Autonomous Systems

Opportunities and Challenges for the Oil and Gas Industry

Norwegian Society of Automatic Control

Foreword

This document has been developed by a group of experts in autonomy and industrial IT. The group named “NFA Autonomy Working Group” consisting of representatives from Statoil, FMC Technologies, Computas, SINTEF and Alfatroll has worked with the document from August to December 2012 in order to define and explore the role of autonomy in the oil & gas industry.

In 2008 NFA – Norwegian Society of Automatic Control started a yearly conference with the purpose to see how experience with autonomous systems in space exploration could be utilized in the oil & gas industry. At the 2012 conference it was decided to establish a group that should work to define autonomy and find out more about the need for and utilization of autonomous systems.

Autonomous Systems are playing increasingly important roles in hazardous or challenging environments and areas where human lives may be exposed to greater risk. Examples include submarine vehicles conducting deep sea exploration and maintenance in oil & gas facilities, remote systems conducting maintenance and repair in nuclear contaminated areas, and lunar and space exploration. Autonomous and remote systems have also traditionally been used in situations where great precision and accurate repetition is important, such as manufacturing and assembly, and more recently, increasingly in surgery for the treatment of tumors, invasive brain and cardiac surgery. However in this report we are concentrating on autonomy in the oil & gas industry.

The oil & gas sector must increasingly develop and operate existing and new fields more efficiently and safer, both over long distances and in increasingly more extreme and sensitive areas (very deep waters and the Northern Regions). Autonomy and automatic control throughout the full value chain is a key to make this possible. The aim of the NFA Autonomy conference is to bring together oil & gas companies, the authorities, technology providers, and the research community to define the need for and availability of autonomous systems today, and into the future.

The purpose of this white paper is to facilitate discussion and interaction between the various actors, and to serve as a reference they can refer to when taking concrete initiatives in development and research of autonomous systems. The document shall represent a baseline for such understanding that the industry and academia can stand behind and use it as a reference. NFA - Norwegian Society of Automatic Control has been the administrator of the development of the document.

NFA is an ideal and politically independent organization established in 1958. NFA is NMO (National Member Organization) for Norway in IFAC – International Federation of Automatic Control, and is also Norway´s most important, largest and oldest society within automatic control. NFA works with networking, development of competence and increased competitiveness for the Norwegian industry. It is with great privilege we have accepted to coordinate and administrate the work of this document.

Lars Annfinn Ekornsæter

Managing Director – NFA

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Purpose and target audience

This white paper addresses a promising opportunity for the oil & gas industry: *Autonomous systems* as an emerging new system category, providing solutions for many challenges facing the industry today.

The target audience for the paper includes oil & gas operator companies, vendor industry, research organizations, regulating authorities and political leaders. Its purpose is to provide basic insight into the business opportunities and challenges that come with autonomous systems and how this new system category impacts industry.

The paper is not overly technical in nature, but provides pointers to further information to those interested in more detail.

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Executive Summary

The oil & gas industry is stretching the limits of what can be achieved with current technology. Future resources have to be explored under increasingly severe constraints, for instance in deep waters and harsh Arctic environments. In such cases human risk can be too high, or humans are unable or not cost effective as decision makers, calling for remotely controlled operations, unmanned facilities and in extreme cases the ability for systems to operate for extended periods without human supervision.

Autonomous systems represent an emerging new system category that can provide solutions needed to meet the challenges faced by the industry. Other industries are already utilizing autonomy in order to execute tasks that cannot be performed by humans alone. Efforts have mainly been driven by aerospace and military applications, such as deep space robots, unmanned aircraft and vehicles, and smart monitoring systems. The authors of this paper believe there are several challenges in the oil & gas industry that can be solved with similar solutions to those mentioned.

We define autonomy as the ability of a system to achieve operational goals in complex domains by making decisions and executing actions on behalf of or in cooperation with humans. Autonomous systems result from developments in control theory (technical cybernetics), artificial intelligence, mathematical modeling, and software engineering during the last decades. A brief history of autonomy in other industries is included in an attachment to this paper.

In the paper, we explore challenges faced by selected areas of oil & gas operations and how autonomy can be applied to improve performance and safety:

- Well construction and drilling
- Production optimization
- Operations and maintenance
- Subsea production and processing
- Environmental monitoring

Autonomy is relevant when human risk is too high or when humans are unfit or not cost-effective as decision makers.

Potential benefits of autonomy in oil & gas operations include:

- New areas: Enables exploration of previously inaccessible areas
- Reduced cost: Less need of costly human supervision, increased up-time
- Reduced risk: Reduced human exposure to danger, rapid detection & containment
- Optimal operations: Increased situational awareness and improved decision quality
- New operational concepts: Autonomy in integrated operations, cooperating robot teams

In the closing chapter we set our eyes 10-15 years into the future and imagine a scenario for how a subsea facility can be operated and maintained by autonomous systems and underwater vehicles working in close cooperation with human decision makers.

Autonomy as such is not a primary goal. It is the beneficial effects that are worth looking into. With these, a number of new challenges arise. These include, if not properly handled, overreliance on new technology, immature system engineering methodologies, human and organizational consequences, and lack of widely accepted industry standards for safety critical applications of autonomy.

Autonomous systems ultimately answer to human users, even if the users are not directly concerned with the system's daily operations. It is crucial that those persons trust the system and are willing to delegate tasks to it. Such trust can only be gained gradually by safe, predictable and beneficial operation demonstrated over time. We therefore recommend a careful and step-wise introduction of autonomous systems in oil & gas operations.

What is Autonomy?

Computerized sensing, monitoring and control of physical processes and systems have allowed an increasing level of automation of operations; computers are trusted with tasks previously carried out by humans, and also tasks beyond human capacity such as keeping a ship in fixed position or allowing unstable airplanes to fly safely.

Autonomy goes beyond automation by adding self-governing behavior, requiring "intelligent" decision making abilities. In practice, autonomy comes in degrees depending on the role of the ultimate human decision maker vs. the computer.

Autonomy represents the most advanced stage of this trend by automating both *decision making* tasks, i.e. deciding on how to meet operational goals such as improved performance or accident prevention, and *action execution*, i.e. realizing the decisions through safe and efficient intervention with the physical world. Both decision making and action execution are especially challenging in complex domains with unreliable and complex data, unpredictable events, and many possibly conflicting decision alternatives. We define *autonomy* as follows:

> ***Autonomy is the ability of a system to achieve operational goals in complex domains by making decisions and executing actions on behalf of or in cooperation with humans***

While the idea of autonomous machines is centuries old, it was only from the 1950ies that autonomy became a scientific research topic, in particular in the AI (Artificial Intelligence) field. Together with control theory (cybernetics) and robotics, AI provides the theoretical tools underlying current implementations, e.g. goal-driven agents, automated reasoning, planning, and machine learning.

