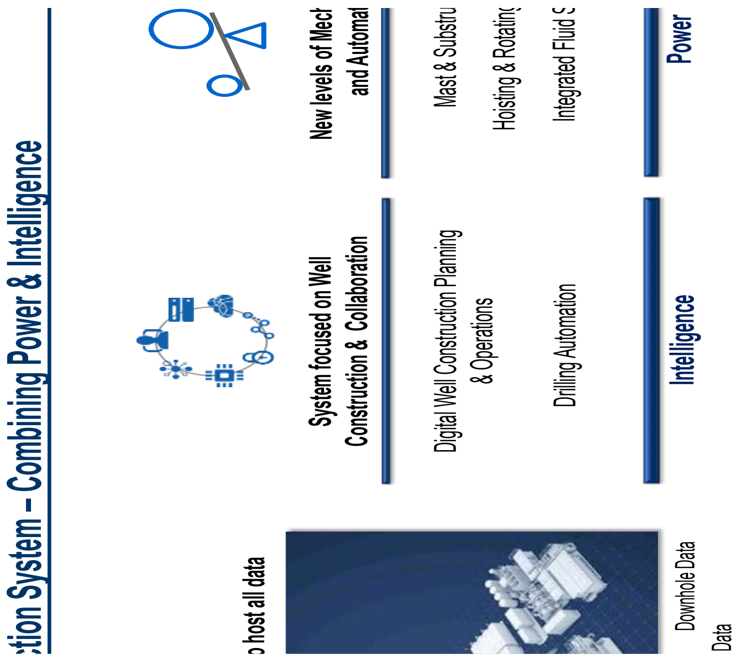

Figure 6: SLB Well Construction System

The rig design attributes presented seek to leverage the minimization of wasted time in operations.

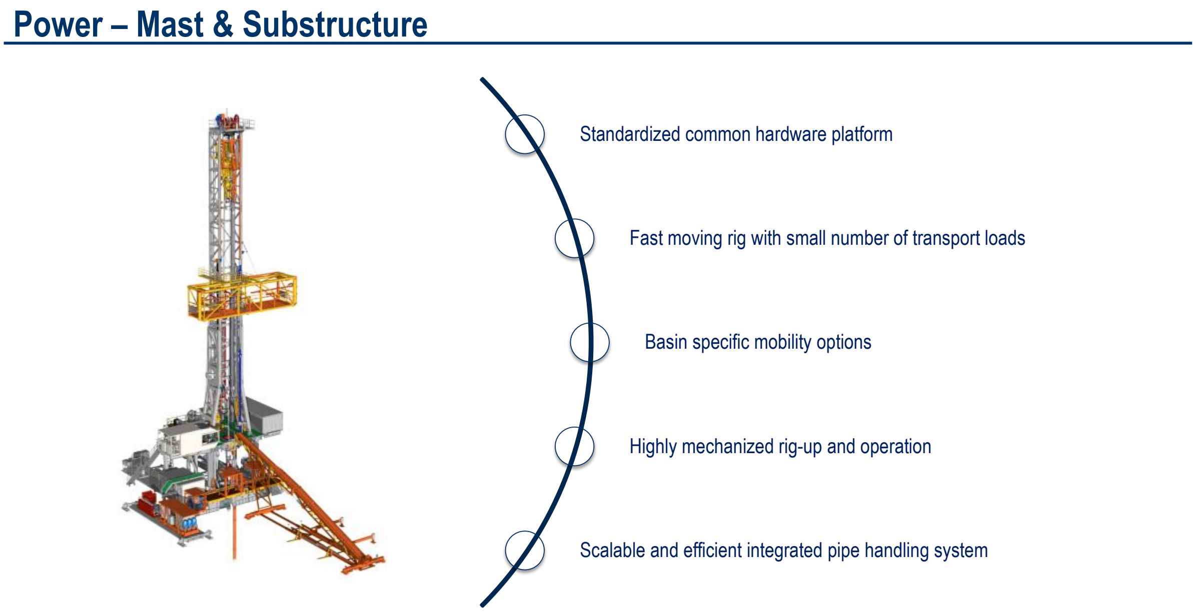

Figure 7: SLB Land Rig

Schlumberger has elevated the digital environment to a cloud based cognitive E&P environment, in which their automated drilling acts alongside subsurface shared earth modeling systems such as Petrel. This is an approach in which automated drilling systems act as part of a digitized world.

Nabors

Nabors has worked on advancing their control systems through their subsidiary CanRig. The company's presentations to the investment community lay out a strong development and implementation plan that combines an advanced pad drilling rig design (SMARTRig™) with integration of their controls development in their Rigtelligent™ Integrated Operating System and their downhole tools and services (Figure 8). Nabors has developed and applied directional drilling automation which has close the loop, 'drill-a-stand' automated cycles, including the multiple-use cases that occur in this cyclic operation. The company has adopted a drilling methodology in which the operator's instructions and procedures are fed into the automated drilling system. The Rigtelligent™ system is designed to perform process automation through the rig control system.

