Institution: King's College London

Unit of Assessment: Computer Science and Informatics (UoA 11)

Title of case study: AI planning research enables Schlumberger to achieve long-term goal of drilling automation

Period when the underpinning research was undertaken: 2011-2016

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Derek Long	Professor	Long: 2011-2016 (20%FTE since 2016); Fox: 2011-2018; Coles, Amanda: 2011-present; Coles, Andrew: 2011-present; Magazzeni: 2011-present
Maria Fox	Professor	
Amanda Coles	Doctor	
Andrew Coles	Doctor	
Daniele Magazzeni	Doctor	

Period when the claimed impact occurred: 2015-2020

Is this case study continued from a case study submitted in 2014? No

1. Summary of the impact (indicative maximum 100 words)

Automated plan construction and execution, developed by King's researchers, has enabled Schlumberger, a Fortune 500 Oil & Gas (O&G) Services Company, to deploy automated drilling capabilities, a technology that no other company is yet capable of providing. This has brought the company improvements in efficiency, consistency and safety, along with a competitive edge. Deployment started in 2016 and was by early 2020 in use on more than 28 rigs in the Permian Basin and elsewhere, including offshore, representing a value estimated in excess of USD150,000,000 per annum (through improved efficiency and consistency).

King's research in automated planning and plan-execution has enabled Schlumberger to fulfil a longstanding ambition in the O&G industry to increase drilling automation, applicable to geothermal and exploration wells. King's work on the AI planner has become the core of Schlumberger's automation products and services - in the short term the company has plans to rollout the approach across the organisation, and ultimately aims to make this the industry standard for drilling automation.

2. Underpinning research (indicative maximum 500 words)

A planner is a system that takes a declarative *domain* model description, describing what actions are available, and a *problem* description, capturing an initial state and a goal condition. From these it generates a proposed course of action to transform the initial state into a state satisfying the goal, using the actions supplied. The planner itself is domain agnostic – it exploits the underlying nature of causal relations between actions to build plans with whatever domain it is supplied. The advantage this offers is that it is comparatively easy to deploy the planner to produce plans for widely ranging and very different domains.

Fox and Long have, for many years, specialised in **temporal planning** – the branch of planning that focuses on plans with temporal structure, including continuous change, concurrency and multiple coordinated agents [R3, R5, R6]. In their work since joining King's in 2011, they devoted considerable effort to the problems of harnessing **the generation of plans for the automation of controlled systems**, interpreting plans as control instructions and managing the mediation between sensed signals and expected state [R1, R2, R4]. This work was conducted in the EU-funded PANDORA project [F4] on underwater vehicles (for inspection and maintenance of sea-bed structures), in the EU-funded SQUIRREL project [F5] on small indoor robot platforms (for tidying rooms and interacting with children in various games) and in the EPSRC-funded project on Future Power Networks [F3] (controlling distribution-level networks to ensure voltage levels and consistent supply). Research funded in these projects, the EPSRC AIS programme [F1, F2] and also the ASUR programme [F6] have all been vital to the success of this work, providing multiple contexts in which to explore the problems of **linking planning and execution and the process of responding to plan failure with replanning**.

Further research conducted at King's that has proven valuable is linking a planner to an external solver. The benefits of a generic planner rest in the idea that a user need only focus on representing the actions of their domain in order to make use of the planner. A price for this is that the domain representation language is not tailored to any particular domain and some specialist structures in a domain might be difficult to model. Fox and Long have found **an effective way to connect an external solver to a planner**, in which the complex dynamics are captured in the external (specialised) solver and accessed by the planner through a simplified query interface [R3]. This makes it possible for the planner to build plans that manipulate complex structures, while relying on the external solver to manage the details of the state changes that the plan anticipates in those structures.