Today, autonomy appears in many areas, including space exploration, military drones and robots, self-driving cars and "lights-out" factories. We also find early implementations in the oil & gas industry, some of which are mentioned later in this paper.

Autonomy and Automation

"Automation" and "autonomy" are expressions often used interchangeably, and it is not easy (or perhaps even possible) to draw a clear line between the two. Instead of focusing on how to distinguish between the two, we will look at the characteristics of automation and autonomous systems, and how they complement each other, as well as how humans can cooperate with autonomous systems in achieving operational goals. Table 1 shows some examples of automation and autonomous systems.

Table 1: Examples of automation and autonomous systems

Automation systems	(Semi-)autonomous systems
Robotized car assembly, ABS (anti-lock brake systems), fighter jet stabilization systems, Dynamic Positioning (DP) for marine vessels, sensor-based collision avoidance for robot manipulators.	Mars Rover "Curiosity"[1], Unmanned Arial Vehicles (UAV), Autonomous Underwater Vehicles (AUV)[2], Autonomous cars[3]

Automation systems typically incorporate a pre-programmed link between sensor input (e.g. a vision system that detects the position and shape of an automotive part on a conveyer belt) and system output (e.g., a robots uses a look-up table in order to determine a correct grasp for the automotive

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[1] The NASA Mars rover "Curiosity": http://www.nasa.gov/mission_pages/msl/index.html

[2] The "HUGIN" AUV from Kongsberg Maritime: http://www.km.kongsberg.com/ks/web/nokbg0240.nsf/AllWeb/B3F87A63D8E419E5C1256A68004E946C?OpenDocument

[3] http://spectrum.ieee.org/automaton/robotics/artificial-intelligence/how-google-self-driving-car-works

part located by the vision system). System models can also be incorporated in order to provide a more "intelligent" pre-programmed link between system input and output (e.g., model predictive control – MPC[4]). Due to this pre-programmed link, an automation system will only to a limited degree be able to handle unforeseen situations.

A fully *autonomous system* is able to handle unforeseen situations and perform high-level problem solving without human intervention. Autonomous systems often require automated functions in order to be realized: E.g., a robot manipulator system can learn how to pick up an object that it has not encountered before by making use of automated functions such as vision-based object detection and sensor-based collision avoidance. The robot can then through methods for robot learning[5] learn how to safely grasp and pick up the previously unknown object. An autonomous system includes one or more of the following capabilities:

- *Learning*: Improvement through practice, experience, or by teaching[6]
- *Reasoning*: Generate conclusions from available knowledge[7]
- *Planning*: Construct a sequence of actions to achieve a goal
- *Decision making*: Select a course of action among several alternative scenarios[8] – includes a notion of expected action outcome[9].
- *Situation awareness*: "Knowing and understanding what is going on"[10].
- *Actuation*: The ability to physically interact with its environment
- *Human-machine interfaces*: How the autonomous systems interact with humans

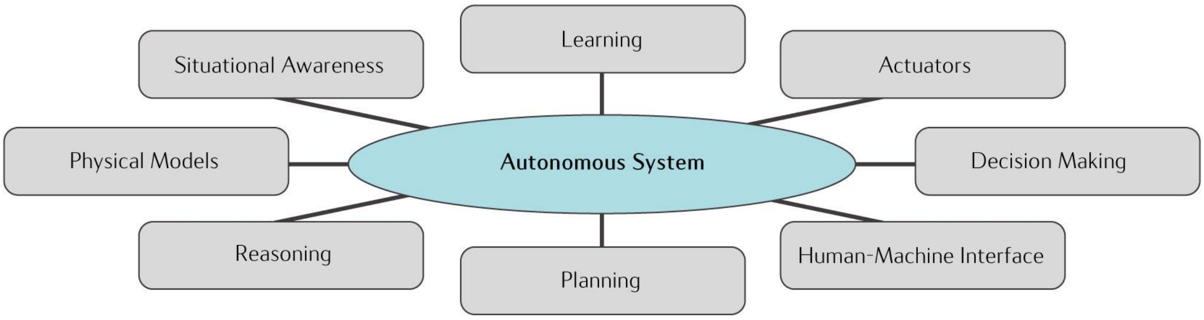

Figure 1 Components of an autonomous system

Autonomy can be divided into different levels depending on how "advanced" the autonomous system is and how (e.g., to what degree) the system cooperates with humans. Table 2 shows how an autonomous system can range from offering "low-level" assistance in decision-making to "high-level" autonomous decision-making and action execution without human intervention.

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[4] C.E. García, D.M. Prett, M. Morari (1989), "Model Predictive Control: Theory and practice—A survey", Automatica, vol 25, Issue 3, pp. 335–348

[5] Sutton, R.S. and Barto, A.G. (1998). "Reinforcement Learning: An Introduction. The MIT Press, London, England

[6] EUROP, Appendix to: Robotics Visions to 2020 and beyond – The Strategic Research Agenda for Robotics in Europe, 08/2009, www.robotics-platform.eu, 7 July 2009

[7] Wikipedia, Reasoning system, http://en.wikipedia.org/wiki/Reasoning_system

[8] Wikipedia, Decision making, http://en.wikipedia.org/wiki/Decision_making (

[9] R. Parasuraman, T.B. Sheridan, C.D. Wickens, A model for types of levels of human interaction with automation, IEEE Trans. on Systems, Man and Cybernetics – Part A, Vol. 30, No. 3, pp. 286–297, May 2000

[10] M.R. Endsley, Toward a theory in situation awareness in dynamic systems, Human Factors, Vol 37, pp. 65–84, 1995

Table 2: Levels of autonomy (from the US Navy Office of Naval Research[11])

Level	Name	Description
1	Human Operated	**All activity within the system is the direct result of human-initiated control inputs**. The system has no autonomous control of its environment, although it may have information-only responses to sensed data.
2	Human Assisted	**The system can perform activity in parallel with human input**, acting to augment the ability of the human to perform the desired activity, but has no ability to act without accompanying human input. An example is automobile automatic transmission and anti-skid brakes.
3	Human Delegated	**The system can perform limited control activity on a delegated basis**. This level encompasses automatic flight controls, engine controls, and other low-level automation that must be activated or deactivated by a human input and act in mutual exclusion with human operation.
4	Human Supervised	**The system can perform a wide variety of activities given top-level permissions or direction by a human**. The system provides sufficient insight into its internal operations and behaviors that it can be understood by its human supervisor and appropriately redirected. The system does not have the capability to self-initiate behaviors that are not within the scope of its current directed task.
5	Mixed Initiative	**Both the human and the system can initiate behaviors based on sensed data.** The system can coordinate its behavior with the human behaviors both explicitly and implicitly. The human can understand behaviors of the system in the same way that he understands his own behaviors. A variety of means are provided to regulate the authority of the system w.r.t. human operations.
6	Fully Autonomous	**The system requires no human intervention to perform any of its designated activities** across all planned ranges of environmental conditions.