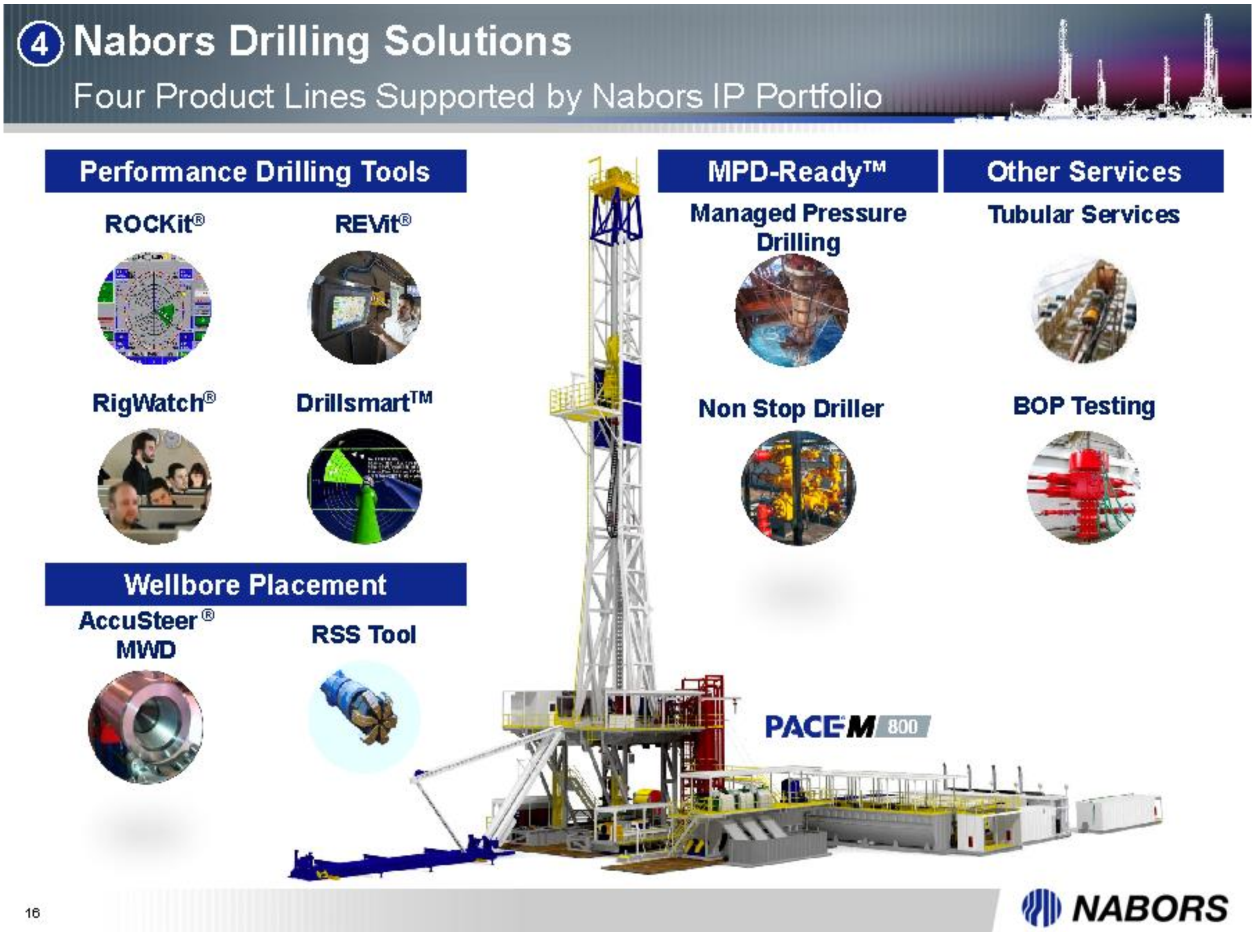

Figure 8: Nabors Automated Systems

H&P

Helmerich and Payne (H&P) is a well-established US drilling contractor that has some overseas operations. In the late 1990s and early 2000s, H&P specifically focused on the development and operation of a new rig fleet driven by delivering customer value and maximizing assembly efficiency. The FlexRig™ was a major success. Specifically relating to DSA, it incorporated the use of VFDs in AC motors that enabled modulation of input with joy sticks. The availability of VFD on drilling rigs was a precursor to the application of algorithms that enable operations automation.

Flexrigs were recognized for their advanced control systems, which were developed and supplied by IDM, subsequently Omron Drilling and Marine Controls. H&P was also recognized for procedural controls, such as initiating drilling, that are known to reduce downhole drilling dysfunction and trip and repair costs. [4]

In 2017, H&P purchased Motive, which had developed a bit guidance system that provides decision automation to assist the directional driller using an advisory mode. This system had been developed within Hunt Energy Enterprises, subsequently also funded by GE and Formation8, which was later to H&P. In late 2018, H&P stated it had “taken the Motive turn-by-turn instructions, and rather than feeding them to the directional driller or our driller on the rigs, we’re feeding them into the FlexRig software; closing the automation control loop.”

H&P has an array of software solutions that control the drilling process (Figure 9).[5]

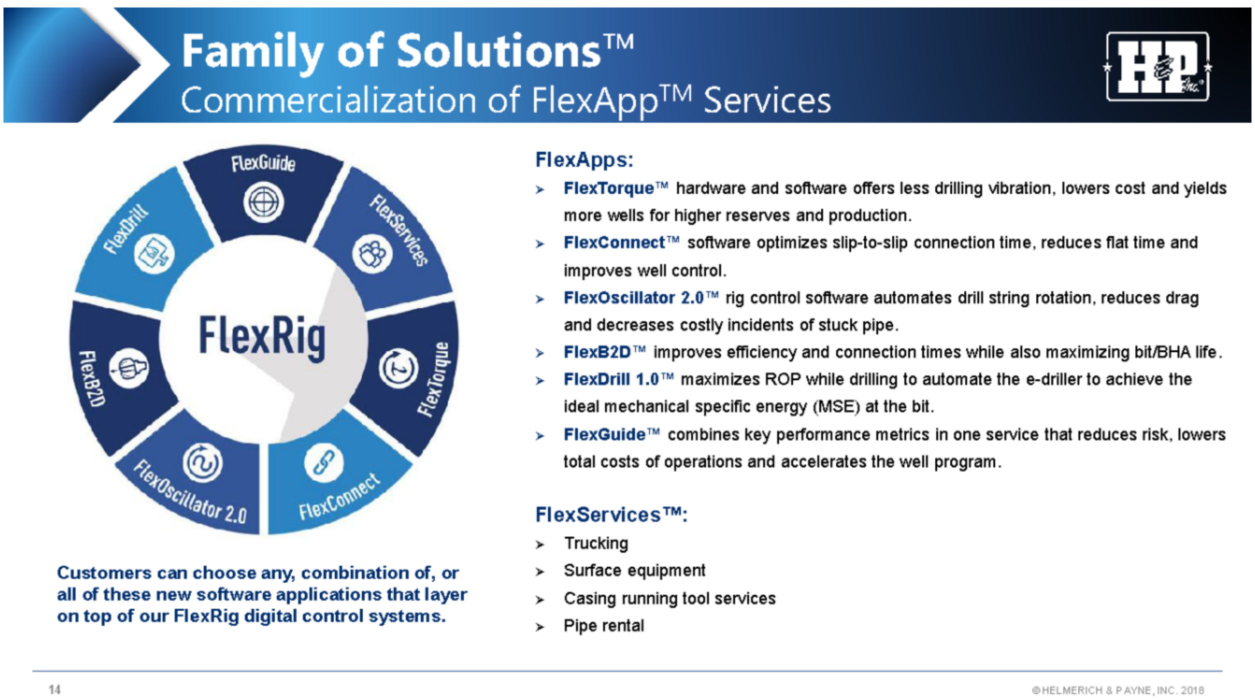

Figure 9: H&P's Family of Automation

Precision Drilling

Precision Drilling (PD) is aggressively adding the NOVOS system with hard wired DP to many of their rigs. In January 2019, it reported installations on 27 rigs with a total 33 targeted by year end. In 2018, the company drilled more than 290 wells using process controls that automate repetitive drilling activities using programmed routines. Precision Drilling is deploying revenue generating drilling performance applications on rigs that have been written by customers, third-parties, and DP.

