Exploring IEC 61499 for a Distributed Software Architecture in an Onshore Oil Field

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Abstract: - Oil and Gas operations across the value chain are fraught with challenges in maximizing margins while mitigating risks of owning and operating critical infrastructures and assets and the need for Integrated Operations (IO) is increasing. Industry 4.0 paradigms act like a lighthouse and researchers combine the holonic approach with Multi-Agent Systems framework to address the required intelligence of the production systems. This may be enabled if there is corresponding support in the lower level automation architecture and one answer is an agent-ready PLC and IEC 61499 architecture. The actual process control systems in mature onshore oil fields comprise disintegrated systems requiring much integration effort to capture data for IO. In this paper we suggest that each equipment in oil field regardless its control generation may become an intelligent mechatronic component. The solution is an abstracting layer build with IEC 61499 compliant PLCs enabling peer-to-peer communicating controllers with distributed intelligence without centralized control. This may be a cost effective solution and may solve issues regarding IO for mature onshore oil fields with great impact on human, environment and process safety.

Key-Words: Multi-Agent Systems, Holonic Manufacturing Systems, Intelligent Mechatronic Component, IEC 61499.

1 Introduction

In the last decades, industrial automation has become a driving force in all production system including oil and gas industry especially offshore. Technologies and architecture have emerged alongside the growing organizational structure of production plants. Every innovation had to start from the latest state-of-art systems within the respective domain. While investigating the introduction of Service-Oriented Architectures (SOA) to automation, and even down to the shop floor, one should consider latest standards, proofed technologies, industrial solution and latest research works in automation domain keeping Industry 4.0 like a lighthouse.

One important industry domain trying to catch up the rest regarding Process Control Domain (PCD) is oil and gas industry in general and oil field operations (known also as Upstream or Exploration and Production (E&P)) in particular.

Oil and Gas operations across the value chain are fraught with challenges in maximizing margins while mitigating risks of owning and operating critical infrastructures and assets.

All major players started to understand the benefit of industrial automation not only in terms of safety but also regarding flexibility and agility of the production system. Digital Oil Field (DOF) emerged in the beginning of 21st century but this concept is hard to implement in many onshore oil fields because the control systems are disintegrated. This happened because the physical production system comprises of individual units named “packaged units” manufactured by very specialized companies where control is dedicated mainly to safety and less to connectivity. The result of integration was hierarchical architectures for process control systems

Recent research works revealed the advantages of holon approach combined with Multi-Agent Systems (MAS) framework regarding production optimization and coordination, abnormal event management, production planning and scheduling etc.

However MAS, although promising, cannot address the coordination and self-organization issues alone require the corresponding support in lower level architecture [1] something like agent-ready PLC. This can be achieved using IEC 61499 compliant PLCs.

The paper is structured as follows: section 2 depicts oil field management challenges and derives the need of mapping to industry 4.0 paradigms; Section 3 describes few contributions regarding holonic approach combined with MAS frameworks to solve some problems in oil fields and depicts a distributed software architecture described in [2] based on IEC 61499 which can be adapted to oil fields control systems. In section 4, we outline a use case of such architecture and the novelty that can be introduced. The last section will try to conclude and define next steps in this journey.

2 Industrial Automation in Onshore Oil Fields

Oil and Gas operations across the value chain are fraught with challenges in maximizing margins while mitigating risks of owning and operating critical infrastructures and assets.

The concept of DOF emerged in perusing the Integrated Operations (IO) goal and major Oil and Gas companies started to implement it with different names (Smart Field, Field of the Future, i-Field, or Integrated Operations, etc.) since 2005, mostly in offshore oil fields. Actual DOF instances don't cover the PCD as they assume that all PCD's elements (staring with sensors and actuators, fieldbuses, and ending to SCADA/DCS in central control room) are part of the physical production system which presents itself like a whole separated from IT-domain. DOF assumes that real-time data may be accurately acquired in a secured manner using standardized protocols, interfaces and systems from central SCADA/DCS. The result is rigid, heterarchic architecture of control system in an oil field. New visions like STATOIL's "Subsea Factory" states that future "vendor packaged units" among other requirements should have a certain degree of intelligence along with open interconnectivity, opening the door to Intelligent Manufacturing Systems (IMS) in oil fields.

Most of onshore oil fields operates on mature oilfields where the components of PCD have been applied separately to separate parts of upstream production process (e.g. drilling, down hole of well, artificial lift like sucker rod pump, pipelines, separators etc.). This resulted in a wasteful disintegrated systems "speaking" various proprietary protocols and with multiple electronic interfaces and poor networking capabilities (serial link usually) requiring much integration effort to capture data but poor flexibility and configurability.

