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3D modeling of drill string and well used for directional drilling

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Abstract

The motivation for directional drilling research are primarily economic, however it also provided other environmental and technical benefits, it has contributed to the reclamation and preservation of thousands of ecologically sensitive acres while allowing a more efficient use of natural resources. In offshore applications helped increasing substantially the production rates, in environmentally sensitive regions and others challenges engineering scenarios. Different planning techniques and steerable tools enables the well to be drilled as close as possible to the planned path and achieve the target correctly.

The purpose of this work is to research existing directional drilling techniques and applications to develop a 3D model of drill string and wellpath calculations to facilitate Hardware-in-the-Loop (HIL) testing of automated intelligent drilling systems when directional drilling is needed. The intension is to introduces the concepts of well dynamics as well as the procedures to use a Rotary Steerable Systems (RSS), their applications and the implications on enhanced well production.

Using a simplified modeling of a RSS tool applied for directional, a HIL Directional Drilling simulator was developed in order to be employed in commercial HIL testing Directional Drilling systems. The simulator implementation was accomplished using Matlab/Simulink development platform.

The HIL Directional Drilling simulator was evaluated against Ullrigg well U2 real testing data provided by Statoil. The comparison between real measurement and simulated data shows the performance of the simulator. The simulator has presented satisfactory results and may potentially be employed in commercial HIL testing.

The thesis was developed at Marine Cybernetics from January 2012 to July 2012 in Trondheim, Norway.

Resumo

A motivação para a pesquisa de perfuração direcional é primeiramente econômica, no entanto, ela também fornece outros benefícios ambientais e técnicos, tem contribuído para a recuperação e preservação de milhares de hectares ecologicamente sensíveis, permitindo uma utilização mais eficiente dos recursos naturais. Em aplicações offshore ajudou a aumentar substancialmente as taxas de produção. Diferentes técnicas de planejamento e ferramentas de perfuração direcionáveis permitem que o poço seja perfurado tão próximo quanto possível do caminho pré-determiado e alcance o alvo corretamente

O objetivo deste trabalho é pesquisar as técnicas existentes de perfuração direcional e suas aplicações, a fim de desenvolver um modelo tridimensional da coluna de perfuração, junto a isso testar diferentes métodos matemáticos voltados para obter o melhor caminho do poço a seguir. Para assim, facilitar o Hardware-in-the-Loop teste (HIL) de sistemas automatizados de perfuração inteligentes. A intenção é introduzir os conceitos de dinâmica do poço, como também os procedimentos para utilizar um Sistema Rotativo Dirigível (RSS), suas aplicações e as implicações sobre a produção do poço.

Utilizando uma modelagem simplificada, um simulador HIL foi desenvolvido neste trabalho com o objetivo de ser empregado em programas comercias de testes HIL de sistemas de perfuração direcional. A implementação do simulador foi realizada usando a plataforma de desenvolvimento *Matlab/Simulink* e a plataforma de criação de testes HIL desenvolvida pela *Marine Cybernetics*, o *CyberSea*.

O simulador HIL foi avaliado usando dados reais de testes realizados pela Statoil no poço U2 do centro de pesquisa *Ullrigg* do *International Research Institute of Stavanger* (IRIS), na Noruega. A comparação entre as medições reais e os dados simulados mostraram o desempenho do simulador. O simulador HIL desenvolvido apresentou portando desempenho satisfatórios e pode potencialmente ser utilizado em testes comerciais de HIL.

O Projeto Final do Curso (PFC) foi desenvolvido na sede da Marine Cybernetics, de janeiro de 2012 a julho de 2012 em Trondheim, Noruega.

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Nomenclature

ρ	$[kg/m^3]$	Density
θ	$[rad]$	Drilling Inclination
$\theta_{well}[\,]$	$[m]$	Inclination of the Well Planning (vector)
g	$[m/s^2]$	Gravity Acceleration
q_{bit}	$[m^3/s]$	Drill Bit Flow
q_{bpp}	$[m^3/s]$	Back Pressure Pump Flow
q_{choke}	$[m^3/s]$	Choke Valve Flow
$q_{cuttings}$	$[m^3/s]$	Cuttings Flow
q_{ds}	$[m^3/s]$	Drill String Outflow
$q_{ds}[\,]$	$[m^3/s]$	Drill String Outflow (vector)
q_{influx}	$[m^3/s]$	Influx from Annulus
q_{out}	$[m^3/s]$	Outflow from Annulus
q_{pump}	$[m^3/s]$	Rig Mud Pump Flow
q_{out}	$[m^3/s]$	Outflow from Annulus
u_{bpp}	$[0,1]$	Back Pressure Pump Control Signal
u_p	$[0,1]$	Rig Mud Pump Control Signal
v	$[m/s]$	Velocity
BHA	$[-]$	Bottom-Hole Assembly
BHP	$[-]$	Bottom-Hole Pressure
BOP	$[-]$	Blowout Preventer
DCS	$[-]$	Drilling Control Systems
DD	$[-]$	Directional Drilling
DP	$[-]$	Dynamic Positioning

DS	[0/1]	Drilling Status
ECD	$[kg/m^3]$	Equivalent Circulation Density
HIL	[–]	Hardware-in-the-Loop
L	[m]	Length
L [ ]	[m]	Length (vector)
MD	[m]	Measured Depth
$MD_{well}[\,]$	[m]	Well Planning Measured Depth (vector)
MPD	[–]	Managed Pressure Drilling
NPT	[–]	Non-Productive Time
P_{atm}	[Pa]	Atmospheric Pressure
P_{choke}	[Pa]	Upstream Choke Valve Pressure
P_{dh}	[Pa]	Downhole Pressure
P_{fric}	[Pa]	Frictional Pressure
P_{hy}	[Pa]	Hydrostatic Pressure
$P_{loss_{an}}$	[Pa]	Pressure Loss Inside the Annulus
$P_{loss_{bit}}$	[Pa]	Pressure Loss Inside the Drill Bit
$P_{loss_{ds}}$	[Pa]	Pressure Loss Inside the Drill String
P_{top}	[Pa]	Wellhead Pressure
PDX5	[–]	Power Drive X5
PMS	[–]	Power Management System
ROP	[m/s]	Rate of Penetration

1 Introduction

Directional Drilling has become a very important tool in the development of oil and gas deposits. Different planning techniques and tools enables the well to be drilled as close as possible to the planned path and active the target correctly. Directional Drilling (DD) is receiving more attention nowadays due to its capability of reach complex reservoir though an accurate control of the deflection of a wellbore in a specific direction, in order to reach a predetermined target.

While third party testing, verification, and classification of structures and mechanical systems are well-established in the maritime and offshore industries, the increasing use of computer control systems has not yet been met by corresponding third party testing and verification activities For a new-build, HIL testing significantly reduces the risk of software related problems during commissioning, startup and first-year operations. For a vessel in operation, HIL testing can be used to assess control system software upgrades to secure a problem-free installation onboard. HIL testing technology can also save time and cost in troubleshooting of known software issues onboard the vessel. In short, HIL testing significantly reduces the risk of off-hire costs and non-productive time due to software related issues.

This thesis presents the development of a commercial HIL 3D model of drill string and wellpath calculations to facilitate Hardware-in-the-Loop (HIL) testing of automated intelligent drilling systems when directional drilling is needed. The directional drilling simulator was implemented at Marine Cybernetics from January 2012 to July 2012 in Trondheim, Norway.

1.1: Objectives

The objectives of the present work is to develop a simplified well simulator when doing directional drilling, and them will be able to capture the main dynamics of the 3D modeling of drill string and well used for directional drilling. There are some necessary requirements for HIL-simulator:

- The simulator must be able to capture the main dynamics of the well to recreate the surroundings of control system;
- The simulation parameters should be easily tuned, since there will be different scenarios to test different control systems.

The HIL well simulator differs from a well design simulator since the HIL simulator does not need to give accurate performance predictions but instead it should capture the main characteristics of the well for real time or faster simulations [1].

Marine Cybernetics AS has shown that it is possible to do HIL testing of drilling equipment on drill floor, including draw works, top drive, pipe handling systems and others. Single machine testing and integration testing of equipment delivered by different vendor have been performed with good results. Marine Cybernetics is expanding the areas for HIL testing within the oil industry, and this thesis is a result of a pilot project of directional drilling. In the next chapter details of implementation of HIL testing well simulator will be discussed.

1.2: Motivation

Automated intelligent drilling systems are being developed by the industry and there is a need for third party test of these systems. Third party HIL testing will be an efficient tool for verification of design philosophy, functionality and failure handling capability of these systems.

When simulating and testing automated intelligent drilling systems in combination with directional drilling, central parts of a HIL simulator are 3D models of drill string and well. The simulator must be able to capture the main dynamics of the drill string and well during drilling in x, y and z-direction. Interaction between drill string and well is also important.