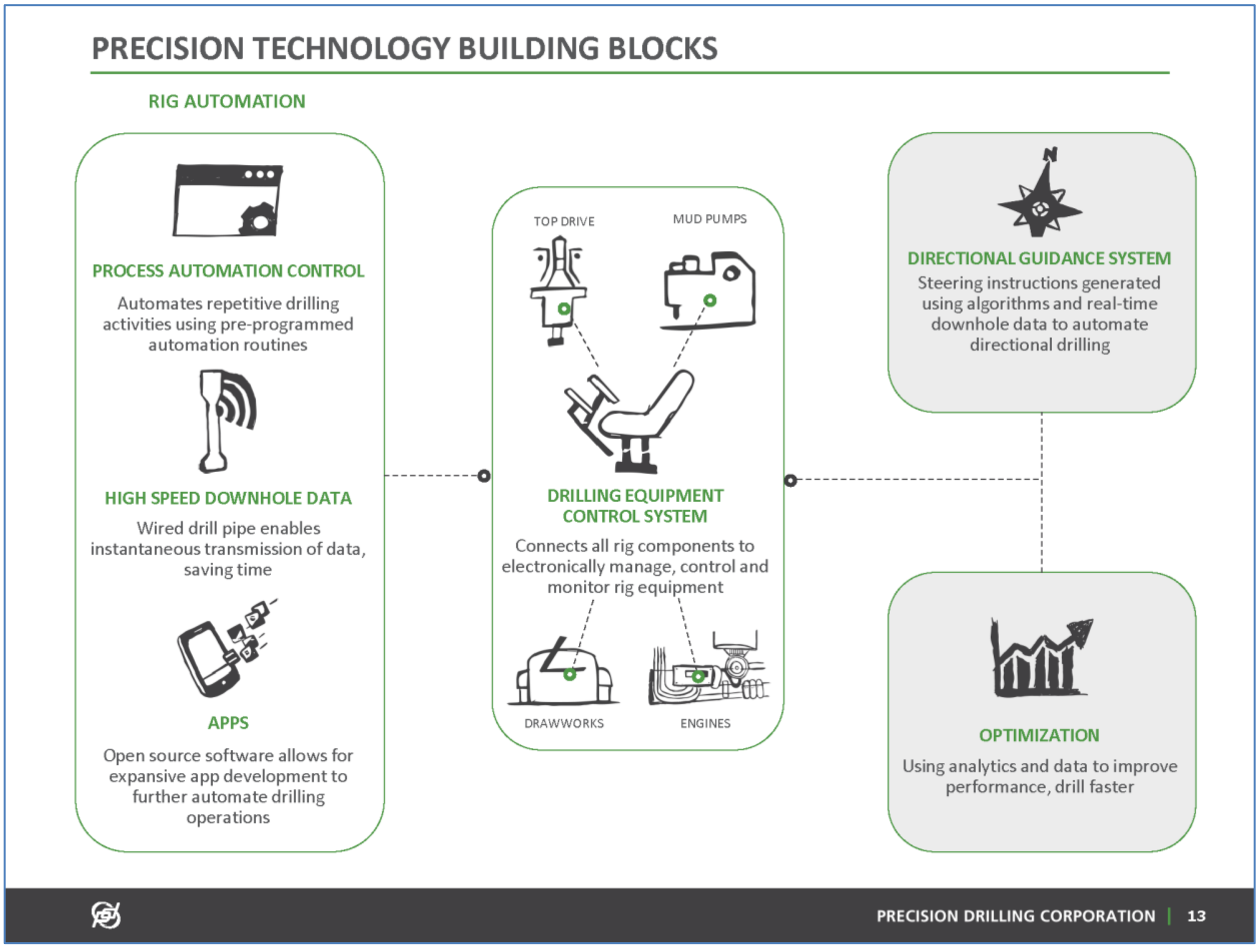

Figure 10: Overview PD Automation

Huisman

An IADC Drilling Contractor March/April 2016 article describes some of the critical success factors for application of robotics into pipe handling systems.[6] Key sections are reproduced below with permission from IADC Drilling Contractor Magazine.

Lessons learned from automotive and offshore pipelaying industries are helping to inform the oilfield's path toward a robotic-driven drill floor

By Dieter Wijning and Ed Adams, Huisman Equipment

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The cost savings, efficiency and safety of robots used in auto manufacturing (left) were transferred to the manipulator arms used on the DMPT robotic pipe-handling and tripping system (right).

As demonstrated during the development of robotic technologies for repetitive and hazardous rig floor activities, robots employed in outside industrial settings provide sound baselines for adaption to meet drilling requirements.

Huisman's robotic drill floor development initiative, highlighted with the engineering of a wholly robotic pipe-handling system, is providing insights into the philosophical and technical strategies that should be considered when developing enabling technologies to reduce the human element on the drill floor. First and foremost is establishing firm objectives as to the intended functions of the envisioned machines and processes. This requires debunking the widely held misconception in which mechanization, automation and robotics are used interchangeably.

Simply put, mechanization replaces human muscle with a machine, but human brainpower still makes the decisions. With automation, the machines perform multiple interrelated tasks but are limited to one repeated set of preprogrammed operations. This makes them unable to react to stimuli or be easily changed functionally. The Society of Mechatronics Engineering and Technology differentiates the two by describing mechanization as saving the use of human muscles and automation as saving the use of human judgment.

Robotics, on the other hand, focuses more on the associated hardware. Unlike mechanization, it also comprises automated controls and typically is adaptive. Thus, robots can be said to combine the best of mechanization and automation, with the capacity to perform several jobs simultaneously and with the sequence of operations readily switched when required. As reflected in the various applications of robotic manipulators developed for new-generation pipe-handling and tripping systems, these machines can change the specific tool attached and, therefore, react to stimuli to best fit an assigned task or function.

Changing the process

Figure 11: Automated Pipe Welding

The precisely controlled manipulators that deliver unprecedented positioning accuracy for continuous pipe welding during pipelay, developed by SMST, a Huisman company, helped lay the foundation for the precise sensors engineered into the robust manipulators used to handle 180-ft stands of pipe.

In contrast to the commonly used “bolt-on” approach that simply mechanizes select aspects of the drilling operation, one of the key learnings of the robotic drill floor development program was the inherent value of engineering the rig floor process to accommodate true, seamless automation. Fundamental to this wholesale process change was to avoid attempts to imitate the human but rather enhance the human-machine interface, where the respective strengths are both recognized and utilized.

Certain traditional pipe-handling processes, such as kicking out bails with elevators, for example, have a historical background. For true and fully optimized robotics, one must step away from these long-held paradigms and rethink the process.

Equally fundamental to both the process change and hardware development is ensuring simplicity in the motions of the machines and in performance measuring, lest the operation becomes overly complex and unmanageable. That thought process was front and center when evaluating the transfer possibilities of robotics used in other industrial applications. While no two robots are created equal, the robotic experiences of two sectors, namely automobile manufacturing and offshore pipelaying, provided conceptual blueprints well-suited for adaption to the rig floor.

<u>Assembly line to pipe handling</u>

The most recognized application of industrial robotics can be found on the typical automobile manufacturing assembly line. There, for example, “bionic” robotic hands incorporate sensors, actuators and simulated nerves to reduce the manual stress and fatigue of the more repetitive and human-driven final assembly tasks, such as wiring and wheel installation. The incorporation of lasers and cameras further enable robotic arms to more precisely direct the installation of individual parts on a vehicle body.

Figure 12: Robotic Drill Tower Demo

Most notably, the so-called collaborative robots work alongside their human colleagues, thereby exploiting respective strengths to enhance safety and productivity with increased flexibility. For repetitive exercises, the “human-friendly” machines take over the laborious, dirty and hazardous jobs, while humans deliver the flexibility and capacity to respond instantly to process deviations and other unexpected events. Thus, the auto manufacturing experience provided the closest non-oilfield analogy to the intended objectives of the robotic drill floor development initiative.

The result of the initiative was a fully robotic pipe-handling system. It features robust, multifunctional and interchangeable manipulators that deliver simple automated movements that rotate, extend and move up and down the corners of an enhanced dual multipurpose tower (DMPT) drilling system specially engineered for floaters. Accordingly, these robotic manipulators can efficiently move stands of drill pipe and casing from two rotating setbacks to and from the well center, thereby eliminating the conventional overhead translating rackers on most drillships.

The entire handling system, which was engineered to handle 180-ft stands, is designed to automate unrestricted tripping speeds to roughly 5,000 ft/hr and increase the efficiencies of running long strings of casing and other tubulars. Performing these functions in an automated and controlled environment without direct manual involvement makes the drill floor inherently safer.

The robust manipulators used for handling 180-ft stands of drill pipe, casing and other heavy BHA stands, required the development of what are considered among the largest industrial robotic manipulators, with a rating of 7 mt safe working load. These manipulators also had to be equipped with precise sensors to ensure the stands of pipe are gripped properly and controlled to a precise location during tripping. Additionally the key requirements for pipe-handling manipulators were speed, consistency and precision.