That is why we belief that an abstraction layer build with IEC 61499 compliant PLCs on top of existing dedicated and disintegrated controllers may be a cost effective solution to solve these issues and open the way to DOF for mature onshore oil fields with great impact on human, environment and process safety.

A typical oil field (Fig.1) comprises reservoirs, wells, manifolds, collecting stations, treatment stations, compressor stations, injection stations interconnected by pipelines [3].

After extraction, the petroleum flows through specialized plants that separate secondary products (gas, sand, water) and transport all them for final treatment, delivery or disposal. All these represent a complex production system, which is geographically distributed by nature especially onshore.

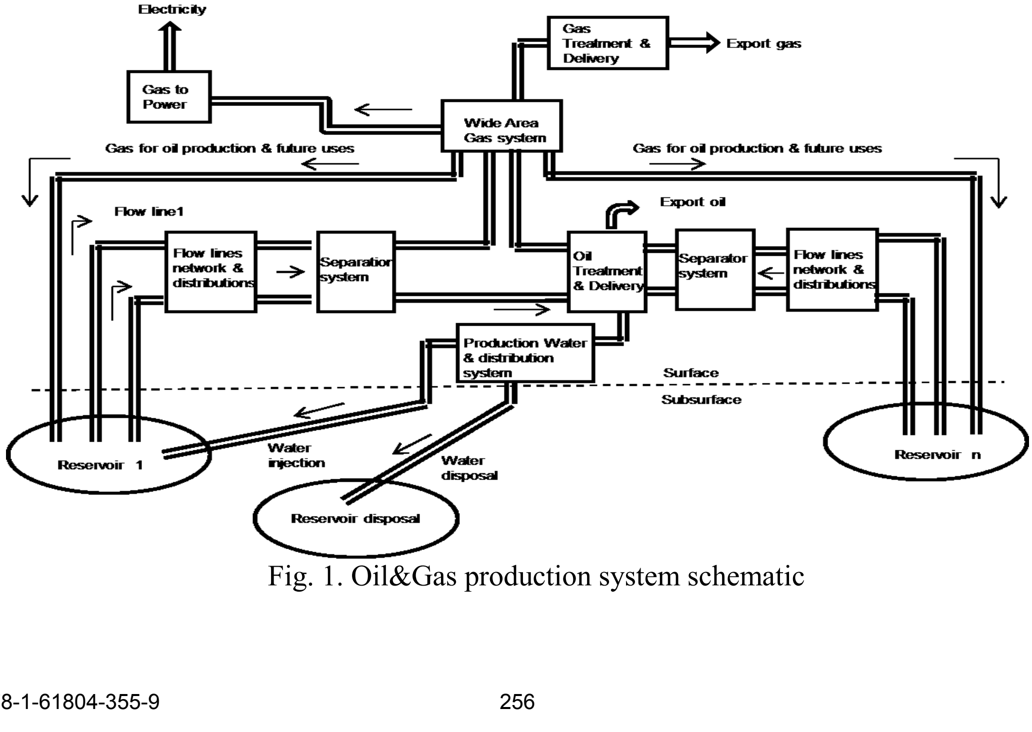

Fig. 1. Oil&Gas production system schematic

So we may say that oil fields can be viewed as an instance of distributed manufacturing systems. Most of onshore oilfields are classified as mature due to their natural progressive decline of production which raise the need of reconfiguration of its components and high degree of flexibility and agility of its control systems [4].

The organization which operates such a production system has as main objective to maximize the production operating safely with minimal costs. Ultimately this goal means a global optimization problem [5].

In such a complex system each component can be considered a subsystem responsible for its own internal process and resources but it must to follow external requirements (upstream, downstream, etc.). So, the external requirements of each subsystem could be defined as global compromise resulting from negotiation capabilities and availability. This lead to the need of self-aware mechatronic components interconnected.

More and more research works and contributions address different challenges like asset management & control [6,7], production planning and scheduling problems [8,9], configuration and reconfiguration of the production system [10], production optimization and coordination [5] in oil field operations and all of them are based on Holonic Manufacturing System (HMS) paradigm [11].

Hence a paradigm shift may be benefic for oil field as proven in manufacturing where Industry 4.0 paradigms act as a lighthouse.