Traditional control systems are found at autonomy levels two and three[12]. As an example, the landing sequence performed by NASA´s latest Mars rover Opportunity was at autonomy level 3. The rover was delegated the responsibility to perform a safe (as possible) landing at a precisely given location. The human operator had no influence on the outcome after initiating the landing sequence. Examples from the oil and gas industry include emergency disconnect and barrier control systems used during interventions and drilling safeguard functions.

The definitions in Table 2 can be used to communicate the ambition level for autonomy in a system. They can also be helpful in setting requirements to the design process, the degree of reliability and availability of the autonomous system, and to a minimum level of required testing.

Oil & Gas Business Drivers

The oil & gas industry is facing an increasingly demanding business environment characterized by higher focus on profitability and cost effectiveness, more demanding safety requirements, and a public demand for a reduced environmental footprint from operations. This is particularly valid for the

On the NCS, the “easily” recoverable resources have been produced. The remaining resources are more challenging and require further technology development. Autonomous systems represent one of the strategic enabling technologies.

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[11] http://www.stfc.ac.uk/resources/pdf/richardwilliams.pdf

[12] In a composite system, the component with the lowest level of autonomy dictates the overall system's level of autonomy

Norwegian Continental Shelf (NCS, incl. arctic areas), as formulated by the OG21 Task force[13] established by the Norwegian government:

> On the NCS, the “easily” recoverable resources have been produced. The remaining resources are more challenging and require further technology development. … The activity moves into new areas with new challenges i.e. deeper water, arctic conditions and developments that are closer to the coast and much further away from infrastructure. These challenges require further emphasis on R&D. … Focus is on the strategic technology themes for adding reserves and maximizing production, achieving cleaner and more energy efficient production and maximizing value creation through exporting technology.

Figure 2 illustrates the resource situation, in particular how current technology leaves valuable resources in the fields when they are abandoned. Low cost autonomous systems could be the means to extract more of the remaining resources.

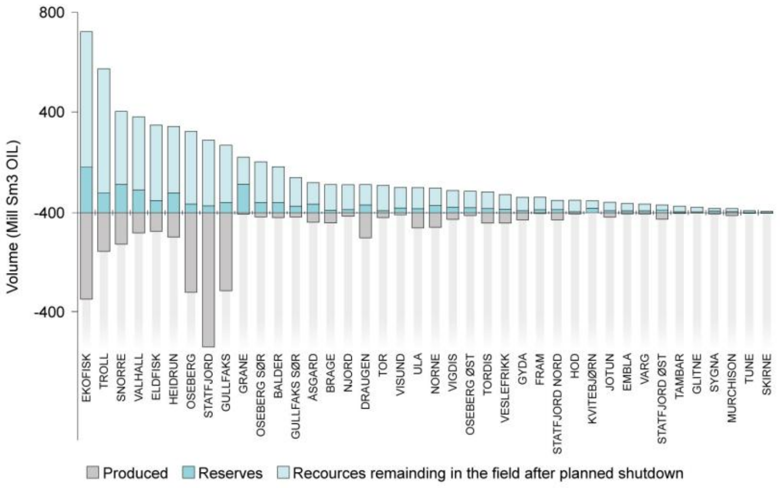

Figure 2 Status of oil extraction on the Norwegian shelf

As an example of how these business drivers translate into strategy, Statoil included in its Corporate Technology Strategy[14]:

- **Well construction and intervention**: More time- and cost efficient drilling and well construction to allow more fit for purpose wells to be drilled, increasing production and recovery rates
- **Subsea production and processing systems**: Half of current and most new fields involve subsea development, and the ambition is to realize subsea gas compression by 2015 and have the required elements for a subsea factory ready by 2020

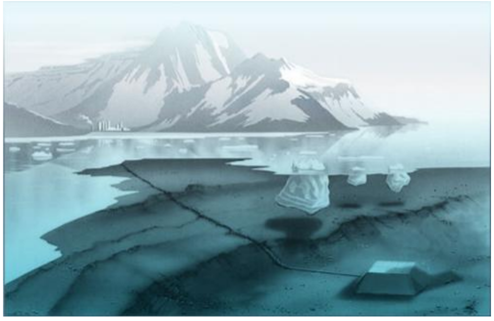

Figure 3 Sub-ice subsea installation

We believe that autonomous systems are one of the enabling technologies required to meet such strategic ambitions.

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[13] OG21 – Oil and Gas in the 21st Century: Norway’s Technology Strategy, http://www.og21.org/

[14] http://www.statoil.com/en/TechnologyInnovation/TechnologyManagement/Pages/teknologistrategi.aspx

Opportunities and Challenges

Autonomy becomes relevant when human risk is too high or humans are unfit or not cost-effective decision makers. Such situations are typically characterized by the need to collect and assess data and make decisions in fractions of a second or dealing with latency imposed by distance. In these situations autonomous technology enables humans to set overall goals and delegate operational decision-making and execution of decisions to autonomous systems.

In the sections below we explore how autonomy impacts selected areas of the oil & gas value chain:

- Well construction and intervention
- Production optimization
- Operations and maintenance
- Subsea production and processing
- Environmental monitoring

We will cast light on business challenges and how autonomous systems can meet these challenges.

Well Construction and Intervention

Well construction represents approximately 60% of a field´s development cost. Add to this that efficient production of wells is a key factor to improved resource recovery. Hold this against an industrial reality characterized by limited delivery of new wells due to low well construction capacity and efficiency[15]. It is not uncommon to experience Non Productive Time (NPT) of 20% or more. In addition, the operations are dangerous and safety is a key concern. Wrong or ill-timed decisions may have disastrous consequences, as shown by the DeepWater Horizon accident.

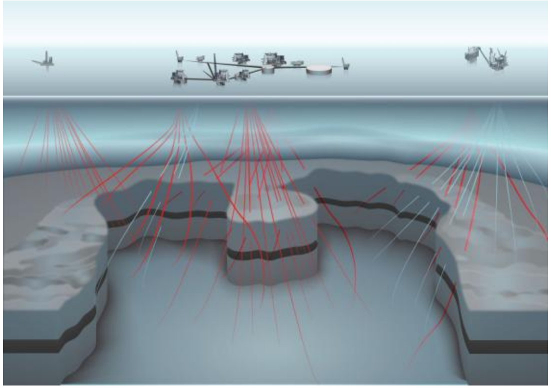

Figure 4 Large multi-well oil field

Improved well construction efficiency and safety depends on:

- Improved situational awareness and understanding of the down-hole conditions. Enhanced capabilities to detect and diagnose undesired events and situations before they escalate to more severe problems such as well collapse and unmanaged well kicks.
- Improved equipment condition awareness enabling detection of equipment weaknesses and faults before the equipment breaks and creates undesired situations.