A pipe gripper, for instance, could be added to a couple of manipulators on one corner of the drilling tower that are then programmed to act in concert with each other and handle pipe stands during tripping operations. A third manipulator on the opposite tower corner could be equipped with an iron roughneck and spinner head, making it dedicated to making up or breaking out drill pipe stands. When programmed together, these three robotic arms become dedicated to the main functions of pipe handling while tripping. Similarly, manipulator arms on the auxiliary or construction floor side of the tower could be fitted with riser aligner tools and bolt makeup tools for automated running or risers.

Like the simple change from one computer or smart device application to another, each of the manipulators facilitate changing of the tool or application within minutes, with little or no human interface. The tools are stored and retrieved from a dedicated tool rack on an as-needed basis, effectively changing the app.

Future State Of Drilling Systems Automation

The Future State of Drilling Systems Automation is expressed in the vision. In technical terms, it requires the advancement of control systems and supervisory automation through the application of surface and sub-surface equipment technology designed for automated control that collectively drill oil and gas wells more efficiently with higher quality wellbores at lower cost.

Drilling rigs will be redesigned around the application of automation to many processes, especially those requiring human manual intervention and those that will transfer the operation from critical path (online) to noncritical path (offline). This transference reduces the overall drilling time but requires that the noncritical path process be achieved repeatedly in the predetermined duration to avoid reemerging on the critical path. This consistent delivery of activity duration is a prime deliverable and so becomes a requirement for automation; mechanical technology will be developed for its ability to apply automation.

As a result of the success of Rotary Steerable Systems (RSTs), downhole automation will increase significantly. This technology has proven itself to be highly successful in achieving objectives and to be highly reliable in very aggressive environments characterized by high shock, stress, and temperature levels.

Intelligent drilling bits will provide input to automated drilling as the Internet of Things (IOT) continues to make 'dumb iron' intelligent. The sensors implanted in these bits will provide the front-end data to subsurface systems, this data is being jumped by a short hop high-rate system to the main brain of the bottom hole assembly (BHA). This BHA brain will decide to act as tools and technology permit, or to transfer the information to surface for surface activation control or human supervisory intervention.

The resulting split between downhole and surface computational control will be driven by the ability of the downhole computational system, the downhole-to-surface and return transmission capability in terms of speed, bandwidth, latency, and by the need for signal inputs to surface hoisting, rotary, and pumping machinery. In the coming years these drivers will deliver specific automated drilling systems.

1. **Intelligent Drilling Equipment on the Drill Floor** (Year 2022): Using existing Drilling Equipment and the current limited ability to extract information about the down-hole state, the industry will develop automated control systems that maximize the information available. It will do this by integrating data from all available sources, possibly including subsurface, or earth models, drilling equipment states, historical information on similar wells, state data from other related systems, such as drill fluid and BHA, and real time cuttings analysis. These intelligent control systems may learn from the rig history, nearby wells, and the current well, to adapt the

control strategy. Adjustments to the equipment from the driller, acting as automation system supervisor, may be monitored for effect and used as input for the learning system.

2. **High capability Sensors** (Year 2025): The physics of the down-hole environment and the challenges of getting data to the surface will not change. However, lower cost sensors and more robust communication, or networking strategies, can be developed; Micro-Electro-Mechanical Systems, or MEMS, is a prime example currently being adopted by the petroleum drilling industry. As the cost of these embedded sensors and processors lessens, it will become feasible to deploy these sensors in large quantities close to the input point for the measurement, for example, on the drill bit, each BHA component, and each piece of pipe. Such solutions will enable better and more data about the state of the drilling system to be collected and can be used to control the drilling equipment. The problem of the actuator being remote from the bit will persist, but better data from along the drill string will permit more sophisticated models that will increasingly enhance actuator outputs.

3. **Intelligent Drilling Equipment Down-hole** (Year 2030): In this paradigm, the primary movers of the bit are down hole and have all the control inputs and processing onboard to not only make machine-level inputs, such as torque control at the bit, but also to make higher level decisions, such as trajectory control and communication with other subsystems. In this way, only high-level command and control needs to be managed from the surface. Although power generation systems that could be adopted downhole are advancing, getting energy down hole will remain a challenge because it is unlikely that energy needs or sources will change significantly. What will change is drilling equipment that will act much more autonomously deep in the earth, where it can be most efficient and effective.

4. **Surface to Downhole to Surface Data Transmission** (Year 2025): A spectrum of telemetry systems that offer low data rate at low costs and low drilling time impact, through to those that offer high data rate at higher cost with some impact on drilling time, or tripping durations, will be developed and implemented. Drill string telemetry systems will become a highly competitive product and service. Some systems will remain proprietary in transmission while others will become open channels using common protocols, enabling any information to pass in either direction. Some systems will offer surface-to-BHA power down capability designed to offset the need for using batteries or a turbine generator downhole. Downhole power systems will compete through advances in generation and storage capacities.

The market will bifurcate into one sector of higher well cost impact, high data rate systems in uncertain drilling environments in which wellbore data drives real-time decision making, and another sector of low well cost impact, low data rate higher latency systems able to reliably communicate sufficient amounts of information on the status of downhole systems and to verify models used to operate drilling parameters. A tug of war will continue between each end of the spectrum of data rate, capacity, and latency capabilities in drill string telemetry and will remain unsettled in a highly competitive environment that has no firm end point by 2025. Ultimately, commoditization of hard wire, low latency high data rate systems that have limited impact on connection time (tripping speeds) will gain the advantage. It is possible that beyond 2025, the industry will adopt a modified business model that shares financial rewards with the suppliers by allowing users to pay for transmission capability used. Such a concept could drive wired pipe to become ubiquitous.

Iteration of Downhole Brain and DP telemetry System.

Because the two systems—downhole computation and to-surface data transmission—are intertwined, higher capabilities in one offset the need for higher capabilities in the other. It is a 'chicken-and-egg' dilemma of which came first. This will be the ongoing dichotomy as DSA advances.

In this roadmap, both technologies are envisaged to advance for different operations that require different transmission demands with different economic viability. Realistically, the development in one path—downhole computation—will directly impact the development in the other path—data rate-to-surface computation. The upside of real-time input of downhole date to surface drilling machinery, as well as the value of along-string measurements, will also have an impact on the balance of telemetry capability and downhole computation. Tracking this interdependency will be critical to maintaining the validity of the DSA Roadmap. High data rate telemetry systems will be needed only when downhole decision-making intelligence is lacking and when controls remain on surface. In the future (2030), downhole technology of high tier companies operating autonomously downhole will send up synthetic information informing the surface of actions being taken, rather than streaming raw data to the surface for decisions to be confirmed and handed back downhole for corrections. Low- to mid-speed telemetry will suffice for this high tier downhole intelligence, which ensures that existing drillstring and rig infrastructure is capable of meeting downhole drilling requirements. This is because the solution to the latency problem is eliminate it by assigning the controls to the downhole system.

In the future, every routine operation performed in the drilling, completion, and well intervention processes will be highly automated and human input will be moved to a supervisory level. This will be a rapidly advancing transformation from today's environment of manual and mechanized industrial processes and equipment supported by islands of advanced control and automation. This transformation will be technically based in large measure on accepted practices and technologies available in other industries and on standards already developed by the International Society of Automation (www.isa.org), IEEE, the OPC Foundation (OPC.org), and others.

Remote operation and autonomy is not an objective per se of this evolution, but will be an outcome based on economic and performance drivers, including safety considerations, as people are removed from "harm's way" and proven algorithms are applied in system reactions to sensor signals that might otherwise be missed or delayed through human control. However, remote operations combined with autonomy can and should be a driver in extreme environments, such as the Arctic, regions of social or political volatility, difficult to access locations, and planetary drilling.