1.3: Methodology

The methodology used in the developing of this project was:

- Literature survey on directional drilling and automated intelligent drilling systems;
- Study HIL technology
- Analyze necessary model fidelity for a 3D string and Well HIL simulator
- Implementation
- Validation of the result analysis

The developed HIL simulator was implemented in Matlab/Simulink. Marine Cybernetics has a large set of libraries implemented in Simulink, so this tool was chosen for the simulation.

The developed HIL simulator is a continuous of a MC project the addition of the third dimension and the mud motor implementation to obtain a directional drilling model is developing in this thesis. The data was compared to measurements from Ullrigg`s well data described in Appendix A, and the results were evaluated.

1.4: Control and Automation Graduation Context

The work is directly related to the Course Control and Automation Engineering, especially with transport Phenomena and Fundamentals of Engineering Oil & Gas.

The use of Simulink environment in the courses of Linear Signals and Signal II (DAS-5113), Feedback Systems (DAS-5121), Multivariable Control (DAS-5131) and Non-Linear Systems (DAS-5141) were important for the implementation of the models defined in this project.

Process Engineering (DAS-5101) provided the basis for the understanding of equipment, valves and control loops.

The discipline Transport Phenomena (EMC-5245) provided the basis for the specification of fluids, types of flow and modeling of turbulent flows that helped to understand the knowledge of manage pressure drilling MPD.

Finally, the discipline of specialization Program prh-34, Fundamentals of Engineering Oil & Gas (DAS-5946), which enable the project specific knowledge related to oil and gas used in this work.

1.5: Thesis Organization

The work was divided into six major chapters.

Chapter 2 explains the theoretical background used during the work. The chapter introduces concepts of Drilling Rig Components, Drilling Operations, , Well Control and contextualizes them with intelligent drilling systems.

Chapter 3 introduces the concepts of well simulator and Directional Drilling

Chapter 4 introduces an overview about directional drilling and introduces the parameters needed to calculate the wellpath

Chapter presents the HIL simulator development. The implementation approach is explained as well as the modular structure employed. The simulator modules are also individually described.

Chapter 6 shows and discuss the HIL simulator evaluation against real testing data.

Chapter 7 concludes the thesis and present some suggestion for future work..

Appendix A presents the real well from which the real testing data was collected. Whereas the Appendix B gives the PowerDrive X5 specifications.

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1.6: Marine Cybernetics AS

Marine Cybernetics was founded in 2002 by NTNU professors Thor I. Fossen, Asgeir J. Sørensen, Olav Egeland and Tor Arne Johansen together with Jan Biti (Business Consultant) and Arild Paulsen (Attorney of Law).

Marine Cybernetics contributes to safer and more profitable ships and offshore installations through third party testing of computer control systems using superior Hardware-In-the-Loop (HIL) testing technology [2].

Until winter 2012 Marine Cybernetics has performed more than 60 HIL tests on drillships, MODUs, jack-ups, construction/diving vessels, offshore service vessels and shuttle tankers, working with major E&P companies, rig companies, vessel owners, system producers, and yards [2].

Marine Cybernetics utilizes CyberSea Hardware-In-the-Loop (HIL) technology to test and verify control system software. HIL testing is a well proven test methodology from automotive, avionics, space, power electronics, robotics, and nuclear industries. It facilitates systematic testing of control system design philosophy, functionality, performance, and failure handling capability, both in normal and off-design operating conditions. HIL testing is performed in a virtual test-bed where there is no risk to man, vessel, or equipment.

2: Background

This chapter presents the principles of drilling rig components, drilling operations, well control and automated drilling systems. It also presents the fundamentals idea of Hardware-In-the-Loop (HIL) testing.

2.1: Oil Well overview

Oilfields areas are derived from decayed plants and bacteria that becomes hydrocarbons. Plant remains must first be trapped and preserved in sediments, then be buried deeply and slowly cooked to yield oil or gas. Those kind of rocks that containing this substances to generate oil and gas are known as source rocks.

As a source rock, deposited under the sea or in a lake, becomes hotter, long chains of hydrogen and carbon atoms break from the kerogen, forming waxy and viscous heavy oil. Most sediments accumulate as a mixture of mineral particles and water. Many oil reservoirs have a “gas cap” , which is an accumulation of gas in the top of the oil trap [3], see figure 2.1.1 from U.S. Energy Information Administration.

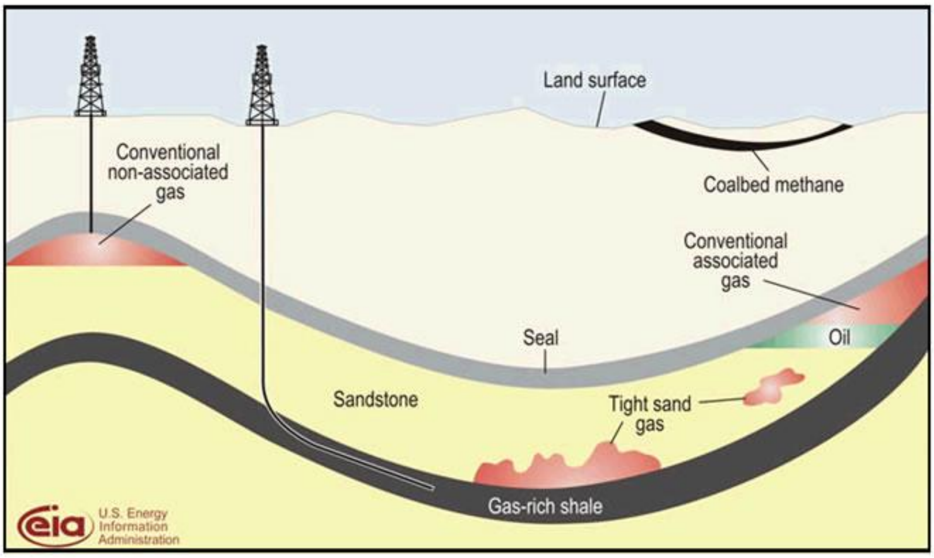

Figure 1 Schematic geology of natural gas resources[4]

Although lately there are a lot of improvements in seismic techniques the only way of actually confirming the presence of hydrocarbons is to drill an exploration well

[5]. Drilling can be a very hard task and it demands a lot of studies before drilling and also very careful with the high formation pressures. To ensure that the fluid does not flow in an uncontrolled way from the formations being drilled, into the borehole and eventually to surface there are some procedures and equipment that must be used. This will be treated in chapter 3.1.

2.2: Drilling Rig Components

There are many different pieces of equipment on a rotary drilling rig, they can be grouped together into four subsystems bellow:

2.2.1: Power System

Most drilling offshore rigs operate in remote locations where a power supply is not available. For generating the electrical power the rig need a generator. Modern drilling rigs (Figure 2) use electric transmission system since it enables the driller to apply power more smoothly, consequently avoiding shock and vibration. The draw works and the pumps are the major users of power on rig.

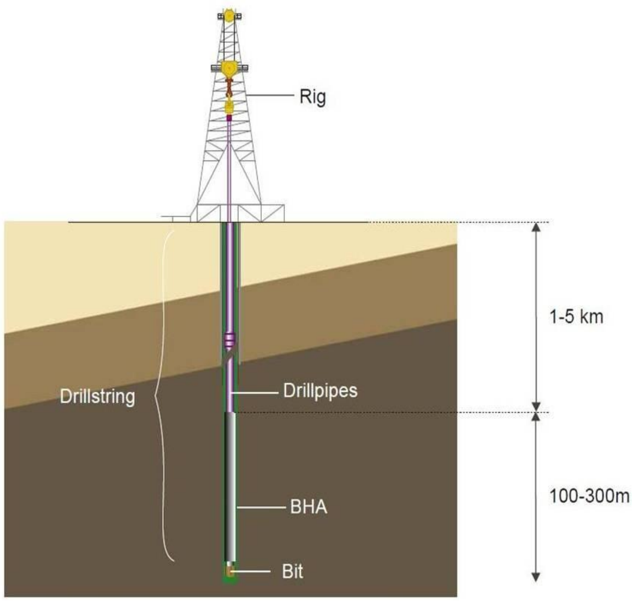

Figure 2 Main Drilling Rig components

2.2.2: Hosting System

This system is used to raise and lower the drill string and casing into and out of the well. 2. Each component in the Hosting System has his function and together they works basically as an elevator, using when running, or pulling, the drill string or casing into or out of the hole[6].

2.2.3: Rotating System

The rotating system is responsible for rotating the drill string and drill bit. There are basically 2 methods to provide the necessary torque to the drill bit: Rotary Table plus Kelly or Top Drive. The latter is more modern and designed for offshore installations.