Improved situational awareness related to well conditions and equipment status requires:

- Adaptive physical well and equipment state models
- Equipment and well condition sensors
- Reasoning and diagnostics related to well and equipment state
- Safety barriers to prevent and contain undesirable events
- Improved decision models for different types of drilling problems
- Intuitive man-machine interfaces
- Changed work processes that take the increased automation level into account

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[15] A. Berg, IRIS, *Drilling and Well*, Petromaks 10 Year Conference, Oslo, Oct. 2012

It is a major undertaking to develop and deploy autonomous systems for well construction support systems at autonomy level 2 to 5, but some of the components are starting to emerge. Physical models are now commercially available, and various sensors are deployed to collect well and equipment data in real-time. The hard part of the job is to transform all the available data into valuable information (diagnoses and advices) that the human operators will trust. This will require use of probabilistic analysis and reasoning technologies.

A number of benefits will likely accrue from an increased autonomy level[16]:

- Improved safety (fewer people in harm's way, reduced number of wrong decisions)
- Improved efficiency (e.g., optimized drilling speed, better operational problem solving)
- Reduced well cost (fewer people required on the rig, less downtime and rework)
- Improved recovery factors (more and better wells, more wells for the same cost)

Some of these benefits were demonstrated by AutoConRig[17], an "automated driller" that controls a complete drill string tripping sequence. One use case involves an emergency situation where a remotely controlled operation has to shut down in a safe manner when communication is lost. The implemented system detects the breakdown, initiates the fail-safe tripping sequence, monitors and corrects the sequence, and is able to dynamically modify its plan if unexpected events intervene. Principles developed in the project found their way into the commercial sphere[18].

Production Optimization

Production optimization is a large area that spans from reservoir drainage strategies to the daily or even hourly trimming of networks of producer and injector wells and utilization of separator trains and storage capacity.

Autonomous systems can improve daily production monitoring and optimization tasks. Benefits include more optimal production where dysfunctional wells and faulty equipment are tended to in a proactive manner.

Challenging production parameters include:

- Implementation of the reservoir's drainage strategy
- Active well control to meet production targets
- Mitigation of equipment failures and unexpected reservoir characteristics

Autonomous system capabilities can play a key role in daily production monitoring and optimization tasks. This includes monitoring of equipment state and liquid flow rates. The offered opportunities from such capabilities are more optimal production where dysfunctional wells and faulty equipment is tended to in a more proactive manner, in line with relevant SOPs (Standard Operation Procedures).

Implementation of such systems depends on updated models of equipment and processes, automated control functions, fault detection and advisory functions. An early example is the iWD[19] (intelligent Watch Dog) application developed by Statoil in collaboration with AOS Group Ltd[20]. iWD is a monitoring and decision support system that is tracking the process state and upon detection of a problem event, iWD will alert human operators with a problem diagnosis and recommended actions in line with the relevant standard operational procedure.

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[16] OG21, ibid. – *TTA3: Cost effective drilling and intervention*

[17] R. Fjellheim, *A Multi-Agent Demonstrator for Autonomous Control of a Drilling Rig*, NFA Autonomy in IO, Stvgr., Feb. 2010

[18] National Oilwell Varco, http://www.nov.com/novos/

[19] http://aosgrp.com/products/iwd-intelligent-watchdog/#.ULU3pKWhDzI

[20] http://aosgrp.com/

For those interested to learn more about the potential of autonomy in production systems we recommend reading the paper *Improving Production by use of Autonomous Systems*[21].

Operations and Maintenance

More and more sophisticated machinery is deployed subsea, calling for strict processes to assess and maintain the technical integrity of equipment used for production, processing and transportation. Inspection, maintenance and repair activities represent the biggest contributors to the overall operational expenditures of an oil & gas field.

In the future low-level equipment monitoring, planning and repair actions will be handled by autonomous systems. Improvements include equipment up-time and longevity, non-stop operations and production, and improved HSE.

As failures may cause significant loss of production, it is important to identify failure modes and failure causes, as well as to define appropriate repair plans. The corrective actions may often be quite complex and considerable time is spent on trouble shooting and generation of notifications for subsequent repair work. Today's systems to support operations and maintenance depend heavily upon human operators and manual analysis and decision tasks. OG21 has identified the following areas for improvement[22]:

- Development of seamless integration of data from various systems
- Enhanced use of prediction models, for example to predict development in degradation
- Development of decision support systems/procedures to achieve “resilient integrity”
- Development of integrity visualization tools
- Establishment of a risk based approach to maintenance management

Many of the improvements suggested by OG21 can be efficiently deployed through the use of autonomous technology enabling:

- Continuous analysis and explanation of incoming data (e.g. diagnosis)
- Model-based prediction of probable failures and remaining equipment life time
- Planning and optimization of inspection, maintenance and repair activities
- Activity monitoring and if necessary activity re-planning/re-scheduling

An example of integrity management moving in this direction is the system proposed by GE[23] (Figure 5). It monitors a number of equipment sensors, streaming data to rule-based event filters and a diagnostic reasoning engine. Maintenance plans need to be updated and optimized according to factors such as transport capacity, travel time and to which degree production is affected.

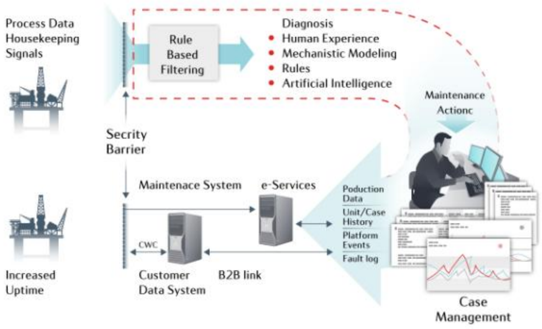

Figure 5 Condition based maintenance

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[21] J. Ølmheim, E. Landre, E. Quale, http://www.onepetro.org/mslib/servlet/onepetropreview?id=SPE-112078-MS, SPE Intelligent Energy Conference 2008
[22] OG21, ibid. – *TTA4: Future technologies for production, processing and transportation*
[23] J. Friedemann, GE, *Subsea Condition Monitoring*, NFA Subsea 2011

Subsea Production and Processing[24]

Subsea production and processing is the key to exploiting deep waters and remote locations. Such facilities will turn into autonomous subsea factories able to run unattended for extended periods of time.