Non-deterministic drilling systems will autonomously "get out of trouble" as events happen during drilling; the autonomy will be the driving force with human supervision intervening when appropriate.

This human interaction will require a center of excellence capable of fast, low latency intervention. In practice, automation and human interaction will coalesce to the point at which the respect and control for each is defined in a hierarchy that includes expertise, knowledge, and latency. This concept is developed in this report under Systems Architecture, Human Systems Integration (HSI) and Levels of Automation Taxonomy (LOAT).

The coalescence of advanced embedded sensors that is driving automation technologies from industrial applications, the advanced research released from military applications, and human systems integration and human factors engineering, will unleash a massive advance in highly automated drilling and completions operations.

Future State: Two Ends of the Spectrum of Operations

The dichotomy of drilling operations is important when considering the advancement of DSA. At one end of the spectrum are wells that can be considered as manufacturing processes and at the other end, wells are very specific, highly uncertain projects akin to space flight.

Low cost land-based well manufacturing (highly repetitive wells that could become fully autonomous).

Land drilling rigs, which operate with human supervisory control, offer ample opportunity for automation through:

- Closed mud systems that fully automat mixing and treatment
- Delivery of pipe and well components into a magazine that loads them into the rig for running into the well
- Drilling systems that continuously learn and share information with other drilling machines in the same basin
- Remote operating centers that monitor operations and equipment health and dispatches technicians when required
- Robots that perform some rig site activities, such as maintenance and repair
- Rig designs that are driven by automation through a systems-engineering approach that creates intelligent iron.

Prototypes of highly automated drilling machines will evolve by 2020 and in the USA will achieve market penetration of 20%. These are wells in which the geology and well-bore pressure regimes and thus permeability are well known, which allows the industry to mechanize the process and to automate the mechanization without complex adaptive technology required in other applications. This is akin to the automation of an industrial process, which we know from other industries can become autonomous.

- Sensors: Sensors will be more accurate and of higher frequency and quality owing to rigorous calibration and maintenance, upgrade improvements in measurement location, and additional sensors. Independent verification and validation of sensors and systems will be a recommended practice (RP) implemented fleetwide, ensuring data are within understood tolerances.
- Learning Systems: Repetitive environments and drilling systems, including humans, will adapt and learn from prior knowledge (prior wells). In the near term (Year 2020) significant opportunity exists to optimize performance in real time and autonomously from data collected from similar wells.
- Predictive models: In addition to geological models for well manufacturing, statistical (probabilistic) models that leverage historical data can be in incorporated.
- In-process control: Sensors and electro-mechanical systems can be developed to automate low-level and mundane drilling tasks. The driller can then focus on higher-value decisions that operate at longer time cycles.
- Autonomous drilling: Longer term (Year 2025), demonstrated capabilities will usher in fully automated drilling with only human oversight of the operation.

Through automation, the rig site will transform the driller's cabin and the service company rig site operations centers into a combined control room remote from the drilling floor. Regional and remote "centers-of-excellence" will enable subject matter experts to intervene in the drilling operation via the control room and its authorization hierarchy. The control center will control operation at wellsite and, compared with those of today, wellsite manning levels will be reduced. Experts will be highly distributed and connected to the control center remotely and on-demand to intervene when needed.

At the wellsite, the rig will be highly automated and the downhole steering and drilling mechanics systems highly autonomous with low-speed, high latency bi-directional data links resulting in surface supervisory control only. Much of the real-time monitoring in the control center will be "condition" monitoring for deviations from plan.

Fleet-based optimization of the drilling process will increase efficiencies beyond the single well to manage the whole reservoir potential through fully automated and predictable drilling systems. These systems will access prime subsurface locations within the dynamic subsurface model through highly automated processes employing Artificial Intelligence under human supervisory control. This steering into a continuously updated subsurface model will yield a significant increase in potential well production.

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Based on such desired business outcomes as cost reduction, quality of wellbore, placement for completion design and others, applied data analytics will adjust the drilling process in real time. The enterprise objectives will become truly linked to the drilling operations at equipment and process activity levels.

High cost, adaptive, deepwater offshore applications.

In deepwater, offshore operations will integrate intelligent downhole tools with surface automated systems and predictive technologies. Remote operations and excellence centers will reduce personnel onboard and automated systems, monitored and controlled from an offshore control room, will combine all the data input and equipment supervisory controls. Eventually, autonomous drilling operations will be routinely updated with a revised subsurface model from the onshore excellence center.

The first wells to be drilled with a comprehensive automation system offshore will not spud until the reliability of the processes and the equipment have been proven on land. The first highly automated well drilling operations will not occur until 2025 and a 10% penetration of the market will take until 2030.

Based on past negative experience with mechanization, an unfortunate assumption persists within the industry that more complex systems are inherently less reliable than simpler ones. To ensure that this is not the case, it will be necessary for the offshore industry to adopt remote monitoring of equipment performance to enable preventative maintenance and to reduce non-productive time.

Reduced dayrates caused by cyclic oil price increases and reductions mean increased automation must deliver competitive advantage through reduced well costs. Typical opportunities to do this include site personnel reductions and improved performance across all repetitious processes. The high cost of offshore drilling operations, including drilling rig dayrates, means that although the potential value from more efficient drilling through automation is relatively greater than for onshore, handing over the drilling of wells to an automated system offshore will not be accepted until the drilling community has gained confidence in automation that is based on its performance on land and adaptive technologies have been developed to “get out of trouble.”

Certain elements to consider in the process of moving automated drilling systems to the offshore arena include:

- While the general modeling techniques are applicable, fewer and more unique operations offshore means data driven principles may be more challenging than on land.

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- Undersea robotic systems will continue to advance and take on larger more autonomous roles. Potentially, the subsea drilling machine may become reality once a high degree of drilling system autonomy has been achieved. A subsea system has numerous advantages over a floating drilling system in deep water, including a firm platform and less hydrostatic impact on the wellbore.

- Rig operations improve safety through more intelligent sensing and interaction between machine and operator.

During deepwater operations, control will be at the wellsite and will be monitored from onshore centers of excellence, again with distributed experts remotely connected to the data center and intervening when needed.

In 2022, certain, selected activities at the wellsite will be heavily automated, including:

- Downhole systems
- Surface rig systems, in particular rig processes such as continuous tripping and fast connections
- Managed pressure drilling systems
- Monitoring and control.

Technology will be still in silos, but data will be shared at the wellsite using more open communications systems. New companies (or new company offerings) will be launched to take advantage of the rich information "spring" at the wellsite and rig floor robotics will make inroads to remove workers from the "red zones."

In 2025, activities will be coordinated across company lines rather than remaining in silos but control will remain at the wellsite with a highly interactive monitoring service through the onsite control center.

Potentially, the future for offshore exploration wells is an intelligent drilling system that enables drillers to think strategically and ahead of time based upon available information. Completely interoperable hardware, software, and services will enable the industry to choose the best solutions without having to waste time on integration of technologies. Real-time process diagnostics will feed back into the process, creating neural networks that constantly improve the process.

In 2025, wellbore placement will be done automatically. Initialization of the drilling machine will be done through integration with well planning and digitized drilling program systems and the rig's drilling control system will run all equipment. The driller will monitor the well and equipment status and will focus on risk identification and mitigation. His "normal state" tool for interaction with the drilling process will be through modifying the digitized drilling plan.