Top Drive is an electric or hydraulic motor which is suspended on any mast of a rig, providing the necessary torque to the drill bit. This system replaces the functions of a rotary table, allowing the drill string to rotate from the top, using its own swivel, instead of the swivel system and conventional rotary table. In addition the system is operated by remote control from the drillers console. The Top Drive is also safer and more efficient. The power swivel, the other name for top drive, also enables drilling using stands consisting of two or three drilling pipes, instead of only one single drill pipe in a conventional system. Thus, the time consumed when assembling and disassembling the drill string is shorter.

The drillpipe, which when joined together, forms the drill string (Figure 2) consists of a heavy steel pipe and drill collars, used to transmit drilling fluid and rotational power from the top drive to the bottom of the hole. There are two important tools that might be present in the bottom part of the drill string: **Measurement While Drilling** (MWD) system and logging while drilling (LWD), both of them will be discussed in a subsequent chapter.

The annular space, annulus, is the place between the drill wellbore and casing, where fluid can flow, the well profile can be seeing in the Figure 3 below.

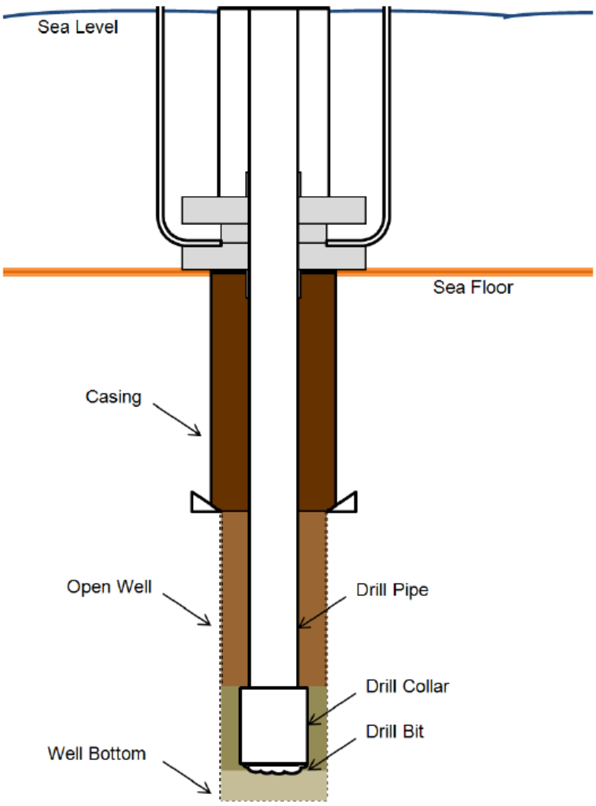

Figure 3 Well Profile

2.2.4: Circulating System

The Circulating System consists of drilling fluids circulating down through the well hole throughout the drilling process. There are number of main objectives of this system, including cooling and lubricating the drill bit, controlling well pressure and also removing derby and cutting.

The starting point is the mud pit, where the drilling fluid ingredients are stored. Mixing takes place at the mud mixing hopper, from which the fluid is force through pumps up to the swivel and down all the way through the drill pipe, emerging through the drill bit itself [7].

There are many important functions of the mud circulating which will be explained in the subchapter 2.3.2.

2.1: Well Control

If the influx are flowing in a way the operator or driller cannot regulate or stop it means the well is out of control. The most dangerous thing that can happen when losing the control of the well is a blowout (more details on the subchapter 2.4). There are two types of blowout: surface and downhole blowouts. Figure 4 shows a offshore blowout deepwater explosion .

Blowouts occurs when the reservoir fluids escape from the well at the surface, causing waste of fluid, may destroying the rig or even hurt people. When fluid migrates from a high-pressure reservoir into a lower pressure reservoir due to different reservoir depth a downhole blowouts happen. That does not produce escaping fluid at the surface. However, damage the environment and waste hydrocarbons by flowing them into other reservoirs where they might become unrecoverable [8].

Figure 4 Blowout deepwater explosion [9]

2.1.1: Well Control Techniques

Every time there is a possibility that a kick occurs, a flow check must be realized. There are few steps to follow and prevent the explosion. First is necessary to remove the drill bit from the bottom of the well, second turn off the mud pump. When this happing no mud must being pumped to the well and either it is expected that no mud returns from the well. The last step is to circulate this influx out of the well. It is extremely important to keep the pressures inside the well pressure window (more explanation on chapter 3.1.5).

There are four main different categories of well control techniques, which are: Driller`s Method, Wait and Weight Method, Volumetric Method and Bullheading. All of them work to keep the bottom hole pressure (BHP) as constant as possible and equal or above the formation pressure.

The method most used by operators is the Driller`s Method, also known as two circulation method. The first circulation the influx circulated out of the well and in the second circulation kill mud will be pumped in the well in order to regain control over the formation. The Kill mud is the mud with the necessary weight to restore the overbalance situation.

In a drilling operation the fluids contained in pore spaces of the formation are under pressure, overbalanced by the drilling fluid inside the wellbore. If the wellbore pressure, for some reason, drops below the pore pressure, an underbalanced scenario occurs, which means that an influx of formation fluid occurs. This event is called kick.

The well control techniques, most of them, are manually executed by driller and dependent of human capacity. Since the corrective action time response in a borehole failure event is the key factor to an effective well control, intelligent drilling systems are highly recommended to prevent of such accidents, to improve efficiency and safety of drilling operations.

2.1.2: Intelligent Drilling Systems

The main objective of intelligent drilling systems is to reduce drilling costs significantly, since the cost of drilling is still more than other operations in exploration and development of oil and gas [10]. With the application of high-techs in exploration and development, petroleum science and technology will be able to have more information about the drilling.

The future drilling technology will be more precise, efficient, less costly and hopefully more environmentally friendly. With the further development of new materials, detection control, microelectronics, telecommunications, computers and robots the work in drilling will become more commonly [10].

The concept of intelligent drilling is more wide than only automation of the drilling process, this approach involves several projects with different technologies. It involves technological development in several areas, such as: directional drilling, measurement while drilling, logging while drilling, well placement and borehole surveying.

Automation helps several of the drilling tasks, from well pressure control methods, to optimized pipe handling robots and multivariable coordinated control of drilling process, including pumps, chokes, mud mixing, drill string rotation and weight on the bit. Using automate methods for pressure control it is possible to drill with narrower pressure windows and also help to manage many problems that might occur during operation, and even help to reduce the Non Productive Time with simpler downhole tools and composed of long-life intelligent bits.

2.2: Drilling Operations

The Drilling Operations can be divided in two main categories: land (onshore) and offshore. The offshore follows the same pattern of the onshore, however, have different depths. The rig components can be installed on fixed platforms, or mobile. There are many different types of mobile platforms such as: submersible or semi-submersible, self-elevating, dynamic positioning and drilling vessels. Some examples are shown in the Figures 5 and 6 bellow.

Figure 5 Semi-Submersible Platform

Figure 6 Different Drilling Platforms [11]

2.2.1: Kick, Blowout and Risers

The drilling fluid is intended to provide a hydrostatic column of fluid pressure to counterbalance the porous fluid permeable formations. However, the well may suffer a kick, this means the formation fluids may enter the well drilling, turning the balance of the system and pushing out the drilling fluid inside the drill string, exposing the top of the well and equipment of the surface high pressures underground. If the direction of the fluids is not controlled, you can get a blowout, a situation where the fluid of formation flow to the surface in an uncontrolled manner.

The consequences of a blowout can be disastrous: personal injury, partial or total loss of the reservoir, pollution and environmental damage. Mechanicals devices such as pit level indicator or mud flow meters which trigger on alarms that alerts the rig crew that an influx is occurring.

For that reason, blow out preventers (BOP`s) must be installed to inhibits the kick from reaching the surface. BOP`S are basically high pressure valves that seals off the top of the well and regulate the flow to the surface. To minimize the amount of influx/fluid that enter the wellbore and also the amount of mud that is expelled from the annular region it is very necessary to act as soon as the influx is detected.

Since the BOP and the wellhead are located on the seabed or on the drilling platform, it is necessary to use a riser, which is a pipe that connects and offshore oil well to the platform. This risers consist of low pressure main tubes along with auxiliary line which carry high pressure choke and kill lines for the blowout preventer. Also carry power and control lines for BOP, and they are usually used by floating drilling vessels [12].

The underbalance drilling (UBD) is one of kind of drilling method where the mud is circulate while drilling, and the mud system pressure plus the pumping pressure has to be less than the formation pressure. In the Figure 2.4.4 and 2.4.5 we can see the difference between the overbalance and the underbalance drilling source, respectively [13].