Current and future subsea fields face challenges like greater water depths and low pressure and temperature at the wellhead. A promising solution to overcome such challenges is to process the oil on (or below) the seabed prior to transportation to shore or surface facilities. The benefits of subsea processing includes increased flow rate/production, reduced topside constraints, improved hydrate management, better utilization of existing infrastructure, reduced development cost and reduced environmental footprint.

Subsea production and processing facilities enable more optimized production from e.g. smaller fields, and is the key to exploiting deep waters and remote locations. Such facilities must be made from functional modules such as:

- Seawater injection
- Separators of dual or multi phase well flow
- High capacity pumps
- Power distribution
- Gas compression
- Unmanned vehicles for inspection and maintenance
- Environmental monitoring systems

Each of these modules will require considerable more monitoring and control logic than we typically see today in subsea equipment. Some of these functions will be related to the equipment's performance monitoring and control, while other functions will relate to condition and safety control of the equipment. By using autonomous technology to realize these functions a cost-effective subsea communication infrastructure can be achieved.

Steps in this direction have been made in subsea gas compression with the Ormen Lange, Åsgard and Gullfaks subsea compression pilots. The Åsgard gas compression system won the 2012 "Engineering Accomplishment Award"[25], and is widely seen as an important "game changer" on the path to complete *subsea factories.*

In a longer perspective, it is foreseen that subsea production and processing facilities will turn into *autonomous* subsea factories able to run unattended for extended periods of time.

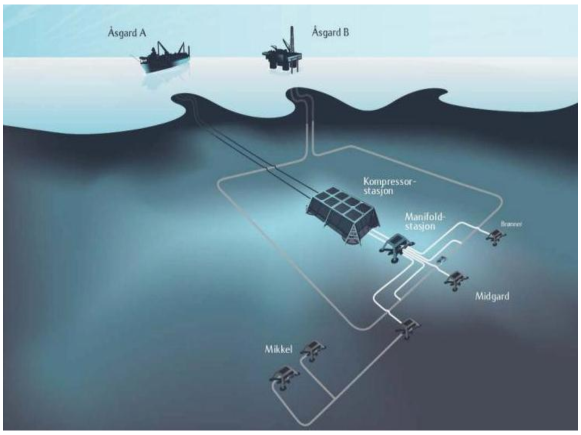

Figure 6 Åsgard subsea gas compression

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[24] This section is based on OG21, ibid. – *TTA4: Future technologies for production, processing and transportation*
[25] http://www.tu.no/olje-gass/2012/12/12/dette-er-arets-ingeniorbragd

Environmental Monitoring

Future systems for environmental monitoring will enable early warning of incidents, risk and impact, and support mitigating actions. Autonomy will result in improved environmental performance, reduced cost, and safer overall operations.

The oil & gas industry faces grave challenges and carries a high responsibility with respect to environment protection. To earn society's acceptance for continued growth and development, it must strive to reduce the environmental risk, improve measures to avoid emission and spills as well as other types of adverse effects, and minimize the damage if incidents occur. These concerns become even more acute as future activities move into new and sensitive areas characterized by deep water, subsea operations, harsh climate, remoteness, seasonal darkness and presence of ice.

To meet those challenges, the industry needs to develop a range of new technologies, including:

- Sensors for e.g. leak detection and environmental and biological phenomena
- Modeling of environmental processes, incl. causal analysis and predictions
- Decision tools integrating expert knowledge, online monitoring systems and site specific data
- Improved and integrated environmental monitoring and management systems

Decision automation and autonomy will play an important role in environmental monitoring:

- Monitoring large geographic areas with many and diverse sensors will require substantial human resources, unless the low-level monitoring and decision making is autonomous.
- For long periods of time, environmental monitoring will be essentially "event free" and not suitable for constant human supervision, again calling for autonomy.
- For safety reasons, distributed sensor networks in harsh environments need robust control and decision systems able to deal with communication failures, physical damage, etc.

The "bottom line" of introducing autonomous systems in this area will be improved environmental performance, reduced cost, and safer overall operations.

An ambitious initiative in this area is the Integrated Environment Monitoring project (IEM) program launched by Statoil[26]. Its purpose is to implement environmental monitoring as an integrated part of normal operations and work processes, not as an isolated side activity. It will allow early warning of potential incidents, verification of predicted risk and impact, and documentation of area of exposure.

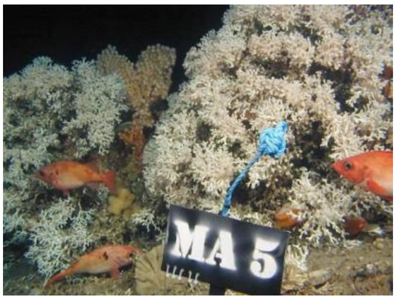

Figure 7 Sensor in sensitive coral reef

Enabling Capabilities

Development and deployment of autonomous systems depends on a wide range of supporting capabilities. Below we pinpoint those that we find most important.

Systems Engineering

Systems engineering understood as a holistic interdisciplinary problem solving methodology is probably one of the most important enablers for successful development and deployment of

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[26] http://www.statoil.com/en/TechnologyInnovation/ProtectingTheEnvironment/EnvironmentalMonitoring

autonomous systems. The rationale behind this claim is that new system concepts based on automated and autonomous functions will require change in operational models, organizational structures and human skills.

Autonomy is relevant when humans are unfit or not cost-effective as decision makers.

On the NCS (Norwegian Continental Shelf), the widely adopted operational model Integrated Operations[27] (IO) captures many of those aspects. There is another connection between IO and autonomy; Decision making. Decision making is at the heart of IO, and autonomy is essentially about improving the efficiency of decision making processes.

Even though it will be beneficial to start to implement autonomy on limited system functionalities it will be crucial for success to have a well-founded understanding of the overall system's design. The system design has to be prepared for the individual autonomous units such that their functions can be utilized in the system's overall functionality. In general it is likely that existing system designs in the oil & gas industry only can implement autonomy to a limited extent before more fundamental changes in the system architecture is required to fully utilize the benefits of autonomy.

Similarly, we recommend a staged process when launching autonomous units in operation, in order to gain experience. A staged implementation process will build trust in the autonomous functions and establish an increased operational and situational awareness. This awareness should include a multi-disciplinary understanding of the organizational and human aspects and how they are affected by an autonomous system.

Finally, since autonomous systems by nature are mission critical or even safety critical, appropriate verification and validation steps need to be performed using formal methods. One such formal methodology and notation is *safety cases*[28]. Safety-cases are developed at the University of York[29]. Based on a system's level of autonomy, as given by Table 2, another methodology is to establish different levels of validation requirements, different levels of stringency to system reliability, etc.

Standards

Existing and proven methodologies and quality standards are applicable for autonomy in oil and gas operations.