Subsurface Model Integration

As drilling systems automation application advances, the drilling process will become tied more closely to the subsurface prognosis and real-time model. Eventually, the subsurface model becomes a driver of the human and automation drilling decision-making to realize greater well value. This close coupling of the downhole earth model with drilling operations will require that data management issues be addressed and overcome. In some instances, sophisticated subsurface model drilling automaton may revert to more manual control in areas where the subsurface data have highly competitive value and therefore are treated as highly confidential information, which would require disabling of closed loop systems. Only an operator, who will be the integrator and prime controller in this automated domain, can manage this.

Invisible Lost Time – the Value Generator

Drilling systems automation must deliver value to the end user, who is typically an operator.

The two key elements of lost time in drilling operations include:

- Non-Productive Time (NPT), which is the reported time spent on activities that were unplanned and unnecessary in drilling the same well. This includes lost time from problems and down time from equipment failure.
- Invisible Lost Time (ILT), which is time lost due to inefficiency while drilling a well that is typically reported as Productive Time (PT) and therefore remains "invisible" in the record. [7]

Automation has the potential to positively influence both NPT and ILT (Figure 15). In terms of NPT, automation can provide controls on operating envelopes that will avoid problems. For example, controls on pump ramp ups, trip accelerations, and traverse rates can reduce the risk of borehole damage. In terms of ILT, multiple opportunities from automated stand building off line to best practices being programmed into the automation, avoids reliance on humans who may or may not have been informed or understand best practices.

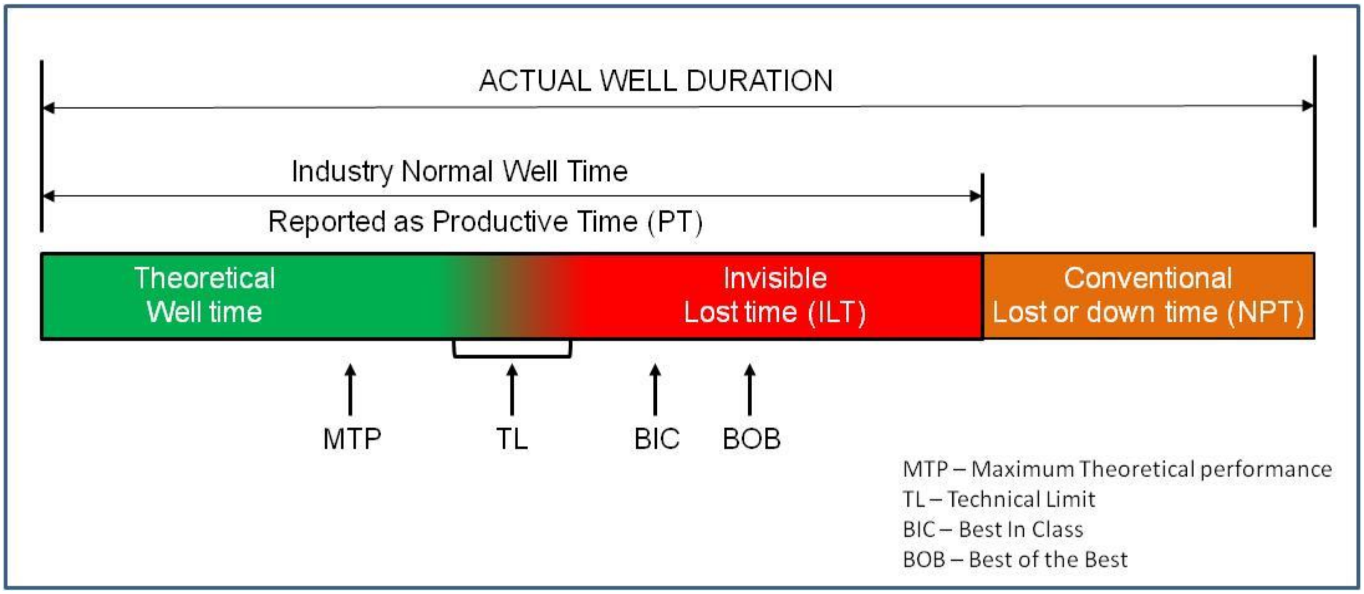

Figure 15: Diagram of NPT & ILT [6]

The future of automated operations is a world in which:

- A digitized detailed activity schedule in a hierarchical breakdown structure defines and implements the planned activities, their sequence, parallel activities, and preparation activities.
- The sub surface model is actively updated in real time, transmitting data that continuously update the initial, or projected, lithological column; this update drives the automated drilling parameters through revised digitized drilling program and operations sequences.
- The critical parameter of depth of the borehole and the bit is known automatically by all systems; time stamps of data and information accurately corresponds across sensors and systems.
- Borehole state–well path, shape, condition—is known continuously throughout the length of the borehole from a combination of measurements and real time updated models.

Current / Future State Transition

The transition from current to future state, reaching towards the DSA vision, is a significant step for an industry that shies away from all-encompassing change and is mired in a financially challenging environment that inhibits activity levels.

However, the low oil-price environment of the 1980s and 1990s is recognized as a period of innovation within the technology segments of the industry. Drilling systems automation is different because to deliver value, the application requires a systems or total approach for ultimate success. Simply enhancing technology in segments (sub systems) will not gain the total advantage. The current challenging oil price environment is again an opportunity for innovation and can lead to a significant benefit in drilling operations results but also remains a challenge to a successful application on the total interoperable systems approach necessary for full DSA.

The oil and gas drilling industry is made complex by the challenges and uncertainties it faces during operations and by the construct of the relationships of the many companies that must be brought together to execute a drilling program. The ability to change this industry does not rely on one entity nor is it driven by value proposition logic without a huge communication effort.

The challenges faced in implementing systems that will beneficially impact drilling operations through the application of automation are significant. These challenges require a script that the industry can review and can adopt to map the transitions toward the goal. Currently, it appears that the investors in DSA, such as the OEM's and drilling contractors, are not the ones receiving the financial benefit. The business relationships treat the investment as a price of entry into a contract and as competitive advantage required to maintain the contract. Current contracts do not typically include payments that necessarily reward investors for DSA innovation and application.

There are multiple possible paths forward to cross from current to future state with two ends of this spectrum:

- The 'Integrator' who has control over every aspect of a drilling project from planning through operations may be through:
    - A single supplier who owns or controls all the equipment and systems, resolving interface issues under a single manager
    - An operator who believes the value proposition and contracts all the parties on a collaborative arrangement.
    - The 'collaborative' approach of various selected suppliers who rely on multiple companies working together with open systems and full interoperability of data and automation commands.

The integrator has the advantage of designing the total interoperable system using their own protocols, communication and interrelationships. Under typical contracting roles, the operator is best positioned to be the integrator. Under integrated project management (IPM) or turnkey contracts, the lead contractor—drilling contractor or service company—is well-positioned to take the integrator role. The IPM integrator gains an advantage from owning or controlling all the data, operations, and technologies required to manifest a complete automated drilling system.

The collaborative approach is a direct reflection of how operators (oil companies) hire services and purchase equipment. However, it requires a manifestation of interoperability between participants, who may be competitors; this level of interoperability commonly does not exist in oil and gas drilling operations because of the very nature of the business construct.

Competition in the oil and gas drilling industry has been built on differentiating at an equipment or sub-sub system level and rarely is achieved at a total operating system level. Recognition of end user—operator/oil company—value is growing regardless of the contractual relationships, which will positively impact uptake of systems incorporating automation that improve value delivery.