3 Challenges for Intelligent Networked Systems in Oil Fields

Intelligent networked embedded systems and technologies ranging from components and software to Cyber-Physical Systems (CPS) are of increasing importance to ICT supply industry, system integrators and all major mainstream sectors of global economy. Monitoring and control are seen as key for achieving visions in several CPS dominated areas including oil and gas industry. Major features of Intelligent Monitoring and Control Systems have been demonstrated under the umbrella of European FP7 IMC-AESOP project where research, development and innovation work has been carried out.

Today, plant automation systems are composed and structured by several domains, viewed and interacting in a hierarchical fashion following mainly the specification of standard enterprise architectures. However, with the empowerment offered by modern service-oriented architectures, devices and applications distributed across the different layers of the enterprise may expose their characteristic and functionalities as “services” Additionally, these devices and systems should be able to access and use those “services” located in the cloud.

Researchers, engineers and industrialists associated the latest advances in ICT with the 4th Industrial revolution (referred as Industry 4.0 in Germany) where physical “things” get connected to Internet allowing real touchable world to integrate part of the cyber-space. Moved to industrial world, a number of different system concept and architectures have become apparent such as collaborative systems, SOA, networked cooperating devices and systems.

Along with the next generation of SOA, the Holonic approach combined with MAS framework provided a lot of contributions for different industry domain including oil and gas.

Most of contributions address the Manufacturing Execution System (MES) level [12,13] and provide certain degree of intelligence at this level, assuming PCD works in an integrated manner.

The AEM (Abnormal Event Management) is a vital process control function especially in the oilfield production systems and an arena for researches to identify. Most of AEM is manually controlled so some works try to tackle down this issue defining an intelligent architecture for Integrated Control and Asset management for petroleum complexes and then develop a MAS for this [6] [14].

A semantic complex event processing architecture was proposed in [6], providing intelligence needed to support operational decisions.

The oil field profitability from management perspective, was also addressed using a MAS [3] based on a detailed ontology [4].

Most of MAS solutions use implicitly or explicitly holonic approaches because a total centralized approach, besides the need of large amounts of information and communication resources determine and centralize decision making.

Solving this contradiction between the need to distributive integrate mechanisms of decomposition of the entire model as a set of models that represent the behavior of processes and production plants would greatly simplify decision making. However, the aggregation process always involves loss of information that makes decision-making processes based on aggregation patterns to risk lead to decisions unfeasible, a situation that has been exceeded in the discrete manufacture by the concept of independent production unit, derived from the concept of Holon.

A nice holarchy for an oil field was proposed in [5] with the main purpose to solve coordination and optimization in Oil and Gas Production complexes where continuous process are involved and discrete decisions mechanisms are used. Each component (equipment) is defined as a holon interacting with others holons to achieve the global goal. Interaction is based on negotiation process performed by agents [5] [10,11].

Based on those contributions we will consider any component of the production system as a Production Unit (PU) to be autonomous. The PU's objective is to safely maintain working in accordance with specifications received from a supervisor. Those specifications (including new control functions) result from assessment in terms of capabilities performance, availability and relations between them and the production strategies and external factors.

The distributed nature of the production system requires aggregation of components that otherwise are controlled independently, but must cooperate to attain the overall production.

The design architecture for a distributed control we intend to use for our abstraction layer is detailed in [2]. It is relying on existing MAS framework but map agent-like functionality directly into the IEC 61499 architecture creating a synergy not only with MAS but also with SOA [1,2].

The plant is supposed to be composed of a set of mechatronic components (in our case is about wells, manifolds, separation stations etc.) denoted by M and assume that each component Y of M has some sub-components S(Y) = {sim, hmi, view, ctrl} where:

- Y(sim): is an accurate simulation model of dynamics of the component to be used for testing purposes in closed-loop with control sub-component(ctrl);
- Y(hmi): is the human-machine-interface (HMI) and provides interfacing to the component like HMI of SCADA. This is connected in a closed-loop with Y(ctrl);
- Y(view): is the visualization of the dynamics of the simulation model. As the simulation model is executing in closed-loop with controller, a live view of the component can be viewed at runtime;
- Y(ctrl): is the controller of component and can be of various degree of complexity.

In the same work [2] Y(ctrl) is further decomposed into two distinct elements in a similar manner the HMS researches describe decomposition of control into low-level and high-level:

- Y(ctrl-LLC): The low-level control (LLC) governs the reading of sensors and triggers the actuators. The LLC should abstract out the details of I/O and other low-level behavior such as initialization routines, fault detection, regulatory control like PID and should be self-contained and communicates with component it is assign to;
- Y(ctrl-HLC): The High-level control (HLC) accesses the abstract interface provided by LLC and provides agent-like behavior so it will be referred as agent for a particular component. The agent should communicate with other agents to fulfill intended goal.