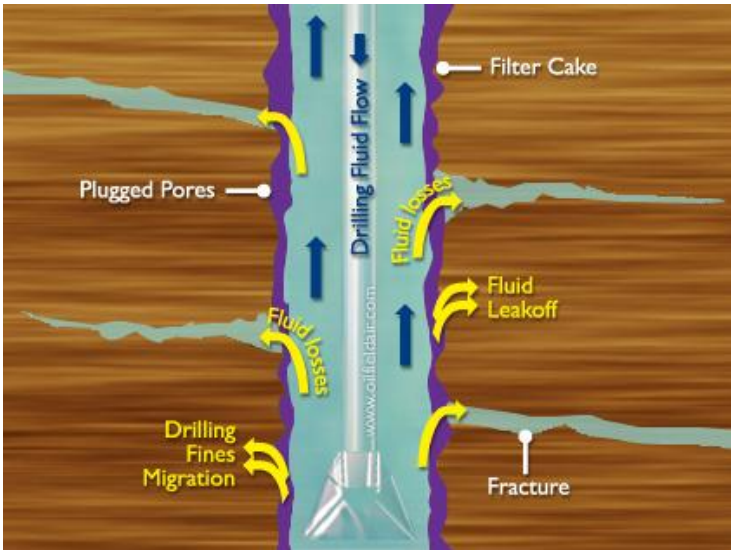

Figure 7 Overbalance drilling source [13]

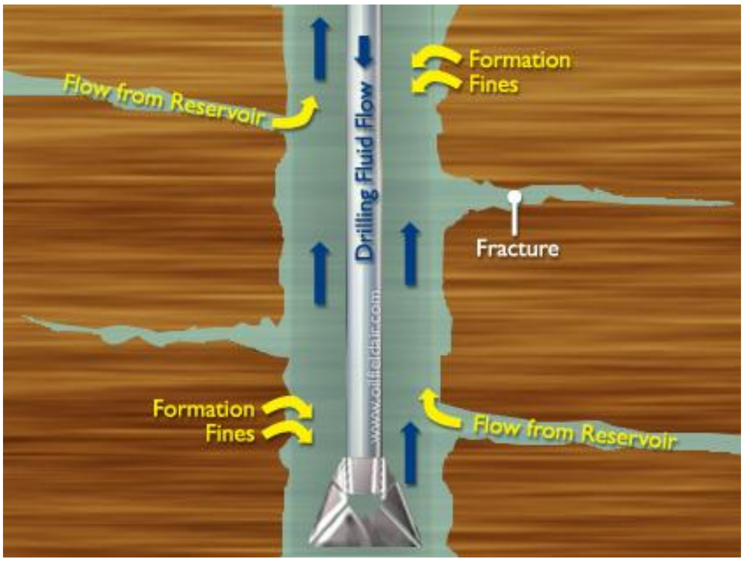

Figure 8 Underbalance drilling source [13]

2.2.2: Mud Functions

The height of the mud column and the density of the mud can change in number of ways during normal drilling operations. Thus it is necessary to continuously monitor the mud weight to ensure that the mud that is been pumped into the well has the correct density.

The main functions of the mud are as follows:

- Exert hydrostatic pressure on formation in order to prevent undesirable inflow of fluids and to stabilize the walls of the well
- Clean the well and transport the drill cuttings generated at the bottom of the well to the surface
- Cool down and lubricate the drill string and drill bit
- Work as a motor, providing additional power to the bit while drilling and creating eccentric motion in the power section of the motor which is transfer as concentric power to the drill bit

During drilling operations the volume of fluid pumped into the borehole should be equal to the volume of mud returned. When the pumps are stopped the fluid should neither continue to flow from the well nor should the level of the mud fall below the mud flow line [6].

2.3: Hardware in the Loop

The level of automation on offshore drilling vessels has been steadily increasing over several decades. These automation systems are essential for the safety, reliability, and performance of the vessels. While third party testing, verification, and classification of structures and mechanical system are well-established in the maritime and offshore industries, the increasing use of computer control systems has not yet been met by corresponding third party testing and verification activities[14].

It is very complex and it can be dangerous to test automation systems onboard the real vessel, since the systems contain safety-critical failure handling functionality. A Hardware-In-the-Loop (HIL) test is accomplished by creating a closed loop in which the control computer system and its operator station are connected to a real time HIL simulator, as illustrated in Figure 9. This virtual environment must be able to simulate the real surrounding so that the control system can operate normally, not noticing any qualitative difference from being connected to the real system. The control system might be thereby tested by simulating realistic operating and failure conditions [15].

Figure 9 Basic idea of HIL testing [2]

The control system is viewed as a black box, it is not necessary to have knowledge about the inner working of the control system and also, access to software code is not required. However, to establish the correct test scope a functional description of the control system is needed. In addition, detailed knowledge of the control system I/O and the system controlling is essential to develop a precise simulator, as well as operators manuals, control system topology, P&ID Diagrams, general arrangement drawing, product datasheet, maintenance instructions, alarm lists and all technical descriptions available.

2.3.1: HIL Testing Concept

HIL testing, which is an industry term for simulator based testing, is an efficient and effective tool to expose the full capability and robustness of the control system software. HIL testing facilitates systematic testing of control system design philosophy, functionality, performance, and failure handling capability, both in normal and off-design operating conditions, and is conducted in a virtual test-bed where there is no risk to man, vessel, or equipment [2].

Third party testing does not replace internal test activities by the vendor or vice versa, even if both third party and internal testing are done using HIL technology; both are important activities for achieving high quality software and meeting necessary standards for safety-critical control systems. Without third party HIL testing, the control system software will not have been tested by anyone except the system vendor at delivery of the vessel [2].

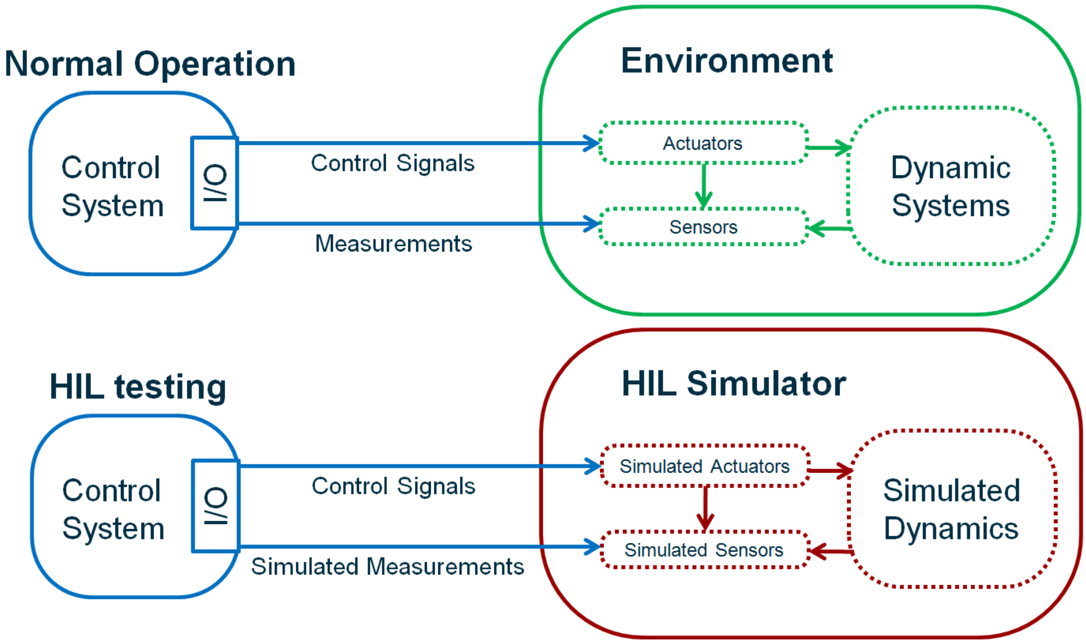

Figure 10 HIL simulator Scheme [14]

A HIL simulator uses mathematical models to reproduce the control system surrounding and devices. They might include complex dynamic equations in order to simulate faithfully the behavior of plants, actuators, and sensors. The models complexity, however, should be sufficient to enable a realistic enough interaction with the control computer system according to the requirements of the HIL testing program requested by the customer.

HIL simulator operates in real time in closed loop through communication links with the control computer system and the user interface, with the objective of facilitating realistic and efficient tests of both the functionality of control systems and the integration of entire automation systems [2]. They are exclusively developed and configured according to particular environments and equipment in order to simulate the real world and thus to deceive the target control system.