Fox and Long proposed the use of temporal planning to provide strategic control for automated drilling systems, relying on both automated planning and also the algorithms for **interpretation of plans** as instructions **for execution by physical hardware** [e.g. R1, R2, R4]. Plans are produced using a planner based on the COLIN/POPF [R6] planners built by Fox, Long, Coles and Coles. The planner relies on models written in PDDL2.1, a temporal modelling language developed by Fox and Long in 2003. In projects at King's, Fox and Long developed the means to link plans to execution, including an architecture for execution of plans using the Robotic Operating System (ROS), ROSPlan [R4]. This work was originally developed for use in underwater vehicles [R1, R2], but subsequently more broadly. The work has been proved influential in the robotics community, but also informed the development of a **plan execution language and dispatcher for Schlumberger** in 2013, **leading to the patent applications** [PAT1, PAT2]. This work rests on extracting the temporal plan structure developed in the planner, to express in an executable and flexible form. In particular, it facilitates the identification of errors during execution, to trigger an appropriate response – replanning or shutdown, depending on the situation. The important technical elements of this work were in identifying the semantics of the dispatch process for the plans expressed in this language, providing a precise formal foundation and specification for the implementation of plan dispatchers in multiple applications within Schlumberger.

This case study is closely related to that submitted by University of Strathclyde: the fundamental planning research was conducted by Fox and Long at Strathclyde, before joining King's, where the key contributions on plan execution, planning with continuous processes and on linking external solvers were carried out.

3. References to the research (indicative maximum of six references)

[R1] Cashmore, M, **Fox, M**, **Long, D**, **Magazzeni, D** & Ridder, B 2017, 'Opportunistic Planning in Autonomous Underwater Missions', IEEE TRANSACTIONS ON AUTOMATION SCIENCE AND ENGINEERING, vol. 15, no. 2, 17685429, pp. 519 - 530. https://doi.org/10.1109/TASE.2016.2636662

[R2] Palomeras, N, Carrera, A, Hurtós, N, Karras, GC, Bechlioulis, CP, Cashmore, M, **Magazzeni, D**, **Long, D**, **Fox, M**, Kyriakopoulos, KJ, Kormushev, P, Salvi, J & Carreras, M 2015, 'Toward persistent autonomous intervention in a subsea panel', Autonomous Robots, pp. 1-28. https://doi.org/10.1007/s10514-015-9511-7

[R3] Piacentini, C, Alimisis, V, **Fox, M** & **Long, D** 2015, 'An extension of metric temporal planning with application to AC voltage control', ARTIFICIAL INTELLIGENCE, vol. 229, pp. 210-245. https://doi.org/10.1016/j.artint.2015.08.010

[R4] Cashmore, M, **Fox, M**, **Long, D**, **Magazzeni, D**, Ridder, B, Carrera, A, Palomeras, N, Hurtós, N & Carreras, M 2015, Rosplan: Planning in the robot operating system. in Proceedings International Conference on Automated Planning and Scheduling, ICAPS. vol. 2015-January, AAAI Press, pp. 333-341, 25th International Conference on Automated Planning and Scheduling, ICAPS 2015, Jerusalem, Israel, 7/06/2015. http://www.aaai.org/ocs/index.php/ICAPS/ICAPS15/paper/view/10619

[R5] Bajada, J, **Fox, M** & **Long, D** 2015, Temporal planning with semantic attachment of non-linear monotonic continuous behaviours. in IJCAI International Joint Conference on Artificial Intelligence. vol. 2015-January, International Joint Conferences on Artificial Intelligence, pp.

1523-1529, 24th International Joint Conference on Artificial Intelligence, IJCAI 2015, Buenos Aires, Argentina, 25/07/2015.http://ijcai.org/papers15/Papers/IJCAI15-218.pdf

[R6] Coles, A, **Coles, A**, **Fox, M** & **Long, D** 2012, 'COLIN: Planning with Continuous Linear Numeric Change', Journal Artificial Intelligence Research, vol. 44, pp. 1-96. https://doi.org/10.1613/jair.3608

Funding:
[F1] EP/J012211/1 Sustained Autonomy through Coupled Plan-based Control and World Modelling with Uncertainty (2012-2015, £237K) [EPSRC AIS Program]

[F2] EP/J012157/1 Automated Plan-Based Policy-Learning for Surveillance Problems (2012-2016, £371K) [EPSRC AIS Program]

[F3] EP/I031650/1 The Autonomic Power System (2011-2016, GBP160,142 to King's) [EPSRC]

[F4] EUFP7: PANDORA (Grant ID: 288273)

[F5] EUFP7: SQUIRREL (Grant ID: 610532)

[F6] ASUR (Autonomous Systems Underpinning Research), DSTL-led consortium funding: Phase A project supported by BAE Systems.