Autonomous systems, as a relatively new discipline, have not yet reached a maturity level characterized by mature explicit standards. However, there are several existing standards that are relevant for autonomous systems and some of the most important are:

- **IEEE FIPA initiative**[30] proposes standards “to promote the interoperation of heterogeneous agents and the services that they can represent».
- **W3C**[31], the Web standardization body, is another rich and relevant source of standards also for autonomous systems.
- **OMG DDS[32],** a standard for a real-time Data Distribution Service, published by OMG

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[27] T. Rosendal and V. Hepsø, *Integrated Operations in the Oil and Gas Industry – Sustainability and Capability Development*, Business Science Reference, 2013

[28] Kelly and Weaver, *The Goal Structuring Notation, A Safety argument notation*, http://www-users.cs.york.ac.uk/tpk/dsn2004.pdf

[29] http://www.cs.york.ac.uk/hise/information.php

[30] FIPA – The Foundation for Intelligent Physical Agents, http://www.fipa.org/

[31] W3C – The World Wide Web Consortium, http://www.w3.org/ http://www.w3.org/standards/semanticweb/

[32] OMG – the Object Management Group, http://portals.omg.org/dds/

- **DO-178B**[33] "Software Considerations in Airborne Systems and Equipment Certification"[34] is a good source for learning about how to classify systems with respect to criticality and the effects of different failure situations.
- **Energistics**[35] is a global non-profit organisation created to facilitate and manage open data, information and process standards for the upstream oil and gas industry. Most of these standards are applicable for autonomous systems.
- **IEEE 1220/ISO 26702** Systems Engineering – Application and Management of the systems engineering practice.
- **IEEE 1362** – IEEE Guide for Information Technology – System Definition – Concept of Operation Document is a standard with guidelines for how to describe a system's behaviour from the users' perspective.

Our view is that the oil & gas industry should try to adopt other industries' generic standards for autonomy. As the industry gains experience and competence by applying autonomous systems, guidelines for the use of these standards will emerge. In addition the industry should participate in further development of relevant standards by organizations like IEEE and ISO. This includes development of new oil & gas industry standards that are not easily adopted from other industries.

Technologies for Autonomy

Artificial Intelligence[36] (AI) is arguably the scientific discipline most directly relevant to achieving higher levels of autonomy in oil & gas operations. AI's proclaimed ambition is to create computer systems that rival humans in carrying out tasks we normally associate with intelligence (and autonomy): Reason and deliberate, solve problems, plan and act (including uncertainty handling), perceive and communicate, and learn from experience. Towards this goal, AI has developed rich representations of knowledge and efficient algorithms for applying it, resulting in an "AI Toolbox" of methods that support a wide variety of autonomy functions (see Russel & Norvig, *ibid.* for examples). The methods closely match the required abilities for autonomy as defined in Figure 1.

Table 3: The AI toolbox – Technology to support autonomy

Autonomy function	AI technology
Representation and reasoning	First order logic, description logic, temporal logic, semantic networks, deduction, rule systems, resource bounded reasoning
Problem solving methods	Search space representations, search methods, heuristic search, branch-and-bound, constraint based search, optimization, genetic algorithms
Action planning and execution	Rich plan representations, partial order planning, search-based planning, GRAPHPLAN, propositional methods (SAT), monitoring/re-planning
Diagnosis, analysis and uncertainty	Expert systems, pattern matching, model-based reasoning, non-monotonic reasoning, probabilistic networks, Bayesian reasoning
Learning from examples	Classifier induction, inductive logic learning, reinforcement learning, neural networks, support vector machines
Perceiving and communicating	Speech recognition and generation, speech act theory, computer vision, scene analysis, grasping and motion planning

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[33] http://en.wikipedia.org/wiki/DO-178B

[34] http://en.wikipedia.org/wiki/DO-178B

[35] http://www.energistics.org

[36] S. Russell, P. Norvig, *Artificial Intelligence: A Modern Approach*, Prentice Hall, 2010 (3rd edition)

In parallel to developing intelligent components as described above, AI workers have also explored comprehensive *AI architectures,* where components are put together in complete solutions. The most widely adopted framework is the *intelligent agent*[37] architecture, possessing the following characteristics:

- *Autonomous*: Agents act autonomously by displaying a degree of self-governing behavior. They can sense the state of their environment and act upon it without direct intervention from humans
- *Social*: Agents are aware of other agents and can collaborate with them by means of some agent communication language
- *Reactive*: Agents are sensitive to changes in their environment and act upon these in a timely fashion
- *Pro-active*: Agents can display goal-directed behavior by initiating actions upon their environment without being prompted by external events

Figure 8 shows the main components of a typical agent architecture. Implementation of intelligent agents is supported by commercial platforms designed for the agent paradigm, like JACK[38]. In *multi-agent* systems, a number of interacting single agents communicate as a distributed computing system, allowing more complex behaviors as well as more flexible scaling of the solution.

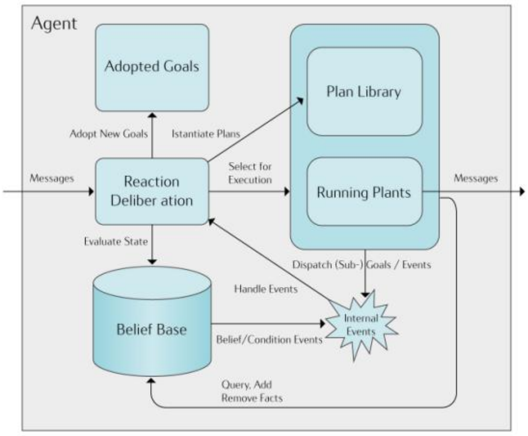

Figure 8 Intelligent agent architecture

Finally, it should be mentioned that while we have focused on full autonomy in this section, actual deployed systems are normally semi-autonomous. They interact with human operators[39], who set goals for the agents and monitor their performance, possibly intervening if required by the situation. Specific methodologies have been developed to support design of (multi-)agent systems[40]

Competence and Research Capabilities

As shown earlier in this white paper, there are close links between the automation and autonomy disciplines. Norway has an internationally recognized capability in automation technology, dating back to forward-looking post World War II initiatives[41]. The cities of Trondheim and Kongsberg have been and are key geographic centers for academic and industrial automation activities, respectively. Subsequently, other universities and research centers have developed complementary skill sets relevant for autonomy. Table 4 attempts to give a brief overview.