Specific inter-component and intra-component communication are detailed in [2] and presented in Fig. 2.

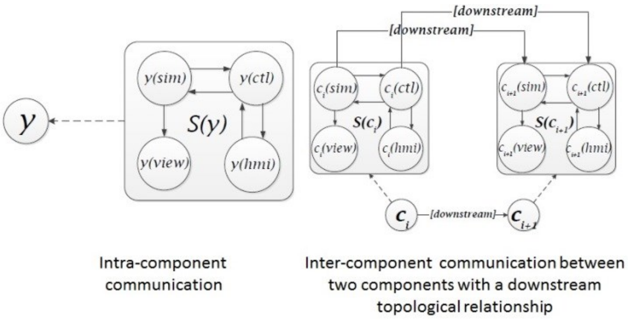

Fig. 2. Intra-component and inter-component communication (Source: [2], p. 4, 5)

4 A use case for IEC 61499 architecture

The particularity of our work is that the IEC 61499 compliant PLC may be connected with sensors and actuators but also with an embedded controller executing a dedicated regulatory control function. So the Y(ctrl-LLC) component should abstract also the external controller and be exposed as a virtual Field Device Object.

Our use case assumes a production system with 3 production units: 2 wells and a flow station.

The wells are in artificial lift and the method is sucker rod pump. We assume that the oil has wax so the flow assurance is achieved with a dedicated unit called downhole heater. From process control perspective each well has 2 embedded controllers. The first controller named Well Manager (WM) is responsible with regulatory control of the pumping unit and varies the speed of electrical motor in order to keep the pump efficiency close to a certain set-point using a set of sensors. The second controller named (DHH) is responsible with regulatory control of the heater and varies the intensity of current in order to keep the temperature at the well head at a certain set-point.

The flow station intakes the flow from the 2 wells and separates the gas and the liquid phase. From the existing process control perspective, the control functionality is achieved by IEC 61131-3 compliant PLCs. All controllers have communication ports for RS485 and Modbus protocol.

The proposed solution is to implement a distributed control scheme on top of the existing control strategy by developing the (Y-ctrl HLC) layer with IEC 61499 intelligent agents. These agents will enable the inter-component communication for tasks synchronization and control strategy reconfiguration in order to achieve optimal performance of oil production. This approach is illustrated in Fig. 3, where the top layer represents the current control scheme and the lower layer represents the abstraction added for intelligent functionalities.

For this we will add three IEC 61499 compliant PLCs that will encapsulate the agent behavior for each system component. Each PLC has 2 communications interfaces: one is a RS485 link for the fieldbus with dedicated controllers, and an Ethernet port for distributed control network and inter-agent communication. All PLC are connected to the same network with a PC in the central control room for HMI and engineering purpose.

In the distributed application, each agent will first acknowledge the network state: if all other agents and all LLCs are connected. Based on this information, different control strategies will be carried out. For example, if all components of the control system are active, each agent will analyze the efficiency of the devices connected to the corresponding LLC, based on the closed loop response. The resulted performance indices of the two well agents are shared and if significant differences are identified in terms of response time or energy consumption, the set-point load is distributed accordingly between the two. The flow station agent determines the total load needed for the two wells.

In case one of the agents connected to well PLCs goes into a fault state, its functions can be easily overtaken by the other well agent.