Patents:
[PAT1] Creating and executing a well construction/operation plan (US Patent App. 15/541,381, 2018)

[PAT2] Method of Creating and Executing a Plan (US Patent App. 15/536,693, 2017)

4. Details of the impact (indicative maximum 750 words)

Background

Schlumberger is the world's leading provider of technology and digital solutions for reservoir characterization, drilling, production, and processing to the energy industry, with product sales and services in more than 120 countries and employing approximately 82,000 people in 2020.

Schlumberger's global R&D activities related to drilling and cementing operations, which represent nearly a third of the overall company, generated a revenue of USD10,000,000,000 in 2019. The portfolio for this covers a wide range of technologies such as drill bits, directional drilling tools, formation evaluation while drilling tools, drilling fluids, pressure control equipment, and rig control systems. An integral part of this business is the services that Schlumberger provides to the wider industry where their technologies are deployed by highly trained field engineers and technicians. However, this model has become extremely challenging to sustain - the company considers that the key initiative for their future success and differentiation is to move their services up through levels of automation. [S1]

Involvement in the 2011-2016 industry-EPSRC Autonomous Intelligent Systems program [F1,F2] led to then Head of Schlumberger Research in Well Construction Automation meeting Professors Maria Fox and Derek Long, and discovering automated planning. Schlumberger's Vice President for Technology Development (Well Construction) observes [S1]:

> *"Schlumberger Cambridge Research has always been at the forefront of innovation. Automation has been an area of research for us for many years. The real step change in our approach to automate highly dynamic and uncertain drilling process started when we engaged Derek and Maria first as consultants and eventually as full-time employees."*

Fox and Long joined Schlumberger, in 2016, to bring onboard their research knowledge and complete the deployment of plan-based automation in the **DrillOps** software, a commercial implementation of an automated drilling function.

Product development, testing, and initial rollout

The initial phase of this process involved product development, testing and initial deployments for field testing. The second phase, of larger scale commercial rollout, began in late 2019 and early 2020, but has been disrupted by COVID-19. Nevertheless, DrillOps has already been deployed on 28 rigs in North America, Saudi Arabia, Italy and also off-shore. As part of the

second phase, all Schlumberger's different businesses have started to deploy the relevant parts of DrillOps.

What this means so far *"is that, [the] directional drilling service in the US is now deployed through a system called Connect BHA, a DrillOps product, while […] trajectory planning and optimization in the US is done using DrillPlan. They will be expanded to other countries in 2021 as [Schlumberger] builds the in-country cloud infrastructure. Additionally, [Schlumberger] has globally* ***deployed [DrillOps] automation in 28 drilling rigs with plans to increase to over 100 rigs*** *that operates in our integrated business".* [S1]

Initial benefits derived from Plan-Based Automation

Schlumberger's Science and Technology Manager (Automation and Planning) explains [S2]:

> *"The work has provided wide reaching business impact, […] through the DrillOps autonomous drilling service, which is not incremental but marks a fundamental shift in the way we approach automation both within our own operations and in solutions we are developing with major oil and gas operators (for example with Exxon Mobil as announced in Q2 2020). Automation, through plan execution enabled by the work of Fox and Long,* ***creates consistency of operations, which drives safety, reduces time-to-target, and the minimization of environmental footprint.****"*

In their 2020 Q3 financial report [S4], Schlumberger reports:

> *"In Saudi Arabia, […] DrillOps* automation well delivery solutions surpassed 63,000 ft drilled, achieving a key milestone for our Integrated Well Construction LSTK operations. The on-bottom rate of penetration (ROP) with AutoROP was 17% higher than previous wells drilled by the same rigs' field average. Furthermore, DrillOps controlled the preconnection, reaming, and backreaming operations, significantly reducing nonproductive time, optimized well delivery time, and contributed to a 30% improvement in on-bottom ROP and shoe-to-shoe run in a recent section of a horizontal well."*

This highlights the incentives, both to Schlumberger and its clients, of the automated drilling function, in terms of improved efficiency, consistency and reliability. In Q1 2019, the typical well in the Permian took 27 days (an industry-wide average, not indicative of typical Schlumberger performance) and costs USD595/foot drilled [S6, figure 2]. A typical well is 6,000 to 7,000 feet and costs at least USD4,000,000 [S6]. With a 17% improvement in on-bottom ROP, as shown in the Saudi Arabia example above [S4] (although more recent figures in reference to Schlumberger's DrillOps solutions suggests about 20%-30% improvements in efficiency [S7]), each well would save at least USD500,000 (a low estimate).