Table 4: Overview of Norwegian autonomy capabilities

Competence Center	Competence and Research Capabilities
NTNU Trondheim	Technical cybernetics, incl. AMOS[42] System engineering Artificial intelligence
SINTEF Trondheim and Oslo	Applied cybernetics Offshore robotics and robot learning

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[37] M. Woolridge, *An Introduction to Multi-agent Systems,* John Wiley & Sons, 2002

[38] M. Winikoff, *JACK intelligent agents: An industrial strength platform*, Multi-Agent Programming, Springer, 2005

[39] J. Bradshaw et al, *Coordination in Human-Agent-Robot Teamwork,* IHMC, Florida, 2007

[40] [40] L. Padgham, M. Winikoff, *The Prometheus Methodology,* http://goanna.cs.rmit.edu.au/~linpa/Papers/bookchB.pdf

[41] NFA, *Automatisering for å bygge Norge* (Automation to Build Norway), 50 Year Anniversary Book, 2008

[42] Centre for Autonomous Marine Operations and Systems, http://www.ntnu.no/aktuelt/sff/amos

	Petroleum technology Safety engineering
IFE Halden and Kjeller	Man-Technology-Organization Safety engineering
IRIS Stavanger	Petroleum technology Drilling technology
University of Oslo Oslo	Logic, reasoning and big data Artificial intelligence
University of Stavanger Stavanger	Petroleum technology Decision science

Contractual models

The oil and gas industry is founded on the EPC (Engineering, Procurement and Construction) contract model used in the construction industry. This model is well proven and familiar to all stakeholders in the industry. However, for autonomous systems, software technology and technology development projects in general the traditional EPC contracts are not fully suitable. The challenge is that an EPC contract is based on the foundation that the builder can precisely prescribe desired system behavior. Development of autonomous systems with built-in automated decision making functions cannot easily be fully specified in advance, introducing change and rework as inevitable effects that contract models have to handle.

Therefore, in moving forward with autonomous systems more flexible contractual models are required, namely contractual models that are designed for change handling.

The Way Forward

We believe that strong business drivers and a rapidly maturing technology will lead to a massive adoption of autonomy over the next 10-20 years. The oil & gas industry is positioned to benefit from this development if addressed properly. This will and should not happen accidentally, but rather as a consciously planned process. We will discuss how this can be done below.

Regulations and Public Trust

For autonomy to succeed in the oil & gas industry it is imperative for regulatory authorities to be actively engaged in how the industry best can use the technology. It is not evident that the authorities need to regulate the use of autonomy to the same extent as e.g. the avionic industry, but they should have a leading role in order to safeguard public interests, including sensitive environment and natural resources.

To have the authorities actively involved in regulating the technology use is also assumed to play an important role in building public trust in autonomy. The authorities represent the public interest by ensuring that requirements as seen from a public point of view are enforced, including requirements to maturity of the technology before it is used in critical functions.

The only real way to build public trust, however, is by earning it. This is best done by demonstrating reliable and efficient operations of autonomous systems over time. Only then one can create the confidence in using such systems that is required before responsible bodies can approve its deployment in mission critical applications. One practical approach to earning this trust is to deploy autonomous function as a support for human decision activities to demonstrate its reliability. When reliability and correct functionality has been proven over time as autonomy on level 2 - 3 (see Table 2) the next step could be to evolve into autonomy at level 4 and higher. However, for a conservative industry as the oil & gas industry, correctness of the design and qualification process of autonomy can be just as important for many of the stakeholders as the operational track record.

Roadmap to Autonomy

Autonomous systems will need to progress through several development phases before becoming accepted as a deployable mainstream technology. Below we outline a general approach to these phases, assuming that they are followed for the introduction of mission critical autonomous solutions used to overcome the challenges facing the oil & gas industry.

- **Phase 1: Idea Generation and Screening** (3-6months)
  Identify promising areas for autonomy in oil & gas (as surveyed in this paper), especially in cases where human risk is too high, or humans are unable or not cost effective as decision makers, followed by a critical selection of the best idea(s).
- **Phase 2: Concept Development** (6-12 months)
  Based on assessment of cost vs. benefit and the overall feasibility of an autonomous solution for the selected idea(s), prepare convincing plans and calculations to enable decisions on proceeding to the next phases. This includes a sound business analysis.
- **Phase 3: Prototyping and Beta Testing** (1-2 years)
  Build a prototype of a solution for the challenges selected in the initial phases, including an evaluation of the technologies utilized and their ability to fulfill the intended goals regarding cost and safety.
- **Phase 4: Pilot and Technical Implementation** (2-3 years)
  Put the prototype into actual operation as a working pilot installation, including real suppliers and real production capabilities. The results will be used to evaluate and plan full scale rollout of the solution in larger quantities and under various operational conditions, including suppliers, logistics, production, and testing capacities. Full quality control procedures will have to be followed during this phase, with online reporting and documentation of each step in the development process. The anticipated costs/benefits for a full commercialization are also checked out and prepared for decisions in the next phase.
- **Phase 5: Product Commercialization and Evolution** (10-20 years)
  Release the autonomous system as a product to the global oil & gas market. For such complex deliveries as autonomous systems, a rapid reaction support organization needs to be kept available throughout the lifetime of the systems. Operational experiences need to be collected, systemized and used as basis for new developments. These experiences will lead to adjustments of already operational systems (updates) as well as for the new products. Continuous evaluation of new markets and applications for the technology will be essential to maintain market interest and create business value.

In an open and competitive industry like the oil & gas industry, this general roadmap will be followed by many kinds of actors in parallel, including operator companies, large engineering and equipment vendors, service providers, small niche vendors, and applied research organizations. Alliances and joint ventures will be formed to explore autonomy, especially for activities in Phases 1-3, while normal business imperatives will lead to competitive product developments by single vendors or small consortia in Phases 4-5.

The authorities will have an important enabling role in the development of autonomous systems for the oil & gas industry. Previously, we mentioned the impact of proper regulatory initiatives to establish public trust. In addition, the authorities can play a crucial role in supporting early development phases through Research & Development programs, such as (in Norway) the PETROMAKS[43], DEMO 2000, and other programs. As has been shown by independent assessment[44], such support has been very successful in building competence and promoting new and innovative products and services. We recommend that autonomous systems become a prioritized area for the newly established PETROMAKS 2 program.

Finally, we point out the importance of supporting peer networks and providing meeting places for all stakeholders interested in autonomous systems. The annual Autonomy in the Oil & Gas Industry Conference hosted by NFA (Norwegian Society of Automatic Control) since 2008 is such a meeting place and has established itself as "the primary forum in Norway for discussing future needs for autonomous systems in the oil & gas industry, and the place for bringing together the right people for forming collaborations to meet these needs" [45].

Vision 2025 - The Autonomous Subsea Factory

Barents Sea November 22, 2025 at 03:07:25:

Autonomous systems can speed up detection and repair work when an error occurs, thereby helping to reduce environmental damage and operational loss.