The advantages of HIL testing are:

- the software testing can be done during the production phases, making possible to test extensively before the product development deadline.
- the testing of failures and off-design situations can be presented outside the vessel, making the process easier, safer and cheaper;
- avoids damaging the equipment in harsh tests;
- reduces troubleshooting time in field, due to the thorough testing procedure performed previously;
- the possibility testing on similar replica hardware at a lab or a vendor`s site when the actual hardware onboard the vessel is not available; Facilitates integration of control system from several vendors.
- all the facilities of being the thirst party testing that it was already explain before;

2.3.2: CyberSea

CyberSea third-party HIL testing development platform has more than 10 years effort of software development and modeling of physical systems such as hydrodynamics, electro-mechanical systems, hydraulics and sensors. The idea behind CyberSea is to exploit the power of MATLAB–Simulink for creating mathematical simulators, and connect it to the flexibility of a general purpose programming language, for instance, java.[2]

The main purpose of CyberSea is to bridge the gap between physical modeling and HIL test application. This technology generates stand-alone modules files which can run in the CyberSea application in any computer, in addition to enable the configuration of models parameters, the connection between modules in order to establish the HIL simulator, the simulator verification, and an easier configuration of I/O interfacing between the HIL simulator and the control computer system.

Some key CyberSea features:

- allows a modular and configurable approach to HIL simulator development, enabling an easy simulator implementation by connecting CyberSea library blocks;
- automates fundamental parts in the process of building HIL test applications from simulation models;

- enables the verification of HIL simulators by simulating signals and showing the simulator response;
- allows to create and to run test programs efficiently;
- includes an extensive library of I/O interfaces for communication between HIL simulator and control computer system;
- includes important HIL features such as built-in signal failure modes, logging, trending, scenario management and web interface;
- includes GUI functionality and configuration tools;
- automatic report generation of test programs from a test case database.

3: Well Simulator

This chapter introduces the concepts of well dynamics as well as the procedures to use a Rotary Steerable Systems. The challenge of drilling a well according to the formation characteristics are covered. The over-running bit problems are discussed. In addition, the tool used in the work for modeling the directional drilling performance is explain with more details in this chapter

3.1: Well Pressures

3.1.1: Hydrostatic Pressure

Mud may be treated as a hydraulic fluid, thus the pressure exerted by the column of fluid dependent of the density and the vertical height depth can be expressed as [32],

$$P_{Hyd} = \rho_L \cdot g \cdot VD \tag{3.1}$$

where ρ_L is the liquid density, g is the gravity and TVD is the true vertical depth.

3.1.2: Bottom Hole Pressure

The bottom hole pressure is defined as the total sum of all pressures exerted on the bottom of a well. The control of the formation pressure it has to assures that the bottom hole pressure (BHP) is greater the formation pressure (P_F).

BHP is the sum of hydrostatic pressures (P_{Hyd}) exerted by the fluids column, plus any circulation friction loss, knowing as Annular Pressure Loss (APL, P_{ann}), plus the back pressures applied at the surface, knowing as the choke pressure P_{ck}.

$$BHP = P_{Hyd} + P_{ck} + P_{ann} \tag{3.2}$$

3.1.3: U-tube Concept

The well bore can be modeled as an U-Tube. One leg represent the drill pipe and the other leg represent the annulus. These legs are connected at the bottom, and the sum of both legs are equal to the BHP:

$$\sum P_{dp} = BHP = \sum P_{ann} \tag{3.3}$$

where $\sum P_{dp}$ is the sum of pressures inside the drill pipe and $\sum P_{ann}$ is the sum of pressures inside the annulus. This representation will be used to represent the following concepts as shown in the Figure 11.

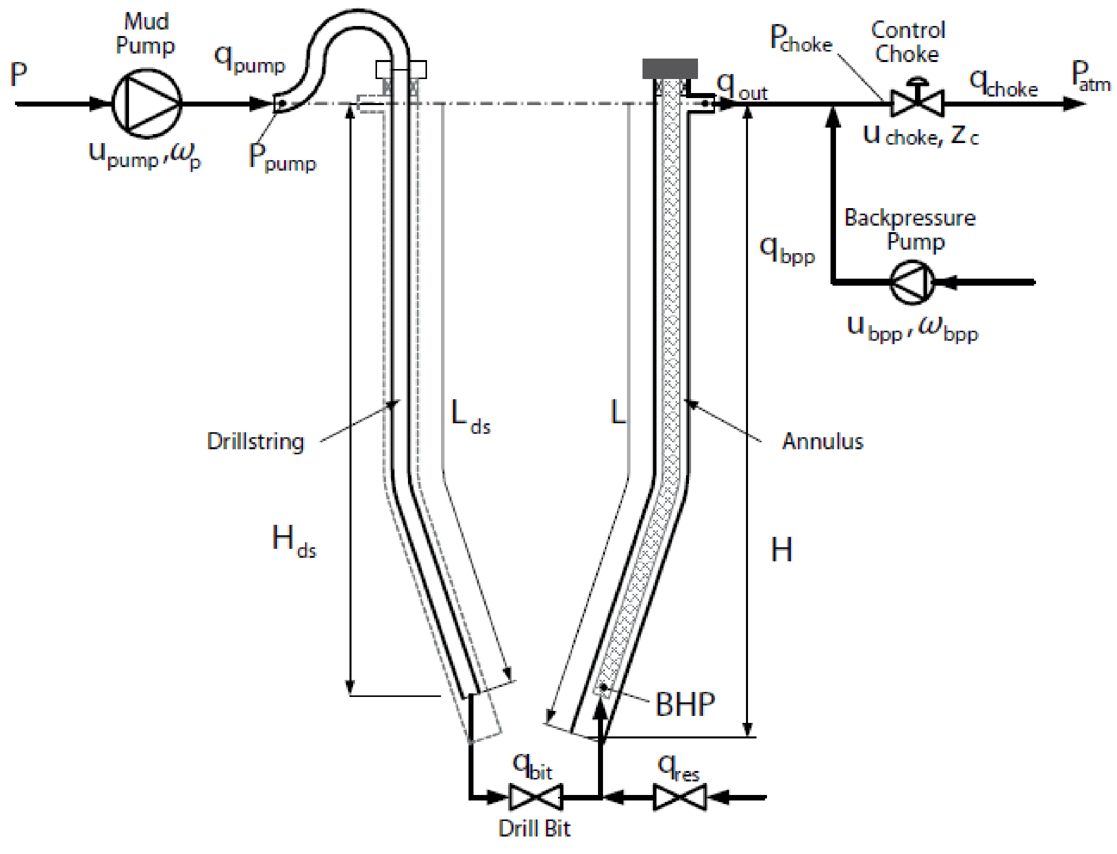

Figure 11 U-Tube Concept of well control [16]

This is a simplified schematic of the MPD bottom hole pressures control system used for Marine Cybernetics AS. The system has a mud pump connected to the drill string in order to inject the mud. The mud flows though the inner region of the drill string to the drill bit. After passing though the bit the mud flows by the annular region and achieve the choke line, where there is installed a controlled choke valve. At the choke valve, in addition to the annulus flow q_{out} there is mud flow generated by the backpressure pumpq_{bpp}. The possibility of influx occurrence is represented by the flow q_{res} that is represented in the figure 11, which also depicts separately the flow regions to facilitate the understanding of the U-tube concept.

3.1.4: Circulating Dynamic Pressure

The necessary pressure required to circulate the mud through the surface lines is defined as circulating dynamic pressure is provided by the rig pump. As it can see in the Figure 12 there is a pressure difference between the mud circulated and no circulation. The friction loss causes a slight increase when mud is circulating, which results in an increase over the static bottom hole pressure and this increase is equal to APL [17] .

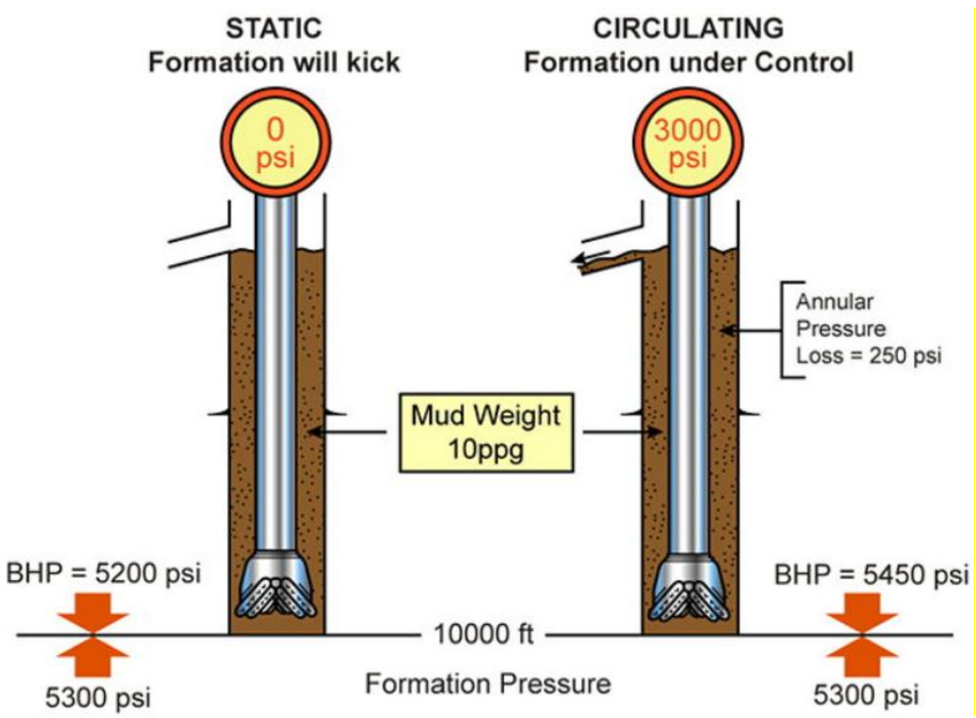

Figure 12 Static and dynamic circulation of the mud [17]

This introduce the concept of Equivalent Circulation Density (EDC) which is defined as the apparent fluid density which results from adding annular friction to the actual fluid density in the well. The ECD [17] is given as,

$$ECD = EMD + \frac{\Delta P}{g.TVD} \tag{3.4}$$

where, ESD is the equivalent static fluid density and ΔP is the frictional pressure loss.