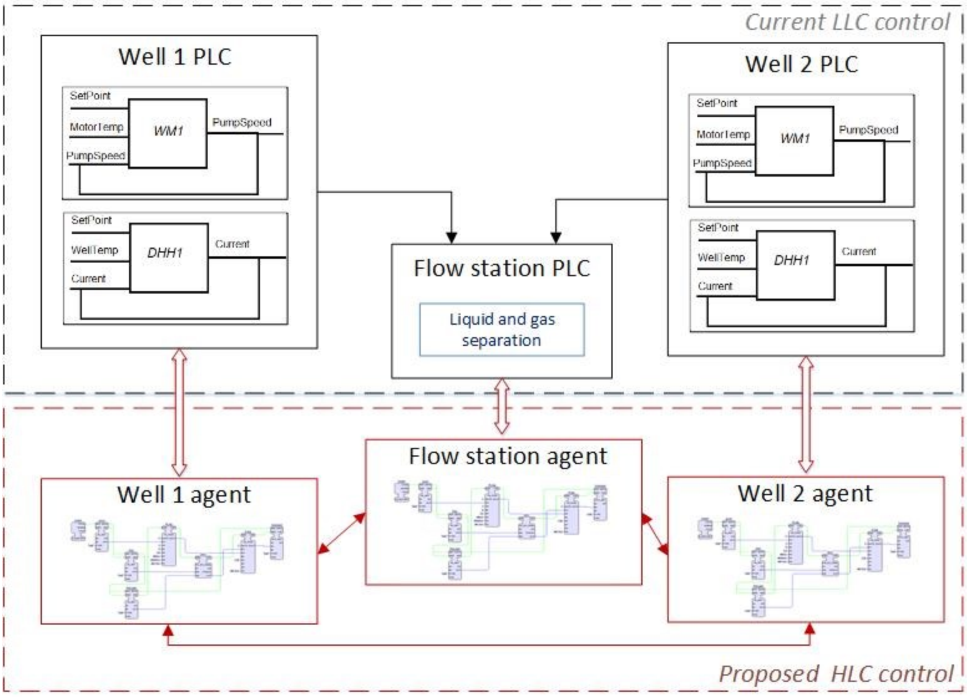

Fig. 3. Redesign of control strategy

The distributed system design is illustrated in Fig. 4. The clear separation between LLC and HLC control allowed us to develop a distributed control strategy that focuses only on the agent synchronization and process optimization using information regarding pump state, motor and heater yield and equipment functioning hours. This way each well is controlled in accordance to the overall status of PU. In addition to this, keeping the LLC physically separated from the HLC increases the system reliability as a fault in the abstraction layer would not affect the functioning of the local control, while the distributed agents can reconfigure their reference levels accordingly. At the same time, a fault in the LLC level can be rapidly assumed by the other agents.

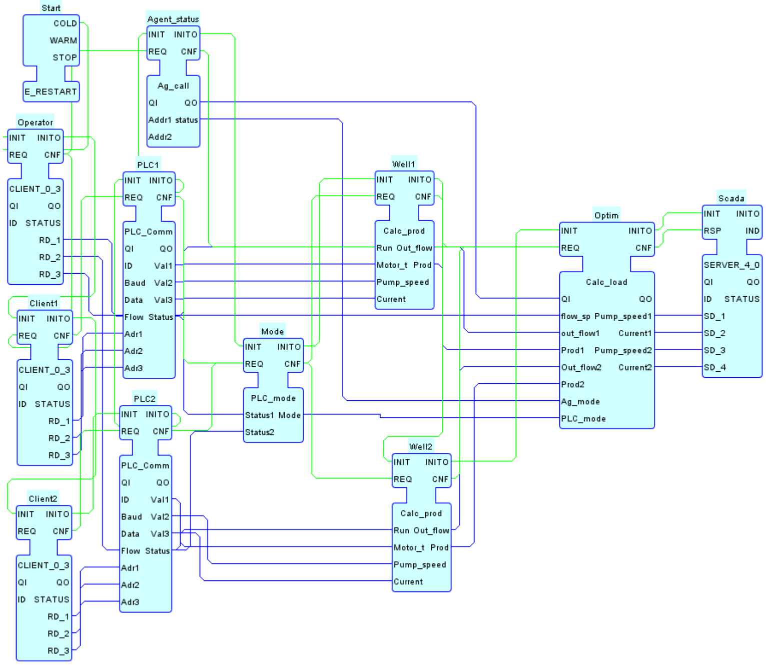

Fig. 4. Agent control application

5 Conclusions

We started our work investigating trends in industrial automation and particularities of oil field production systems and business challenges in order to rationalize the need to map Industry 4.0 paradigms and methodology for on oil field.

We proposed a solution for disintegrated process control system in an onshore oil field, based on a distributed software architecture enabling peer-to-peer communication in order using IEC 61499 compliant PLC.

The solution presents like an abstraction layer on top of existing embedded controller with poor communication capabilities instead of classic hierarchical approach.

The benefits we foreseen is the cost effectiveness compared with classic approaches and keeps interoperability with MAS framework and makes integration easier and opens the door to provide control functionalities as a cloud service.

Next steps involve the development of the simulation model Y(sim) and view Y(view) using Matlab and Simulink and linking the simulation to the controlled process. In addition to this, we will define a self-reconfiguration strategy for fault management, integration of several PU in a distributed control scheme and implementation of cloud interfaces for enabling complex optimization strategies.

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