The synthetic operations control agent OpCon receives a message from processing unit Zebra that it experiences a pressure drop on the flow-line to pump-station Lion, at the same time as the communication link with Lion is dead. All procedures for reconnecting the communication have failed. Zebra has followed its SOP (Standard Operating Procedure) and has negotiated a reroute of 50% of its volume through pump-station Bear. The remaining volume must be handled by reducing the inflow, while buffering the extra fluids in its local storage tank. Now it requests permission from OpCon to perform suggested course of action.

OpCon acknowledges pump-station Zebra´s request and responds by tasking the Munin surveillance vehicle to perform an inspection mission between pump stations Zebra and Lion. Mission objective: Find out what is the problem with pump-station Lion. Munin responds immediately, switches on its headlights, cameras and sensors and heads toward pump-station Lion.

OpCon begins to receive other alarming messages from key components involved in transporting the fluids from the new subsea factory at the Odin discovery, 2000 meters below sea level.

Hammerfest November 22, 2025 at 03.12:34:

Operations manager Per Pedersen is woken by his smartphone ringing at the side of his bed. He takes the phone and recognizes the name of the caller in its display. When he connects he hears the familiar but static voice of OpCon telling him about a pressure drop between Zebra and Lion and that Munin has been dispatched. Munin is expected to arrive at Zebra in 15 minutes. He is also given an orientation of the other alarming messages from the equipment on the main transport pipeline.

Per heads for his computer in the living room with a worried expression on his face.

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[43] http://www.forskningsradet.no/prognett-petromaks2/Forside/

[44] http://www.forskningsradet.no/prognett-petromaks/Nyheter/The_PETROMAKS_programme_A_major_boost_for_petroleum_research/

[45] http://www.nfaplassen.no/index.php?eventId=268&expand=257

Barents Sea November 22, 2025 at 03:26.04:

Munin is approaching Zebra and starts to follow the pipeline toward Lion. The distance between the two pump stations is 6 km, a journey that will take Munin an hour to cover at inspection speed. Munin checks his power reserve and reports his whereabouts to OpCon using the wireless connection at Zebra.

300 meters from Lion Munin´s sensors detect hydrocarbons in the seawater. Munin responds by deploying its satellite communications link (a buoy that will rise to the surface and provide a high-speed communications link) and connects with OpCon. Munin continues with all sensors activated toward the pump-station Lion in 2 knots speed.

Hammerfest November 22, 2025 at 03:31.06:

OpCon relays the first message from Munin to operations manager Per Pedersen. He swallows hard from the disturbing message. Then OpCon connects Per´s computer to Munin's control systems, granting him full access to Munin. As Per can see the contours of pump-station Lion through Munin´s camera he switches Munin into human control mode. In this mode Munin will respond to requests related to performing various operations, as long as they do not harm the craft.

This little history illustrates how autonomous systems can be used to perform sophisticated decision making in collaboration with a human. For this to take place the pump stations and any other major functional node at the subsea facility must be given the authority to perform local decision-making and negotiate with neighbouring entities. It will require that pumps, valves, compressors, storage tanks and pipelines are made more intelligent.

Appendix - Lessons from Other Industries

The oil & gas industry is a late adaptor of autonomous systems, partly because there has not been a pressing need for it, and partly because the task of introducing it has been regarded as being beyond reach. New and up to now unknown challenges (subsea and operations in the arctic), as well as new and proven technologies now seem to open up for more use of autonomous technologies also in this industry. Below are some examples from other industries.

Space Industry

The recent successful landing and operation of the "Curiosity" rover[46] on Mars is a significant contribution to what can be achieved by today's technology. With long signal transmission times, the rover needs to be able to take its own decisions for immediate actions, since the turnaround time for signals to and from Earth (about 14 minutes each way) makes it necessary to make local decisions fast. For Curiosity, especially the landing sequence was autonomous, for the reasons stated above. Autonomy in the future may include autonomous path planning, dealing with obstacles, and selection of objects to examine closer.

Aviation

In aviation, automatic landing systems and autopilots have been around for decades. For military aircraft, a lot of effort has been made to increase the pilot's situational awareness by relieving the

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[46] http://en.wikipedia.org/wiki/Mars_Science_Laboratory

pilot from more trivial tasks, and by providing the pilot with condensed information to act upon. Lately, RPA's or UAV's or drones[47] have become commonly used, with a variable degree of automated functions. These functions will be significantly increased in the coming years, and Knowledge based or Artificial Intelligence solutions will be introduced in large numbers.

Defense

The US military, who spends nearly half of the world's military budgets, has decided to go for automated solutions to a much larger extent than today: The U.S. Congress has set a Congressionally Directed Goal of 1/3 of ground combat vehicles should be unmanned by 2015 and 1/3 of deep strike aircraft should be unmanned by 2020. It is recognized that a dramatic increase in autonomy is required for the operation of unmanned vehicles of all kinds in ordinary environments in the air, on land and sub-sea. An autonomy roadmap document covers all US military forces in the time period 2011-2035[48], identified the need for greater system autonomy as the "single greatest theme" for future USAF S&T investments. It cited the potential for increased autonomy to improve effectiveness through reduced decision cycle time while also enabling manpower efficiencies and cost reductions.

Transportation

In the transportation sector a European multi-discipline project, "CESAR"[49] (Cost-efficient methods and processes for safety relevant embedded systems) is funded from AARTEMIS. The project covers three transportation domains: automotive, aerospace, and rail, as well as the automation domain, and share the need to develop ultra-reliable embedded systems to meet societal demands for increased mobility and ensuring safety in a highly competitive global market. To maintain Europe's leading edge in the transportation as well as automation market, CESAR aims to boost cost efficiency of embedded systems development and safety and certification processes by an order of magnitude.

Hydro Power

Norway has experience in the use of autonomous systems within hydro-electric power production, dating back to the early 1970's. A system was developed for the Tokke Power Station in Telemark, including a function to control lines transporting the power to the Oslo area[50]. The system analyzed the state of the network, and - if oscillations occurred and might lead to dangerous situations – could rearrange it as required to prevent a general collapse. Action had to be taken within a few seconds, and a human in the loop would cause the action to be too late. This was more than just an automatic action, since a qualified analysis of the network state was necessary before any autonomous action was taken. The system, based upon an ordinary Nord-1 minicomputer with 256 KB core memory and 256KB drum mass storage, made several decisions to adjust the turbine power, and also disconnected the Tokke - Oslo line a few times during its 20 year continuous operation.

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[47] http://en.wikipedia.org/wiki/Unmanned_aerial_vehicle

[48] http://www.defenseinnovationmarketplace.mil/resources/UnmannedSystemsIntegratedRoadmapFY2011.pdf

[49] http://www.cesarproject.eu/

[50] http://www.energy.sintef.no/publ/xergi/2001/3/intervju/Faanes.htm