3.1.5: Pressure Gradient Window

The success of an operation depends largely on managing the pressure throughout the well to avoid borehole failures and, thus reduce non-productive time (NPT) of operations. While drilling it is important to keep the pressures inside a pressure window as follows:

$$P_F < P < P_{Max} \tag{3.5}$$

where P_F is defined by formation pressure, also known as pore pressure, which is the pressure within the reservoir rock. The wellbore pressure thereby should be higher than the pore pressure, in order to avoid influx from the formation into the wellbore, and at the same time, the pressure should be lower than (P_{Max},) in order to avoid damages to the formation. As shown in the Figure 13 bellow.

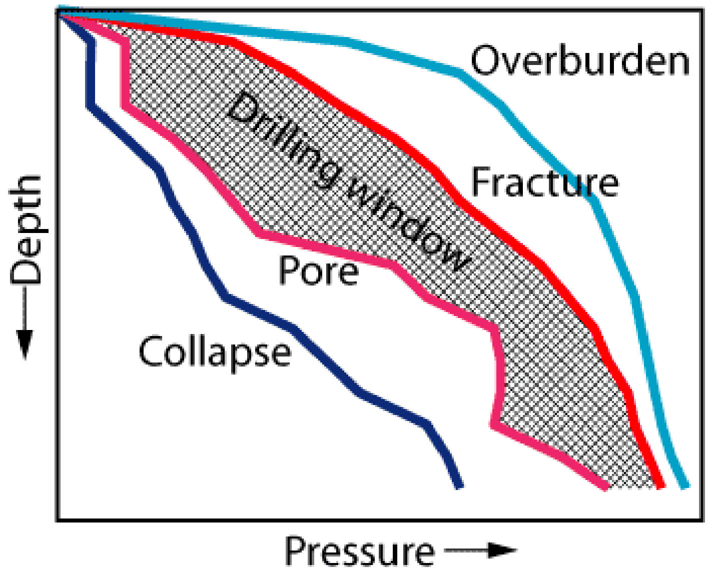

Figure 13 Wellbore pressure window

3.2: Rotary Steerable Systems

Rotary Steerable Systems (RSS) are well known as drilling optimization steering tools, it allows to plan complex wellbore geometries, including horizontal and extended-reach wells. These systems represent a step change in reliability and efficiency, facilitating the drilling of longer runs, optimizing wellbore placement, and reducing time [18]. Better borehole quality and faster rates of penetration (ROP) are achieved by RSS capability to steer the wells without sliding (Figure 14). In total, Rotary Steerable Systems tools are well suited to the application of automation to improve performance. They are capable to control the inclination and direction in which a well is drilled using a steering mechanism that continually rotates. For this among other reasons, this work will approach the modeling of a RSS tool. The modeling focus on obtain a better simulation of a modern directional drilling tool.

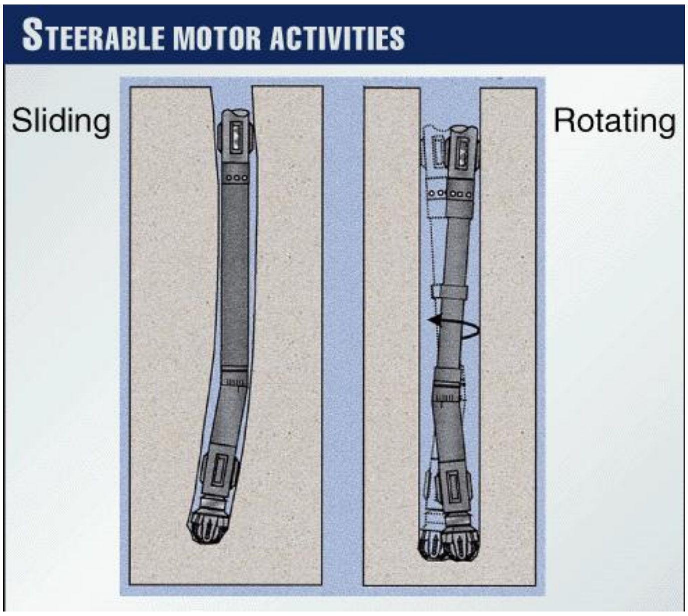

Figure 14 Steerable Motor Activities

3.2.1: Evolution of RSS

Before the development of leading-edge steerable systems, expedient placement to drill collars and stabilizers in the BHA allowed drillers to build or drop angle. These techniques allowed some control over hole inclination, but little or no control over the azimuth of the wellbore [19]. Nowadays, a steerable motors consists of a power-generating section, through which drilling fluid is pumped to turn the drill bit, a bend section of 0º to 3º, a drive shaft and the bit, as shown in the Figure 15.

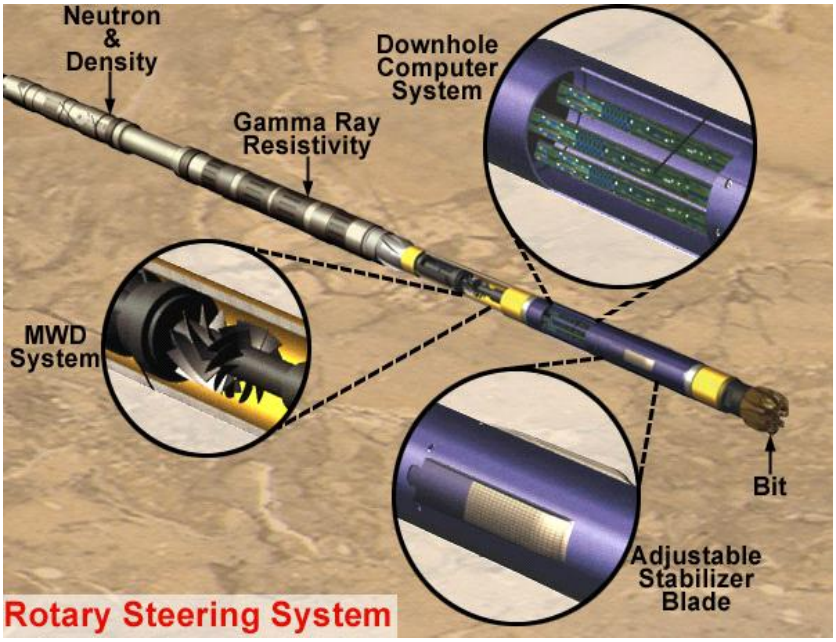

Figure 15 Rotary Steerable System assembly

Probably the greatest challenge in conventional slide drilling is the tendency of the nonrotating drill string to become stuck [19]. Since the sliding-mode drilling decreases the horse-power available to turn the bit, which, combined with sliding friction, decreases the rate of penetration. Eventually, frictional forces during sliding build to the point that there is insufficient axial weight to overcome the drag of the drillpipe against the wellbore, and further drilling is no possible. The numerous undulations or doglegs in the wellbore increase tortuosity. During production, gas may accumulate in the high spots and water in the lower, causing choking production, that it must be avoided. The use of rotary steerable system eliminates the sliding mode and produces a smoother wellbore. Directional drilling in the sliding and rotating modes typically results in a more irregular and longer path than planned (red trajectory) see Figure 16. Doglegs can affect the ability to run casing to total depth. The use of a rotary steerable system eliminates the smoother wellbore (black trajectory).

RSS works with continuous rotation of the drill string while steering the well. Because of the full rotation plus no stationary components to create friction that reduces efficiency and anchors the BHA in the hole penetration rates are improved. This reduces drilling torque, improves drilling efficiency, and eliminates the need for unplanned wiper trips. The smooth wellbore also makes it easier to run casing.