Integrator Path

A limited number of companies are willing to take the integrator path. Initially these companies were operators, such as Shell and Apache, with their bespoke programs. These companies developed and demonstrated automation methodologies that were focused on drilling rock—ROP, adding pipe, etc.—and both Apache and Shell focused on repeated wells.

Apache released their technology patents to Canyon Oak drilling, who planned to deliver significantly automated performance to the USA land drilling business, which to date, has not happened.

Shell developed SCADADrill, which is focused on repetitive operations and driven by automation experts from mid-stream and downstream process flow environments. This effort changed course when the oil prices dropped and Shell found itself focusing more on a one-off well than multiple repetitive wells. This has redirected their drilling automation efforts.

In 2016, Schlumberger entered this path with the launch of its 'Rig of the Future™.' This effort is initially focused on land drilling of repetitive wells. Schlumberger set up a JV with Bauer Deep Drilling to access their rig and purchased Omron Drilling and Marine Controls and TT

Engineering. In addition, Schlumberger acquired Cameron and with it a suite of drilling rig designs and drilling equipment. Schlumberger initially based their Rig of the Future automation on their subsurface computing suite Petrel with the intention of applying automation more broadly than drilling the well. Subsequently, the company has developed Delphi, an overarching cloud-based environment for collaboration on all types of data.

Some land drilling contractors in the US have added directional drilling and surveying (Magnetic MWD) to their services with remote operations support. Furthermore, they have added software systems to enable automated drilling, rock the drill string for steering with a bent motor, and provide surveillance of numerous rigs, well equipment and operations. The automation of these drilling sub systems by drilling contractors and service companies is progressing rapidly.

Although it requires significant sums of money from one entity, many issues are resolved by the integrator path, such as data ownership, interoperability, and control input to machinery.

There appear to be three classes of integrator:

- The single supplier (JV or other relationship) that owns or controls all the equipment and systems required to develop an automated drilling solution.
- The operator that believes in the DSA value proposition.
- The drilling contractor that expands its offering with key drilling services and advanced software systems.

The ability of each of these classes to bridge the gap between current state and future state will determine the ranking of automated drilling system providers in the future.

After investments have been made in the portfolio of requisite technologies, the single supplier has a clear advantage. Schlumberger stands as the current leader with its portfolio of companies and current field launch of its Rig of the Future. Its rig designs demonstrate that Schlumberger's solutions include parallel path—offline or flat time—automated technology. Furthermore, the company is integrating its drilling automation with its shared earth model software platform.

Similar large suppliers that have managed turnkey or lump sum drilling projects are likely to follow Schlumberger as they see value delivery that can be rewarded in the fixed well price environment. On the service company side, Halliburton, BHGE, and Weatherford fall in this class. On the drilling contractor side, the US land drillers, who have changed their viewpoint from backlog of contract days to declaring cycle time performance on wells as a competitive advantage, are using advances in control systems on VFD and adding services to their portfolio.

Nabors, for example, is positioning itself to take advantage of this value proposition by advancing control systems on a range of drilling equipment technologies. Likewise, H&P is aggressively building a portfolio of automated processes onto its Flexrig 'platform'. Precision drilling has adopted the NOV Novos system, which it often uses with wired dp.

The IPM business model for delivering wells offers single suppliers the greatest opportunity for return on investment; day rate contracts may transition to more pay for performance and value.

Operators have an advantage as prime contractors. But because they do not own much of the technology, they will require interoperability as developed in the collaborative path. Another operator strength is ownership of the subsurface model that they can link to automated drilling operations; their weakness is that they are not equipment designers and therefore lack the expertise to develop parallel path automated technology solutions that are required to deliver total value on a well.

On the financial side, operators desire lower cost wells as an outcome from advanced automated technologies. However, their investments are driven more toward production of hydrocarbons and not the construction of wells, which has typically been significantly outsourced.

Currently, Shell appears to be the leader in operators' drilling systems automation. Equinor, formely Statoil, is pursuing the application of automation, often incorporating technologies from Norwegian research. Recently it has taken a decision to equip many of its drilling rigs with wired drillpipe. Total has embarked on an aggressive strategy to adopt DSA. BP communicates their commitment to DSA and are pursuing a major project in Oman with Deutag and Schlumberger.

Drilling contractors with expanded service offerings will advance the application of control to their equipment and add software systems. However, they too will require very large financial investments to complete their portfolio and data and control interoperability. Some drilling contractors are designing technology improvements, such as pipe racking in stands offline, that can be automated with value benefits.

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Patterson has recently acquired Warrior, who designed and trademarked the Zipper Rig, a continuous running rig whose name is taken from a carnival ride. Raptor rig is a start up by established drilling technology experts that has designed a land based, highly automated continuous tripping rig. The lack of access to an earth model system will hinder drilling contractors' ability to maximize the fast delivery of a quality wellbore in the right place but their prowess in rig design can maximize the benefits from parallel activities.

Collaborative Path

The collaborative path is the alternate to the integrator path. The collaborative path relies on multiple companies working together to combine their automated equipment, machines, communication and control technologies to drill a well. This is the traditional method by which drilling rigs and services have been contracted. The key to success with this approach is the ability of the industry to create interoperability though defining standards and protocols for connectivity and control. An initiative has been launched under SPE DSATS to generate protocols for interoperability. The first step in this initiative is an industry workshop to establish a collective view of the gap between current state and future state for interoperability.

Every industry participant, except perhaps the single supplier, needs interoperability to deliver a successful drilling automation solution as quickly as possible. Unfortunately, the rampant focus on building walls in the drilling and drilling service industry, in the perceived interest of competitive advantage, has inhibited the rate at which interoperability is delivered. Recently, the common shift in focus to delivering fast wells in North America has generated some degree of collaboration. An unstructured transformation to partial interoperability appears to be underway.

Multiple industry groups, inside and outside the oil and gas industry, will continue to develop the tools and standards for interoperability; the challenge will be to communicate to the industry the overall advantages of interoperability versus wall building. Thereafter the industry must share a plan for industry organizations, such as Energistics, to provide the collaboration platforms for new and updated interoperability methods.

Initially, interoperability will be supported by the technologists and resisted by the managers and sales people. As and when a single supplier distinguishes itself with a solution, the managers and sales personnel will rapidly turn to interoperability to remain competitive.

Integrator versus Collaborator

Rio Tinto's development of its Mine of the Future™ (the obvious similarity to Schlumberger's Rig of the Future is not a mere name adoption but more a "lessons learned approach) created a major advancement of automation in open pit mining. The application was very successful in a short period of time. However, the OEMs that developed solutions also built vertically integrated walls. A Komatsu autonomous truck cannot drive on the same road as a Caterpillar autonomous truck, for example, because each OEM delivered its own communications solutions.

John Berra, Chairman Emeritus of Emerson, has spoken once to an SPE DSATS event and once to a DSA Roadmap event organized by IADC. In both cases he gave an eloquent description of the value to the industry of standards collaboration, particularly communication. Essentially, Berra described how the 'pie becomes larger' for all participants in a collaborative future rather than a competitive future. He demonstrated this by showing how Emerson revenue grew by taking an open communications approach and other established companies that did not contracted and became dinosaurs.

The automotive industry is advancing toward autonomous vehicles with its own developments and with developments from outside its traditional players. They have established an industry organization, Autosar, to develop standards that advance interoperable and reusable technology in automotive products. This organization clearly distinguishes between "collaborate on standards" and "compete on innovation." This is a high value lesson for the upstream oil and gas drilling industry to articulate needs that are collaborative standards and areas in which innovation creates competitive advantage. Such a solution will increase value for all as the industry drives well costs lower and enables greater hydrocarbon production. Altruistically, this may result in competition between hydrocarbon resources on a geographic as well as on a prospect (investment cost) perspective.