Assuming that drilling a typical well takes 27 days, a rig would typically drill about 12 wells per year. As evidenced previously, the automated system has been in use on selected client rigs since 2016 and is now deployed on 28 commercial rigs. Based on these numbers it is possible to estimate that the automation system, built around the planner and plan-execution components, **is currently worth at least USD150,000,000 per annum in savings** (USD500,000/well savings x 28 rigs x 12 wells/rig/year) to Schlumberger.

A key part of the Schlumberger's long-term strategy

As the industry recovers from the COVID-19 crisis, Schlumberger has positioned itself to move quickly with its new technology to offer efficient, consistent, and cost-effective drilling automation, in order to maximise benefits for its clients and shareholders. As part of the company's long-term strategy and its commitment to the technology, Schlumberger's Science and Technology Manager (Automation and Planning) observes [S2]:

> *"The approach to AI planning has subsequently been investigated in other aspects of Schlumberger's services business. In particular the automation of measurement operations (known as Wireline) and well-site service delivery,* ***we expect to embed the approach across the organisation as part of the digital transformation*** *to further realise the benefits."*

Additionally, Schlumberger's Vice President for Technology Development (Well Construction) states [S1]:

*"[The] **goal with this product is to make it available to the wider industry and become the industry standard for drilling automation.** A good example of this is the recent agreement that [Schlumberger] signed with Honghua where every new rig that Honghua build will have the DrillOps system built in it."*

The importance of this work to Schlumberger is also highlighted in the 2020 Q2 financial report to shareholders [S3] in which it is observed:

"As announced last quarter, Schlumberger and ExxonMobil are jointly working on the deployment of digital drilling solutions around planning, execution, and continuous improvement through learning. As a next step, ExxonMobil and Schlumberger have finalized an enabling agreement for the deployment of DrillOps on-target well delivery solution in ExxonMobil's unconventional operations. The technology is expected to enable faster, lower-cost wells through drilling automation".*

The Q2 financial report goes on to say:

"Schlumberger and Honghua Electric Co., Ltd. entered into a memorandum of understanding (MOU) for the seamless integration of the DrillOps on-target well delivery solution with all new Honghua rigs. Under the MOU, Honghua will manufacture and sell rigs that have plug-and-play capability with the DrillOps solution, which integrates planning and operations while automating well construction tasks in order for the rig to operate at peak performance throughout the execution of the drilling plan."

As the globally leading well services company (reporting revenues of over USD32,000,000,000 in 2019), Schlumberger has consistently been part of investment portfolios for a wide range of pension funds and other large institutional shareholders, so its public financial statements are widely analysed and thus a key indicator of the direction it is heading strategically.

The future of Drilling Automation

To conclude, it is worth quoting Schlumberger's Digital Strategy Development Manager in her article about DrillOps and drilling automation [S3]:

*"**Digital and automation technologies present the best opportunity for the drilling industry to innovate its way out of the current crisis.** However, seizing the opportunity will require preparation, collaboration, participation and commitment to transform the way wells are drilled, to move away from working in isolation to working together to capitalize on each other's strengths. Doing so will not only help the industry to survive this downturn but to thrive in the future. When it comes to automation, all players have a key role to play, including operators, service companies and equipment manufacturers; however, rig contractors, as the owners and operators of the rig, are at the center of it all."*

5. Sources to corroborate the impact (indicative maximum of 10 references)

[S1] Testimonial from Vice President for Technology Development (Well Construction), Schlumberger Cambridge Research, Schlumberger

[S2] Testimonial from Science and Technology Manager (Automation and Planning) Schlumberger Cambridge Research, Schlumberger

[S3] Schlumberger Q2 2020 Press Release, July 2020

[S4] Schlumberger Q3 2020 Press Release, October 2020

[S5] Drilling Contractor (Official Magazine of International Association of Drilling Contractors): "Digital drilling system aims to close gap between well plan, rig workflow", Sept 2020

[S6] Oil&Gas Journal: "Permian basin operators cut drilling time, lower expense", July 2019

[S7] World Oil Magazine: "Beyond automation: Driving advances in autonomous drilling", January 2021