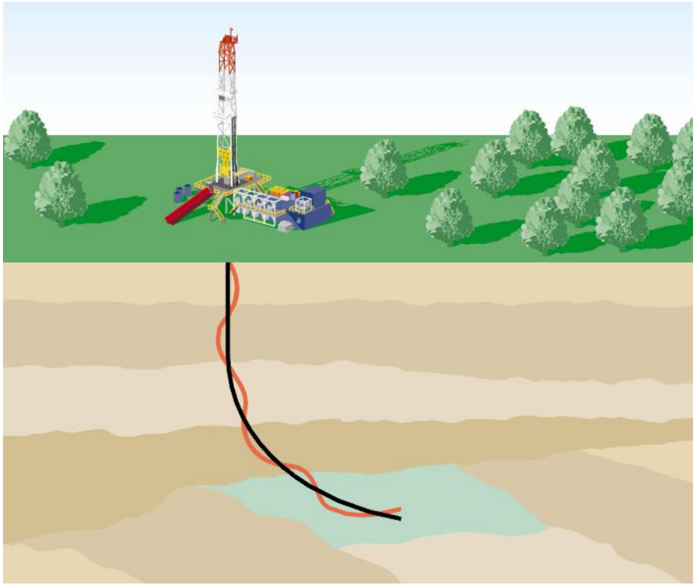

Figure 16 Conventional DD (red) and RSS (black) [19]

3.2.2: Technical development of RSS

The news RSS are operate by the directional driller located remotely in the operator`s office, with the ability to remotely control the mud pumps. If a command is required for changing the RSS program, the system remotely controls the rig pumps to execute the downlink sequence and change the downhole settings of the RSS [18]. RSS tools are changed to the application of automation to improve performance. The latest high performance RSS tools include fast closed loop control systems to allow the RSS to hold inclination and azimuth for long well tangents. This is achieved by programming the tool to follow a specific direction, and the RSS tool with adjust its configuration to follow this instruction without further human intervention. This is the first step to automating directional drilling, and consequently the main situation where HIL testing is needed. Also, the objective of this work is based on the simulation of the PowerDrive X5 Power System from Schlumberger, which has this functionality and will be explain in the follow subchapter.

3.3: PowerDrive X5

The PowerDrive X5 is a push-the-bit Rotary Steerable System tool from Schlumberger that deflects the BHA to the desired well path. The choice of modeling this specific tool came because of some reasons: it is easy to operate and deflect, can be use it in different scenarios and my co-supervisor in the company, John During, indicates as this tool to obtain good results on modeling for directional drilling[20].

PowerDrive X5 is engineered to provide drill longer runs, optimize wellbore placement, and reduce drilling time. Automatic inclination hold and efficient downlink funcions maintain directional control while drilling ahead.

3.3.1: Characteristcs

The tool uses mud actuated pads to change the direction of drilling by pushing against the formation, the figures 17 and 18 bellow shows step by step of pads functionality. All external parts rotates together. Includes an automatic inclination hold and efficient downlink functions maintain directional control while drilling ahead. It is applicable for extended-reach drilling, deviated and horizontal wells, also for land, offshore and deepwater locations.

The tool exert a side force on the bit to achieve bit deflection and the required hole curvature. Since the system uses the mud flow to activate the steering pads, exerting a side force on the bit. This operational principle requires a pressure drop through the bias unit, which can be achieved by bit nuzzling or a nozzle inside the bias unit. The amount of steering force is proportional to the differential pressure across the pads.

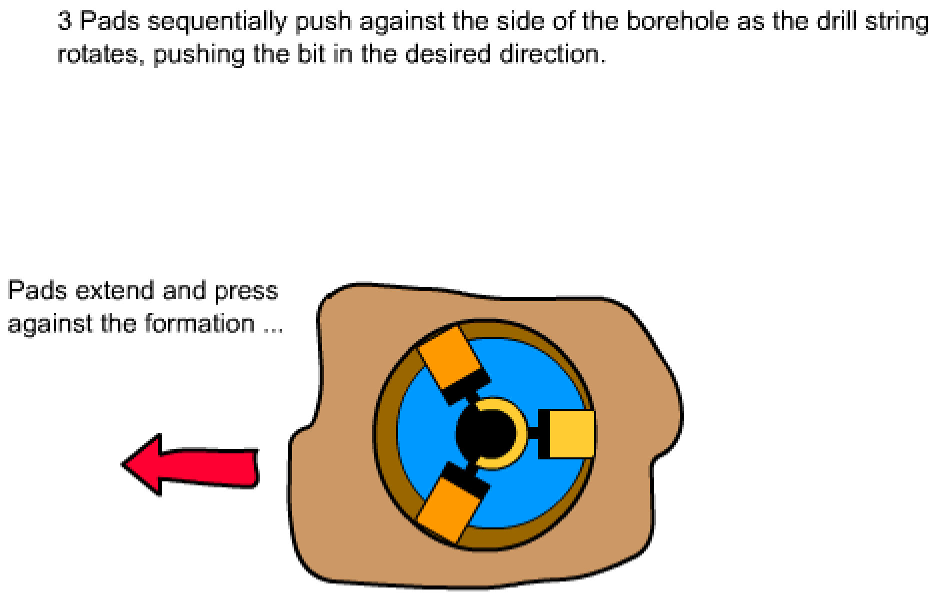

Figure 17 Pads Performance [21]

Figure 18 Final step of the pads [21]

3.3.2: Functionality

The PowerDrive system is composed for two main parts: control unit and bias unit. The first one is responsible for provide the average magnitude and direction of the bit side loads required to achieve the desired trajectory. The bias unit, applies force to the bit in a controlled direction while the entire drill string rotates. As shown in the Figure 19 below:

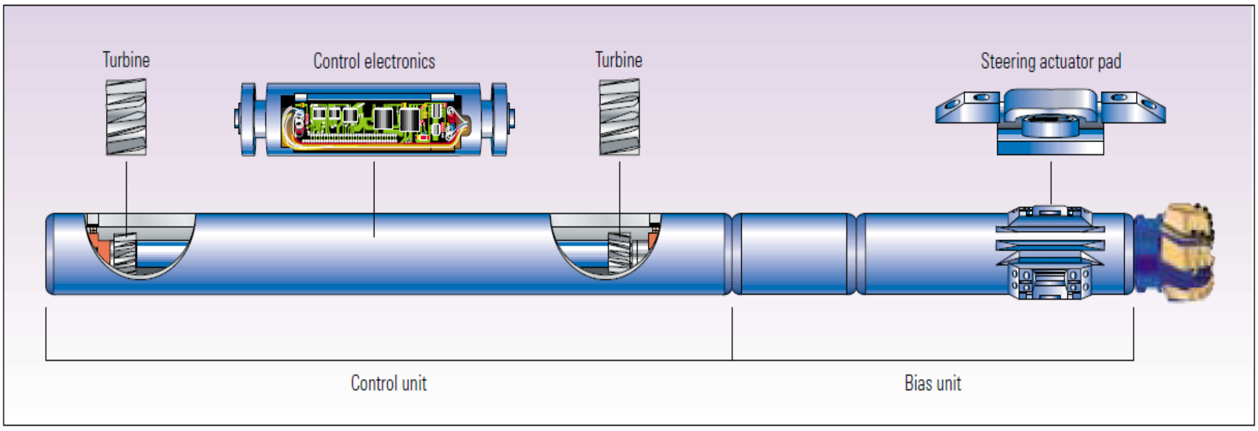

Figure 19 Power Drive Steerable System [19]

The pads located in the bias unit are activated by controlled mud flow through a valve. The three-way rotary disk valve actuates the pads by sequentially diverting mud into the piston chamber of each pad as it rotates into alignment with the desired push point –the point opposite the desired trajectory- in the well [19]. After a pad passes the push point, the rotary valve cuts off its mud supply and the mud escapes through a port. Each pads extends maximal $^{3}/_{8}\, in\ [1cm]$, during each revolutions of the bias unit. The performance illustration of the control unit can be seen in the Figure 20.

The three-way rotary disk valve actuates the pads by sequentially diverting mud into the piston chamber of each pad as it rotates into alignment with the desired push point. An input shaft connects the rotary valve to the control unit to regulate the position of the push point.

The control unit is responsible to maintains the proper angular position of the input shaft relative to the formation. If no change in direction is needed, the system is operated in a neutral mode, with each pad extended in turn, so that the pads push in all directions and effectively “cancel” each other effects [19]. Also the control unit, can be commanded to hold a fixed roll angle.

The downhole information carried by the control unit are transmitted to surface by the PowerPulse communication system and are monitored by MWD tools. Three-axis accelerometer and magnetometer sensors provide information about inclination and azimuth of the bit as well as the angular position of the input shaft. Additional sensors record the instantaneous speed of the drill string with respect to the formation, thereby providing useful data about drill string behavior. There are also shock and thermal sensors.