Shift to Drilling Performance

USA land drillers, especially shale and unconventional resource drillers, have significantly improved drilling performance as a means of reducing well costs despite increased daily costs from additional and more advanced technology and as a means to deliver earlier production. These 'drillers' have differentiated themselves from the rest of the world to the extent that USA land drillers are achieving overall ROPs that are 3-to-4 times that of European land drillers.

In one instance, a land operator in the USA with tight gas wells that have been drilled in an 'S' shape to 15,000 feet, reduced the well drilling duration from 70 to 8.5 days. This performance was achieved with the latest VFD rigs, modern wellbore steering technology, and some manual operations. The opportunity for automation to deliver value in such operations is challenging.

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Mile-a-day (MAD) wells are now appearing as service providers ramp up automation of data acquisition from MWD tools, assessment, and decision making. Directional drillers are being elevated to supervisory control, often remote from the wellsite. Open hole penetration rates from the vertical, through the build, into the horizontal have achieved rates of 6,000 ft/d.[8]

In North America, some proponents of drilling systems automation have noted that the significant reduction in active drilling rigs has produced a high-grading of drillers; drillers currently operating these rigs are consistently high performers. Consequently, the gap between average performance and best performance has diminished. Performance benefits derived from drilling system automation through both performance capability and consistency across rigs leave little opportunity for improvement through the application of automation. Automation application will need to realize additional value from improved well bores in terms of quality, position in the reservoir and other similar factors.

Reduced well costs and quicker production delivery as a result of improved drilling performance is fast becoming a competitive advantage in hydrocarbon production. The ability of automated drilling systems to offset reduced performance in the lower performing regions of the world through transfer of programmed knowledge from high performing regions will become extremely attractive. This is because ADS can overcome a lack of competitive advantage, which may lead to increased hydrocarbon production.

Super drillers—operators, contractors, and suppliers—in the USA will continue to dominate the scene of drilling performance. They will adopt subsystems of drilling systems automation where it adds value, which they will measure in progressive increments. Some key subsystems will be applied to redesigned drilling equipment that moves critical path activities to non-critical path activities, thus reducing well drilling cycle time without adding to rig crew size. Non-super drillers will buy drilling systems automation to gain performance advantages they have not managed to create through their own organizational or procedural improvements.

The global lack of drilling performance is a huge opportunity to translate the experiences of the super drillers in the USA land drilling to global operations in the form of algorithms, and to bypass massive efforts of cultural change and performance training. This progression will require interoperability between companies supplying services to avoid delays that will slow progression.

At very high drilling rates, distinctions between fields and regions do indeed include the impacts of geology in many facets, such as formation hardness, fractures and drilling fluid losses, and tectonic stresses acting on borehole stability. These impacts will drive the ultimate performance attainment through the translation of DSA from high performing regions to other regions. Regardless, the positive impact of suites of automation applications tailored to local environments will enable more consistent and faster drilling.

Drilling Contractor Contraction

The increased efficiency in drilling wells in the USA and further advances from technology design, combined with automation, will result in fewer rigs required to deliver sufficient oil and gas production to meet market needs. Figure 16, below, indicates that the number of drilling rigs required in the USA with advanced performance in drilling unconventional oil will drop to that required for drilling unconventional gas. This means that there will be far less than the 2,000 rigs drilling in 2014. The rig activity level has already developed a plateau at some 1,000 operating rigs per day. This contraction will create significant pressure on the drilling contractor business and result in fewer companies operating. The resulting rigs will be high-graded on performance to deliver wells fast, which will be driven by a combination of technology and crew competence. As time progresses, the ability to reduce operating costs by replacing humans with automation which will result in fewer personnel per rig and more consistent and more reliable high-performance levels.

Winning drilling contractors will:

- Deliver quality wells faster at lower cost
- Transition to more automated systems that deliver value in a consistent manner
- Use automation with supervisory control to reduce crew and associated operating costs.

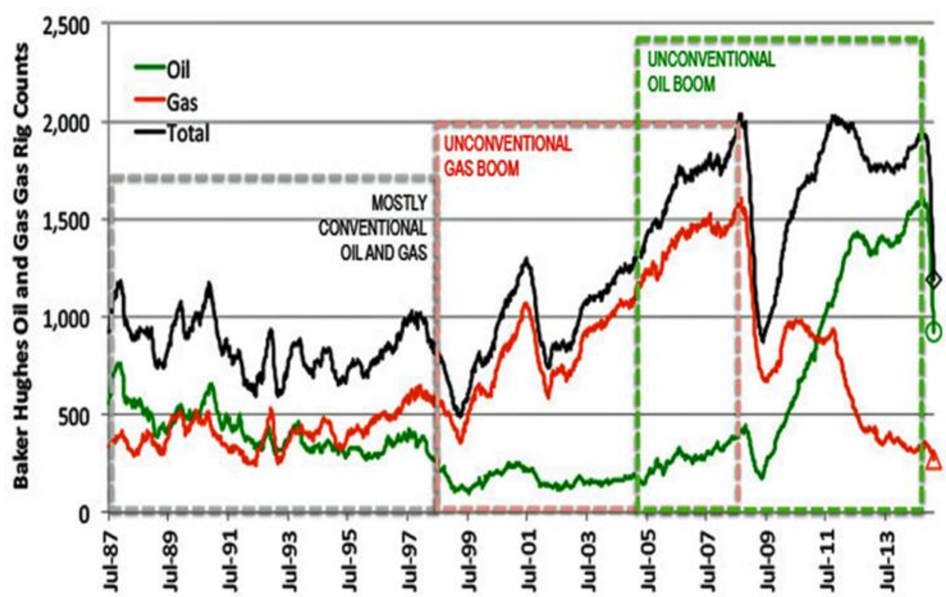

Figure 16: Nat Gas and Oil rig counts. Source Gary Flaharty: Managing Partner for SCLinx

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In 2015, the oil rig count in the US fell off a cliff, reminiscent of the 2008 gas rig count fall after the shale gas boom. This plot shows an almost exact profile-trend match, providing insight to the future oil rig count based on the past gas rig count.

Extremely efficient drilling for unconventional gas in the USA, combined with major improvements in well design and production capability of gas wells, has created a new world in which fewer rigs deliver the required quantities to sustain gas market demand. In addition, significant volumes of natural gas produced as a byproduct from oil wells feed natural gas into the system as oil production rises. Consequently, the gas rig count need not be increased to achieve a balance between natural gas demand and natural gas supply.

The US land oil drillers have become recognized as the marginal producers in world oil production, taking that role away from Saudi Arabia. This is creating a new world order in which US land drillers can drive the global oil price.

The stark reality is that, globally, inefficient drillers will not continue to operate because their costs and delays will be too high for hydrocarbon field development. The differential is not a few percentage points of efficiency; Europe land, for example, trails US land by some 75% in terms of overall spud-to-TD well times. And except for a short uptick of 40% from 1999 to 2005, when the application of Lean Drilling™ was in full swing in the region, the North Sea has consistently declined in drilling performance over the past 20 years.

Today, land-based US drilling contractors present their drilling records to investors, rather than days on contract. These new super performances achieved by operators and drilling contracts offer both a barrier and an opportunity for DSA. The barrier is that any further increase in performance realized by DSA can only be incremental, which offers limited upside. The opportunity is that these high performers are looking for the next step to improve both drilling times and well quality which may be a DSA application.

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