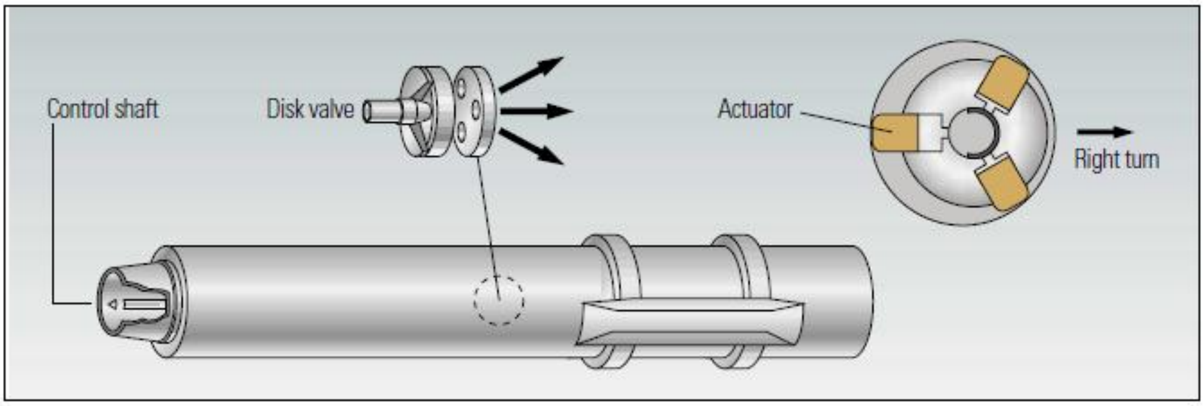

Figure 20 Control shaft illustration of PowerDrive X5 [19]

3.4: Over - Running the Bit

Rotating the drill string with any positive displacement motor in a stalled condition may cause the upper portion of the motor and drill string to over-run the bit. This condition can damage the motor and also cause an undesired deviation position from the wellpath. The dynamic of a drill-string is complicated, consisting on coupled axial, lateral and torsional vibrations. Figure 21 illustrates these vibrations, which can develop a motors fractures, and must be avoid it.

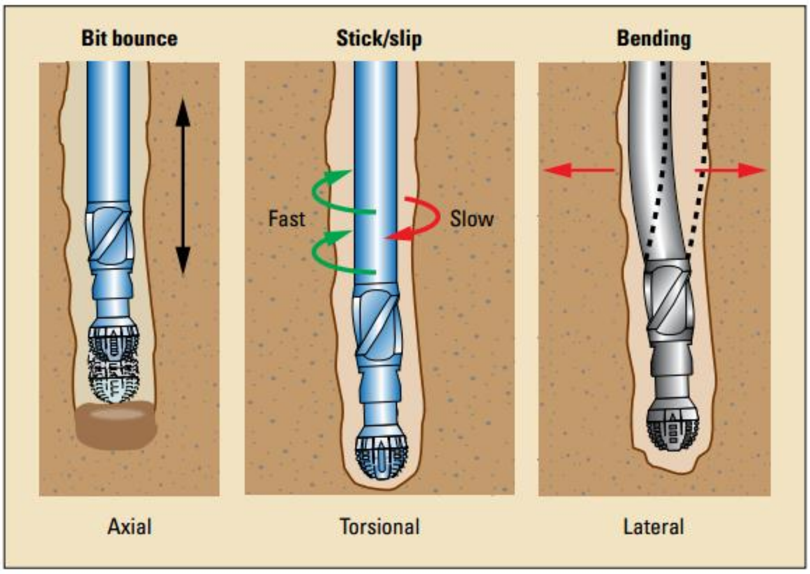

Figure 21 Drillstring dynamic

3.4.1: Stick Slip (Torsional Vibration)

It is caused by the cyclical rotational acceleration and deceleration of the bit, BHA, or the drill string. Stick slip is the momentary stop in rotation of the bit or BHA that can cause the drill string to instantly torque up then release, accelerating the BHA to dangerously high speeds. Torsional fluctuations fatigue drill collar connections and can damage bits.

3.4.2: Bending (Lateral Vibration)

It can creates large shocks as the BHA impacts the wellbore wall, causing a high bending. Lateral vibration can be extremely damaging to all drill string components and result in energy being removed from the system that would otherwise be used to drill ahead. High lateral vibration will result in a reduction in penetration rate and premature bit and BHA failure including motor housing fractures [22].

3.4.3: Bit Bounce (Axial Vibration)

Axial is also caused by a cyclical loading and unloading as the torsional vibration, but this time occurs in the axial direction. It can cause bit bounce, which may damage bit cutters and bearing.

3.5: Measurement While Drilling

To transmit data from downhole assembly to the surface it was necessary to create a measurement transmission system. Before MWD, all survey data were obtained by stopping the drilling process for wireline logging. That entailed too much work, stop drilling process, put the drill pipe on slip, break out Kelly, lower the wireline tool, retrieve tool, read the survey and plan the further action. This used to increase considerably the non-productive time (NPT) [23].

From the develop of those systems the recognition data as inclination, direction, and tool face angle could be measured while drilling and the data could be transmitted to surface though the mud stream. These measurements provide information of the forces acting on the drill string and BHA including dynamic behavior and the occurrence of vibration. Also, the size and shape of the wellbore itself providing drilling optimization .

Initially there were three basic acquisition data: inclination, Azimuth and toolface. Those parameters helped the directional driller to position he well correctly. Later on, MWD was equipped with Gamma Ray for geosterring data evaluation, gauge to measure the annular pressure, and strain gauge to measure the WOB and torque on the bit.

Data transmission methods usually involve digitally encoding data and transmitting to the surface as pressure pulses in the mud system. These pressures may be positive, negative or continuous sine waves. MWD tools that measure formation parameters (resistivity, porosity, sonic velocity, gamma ray) are referred to as logging-while-drilling (LWD) tools [21].

3.5.1: Stabilizer

Stabilizer are mostly used to control hole deviation, reduce risk of differential sticking and ream out doglegs. There are several different types, they differ on where they are located in the BHA, the material, the format depending on several conditions on where they will be applied, the kind of formation, size of the hole, the depth, the motor, the bit, etc.

The type of stabilizers depend upon the formation in which they are to be used. It is also possible to use more than one stabilizer if it is necessary. By controlling the span between the stabilizers, the directional driller can control the rate of deflection angle movement reasonably well.

The addition of stabilizers modifies the trajectory depending where they are located. It can build, hold or drop the rate. The figure 22 bellow shows some of the common rotary assemblies currently being used.

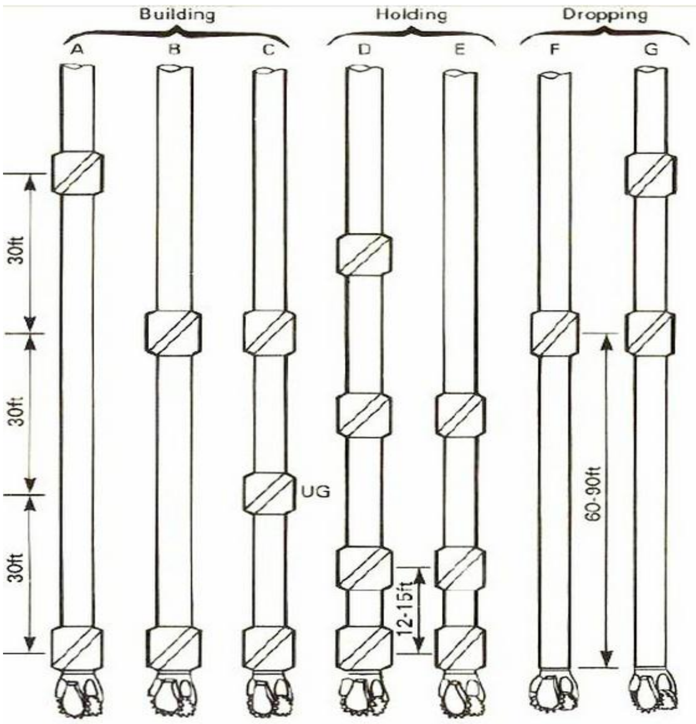

Figure 22 Different location for stabilizers

3.6: Deflection Tools

Although mud motors and rotary steerable systems are overwhelmingly the tools of choice for controlled directional drilling, there are other tools that may be of some use in certain areas. This section describes the simplest tools used to make a controlled trajectory change.

3.6.1: Whipstocks

Whipstocks is a very simple device used to kick off the well. The wedge is attached to the bottomhole assembly by means of a shear pin. The assembly is lowered to bottom and oriented in the proper direction [24]. The driller than applies weight to set the wedge and shear the pin, and then trips the tools so that a full-gauge hole opener can be run. After that, assure if the direction is correctly and the process is repeated until the build section of the well is completed. The figure 23 shows a typical step by step of openhole whipstock.

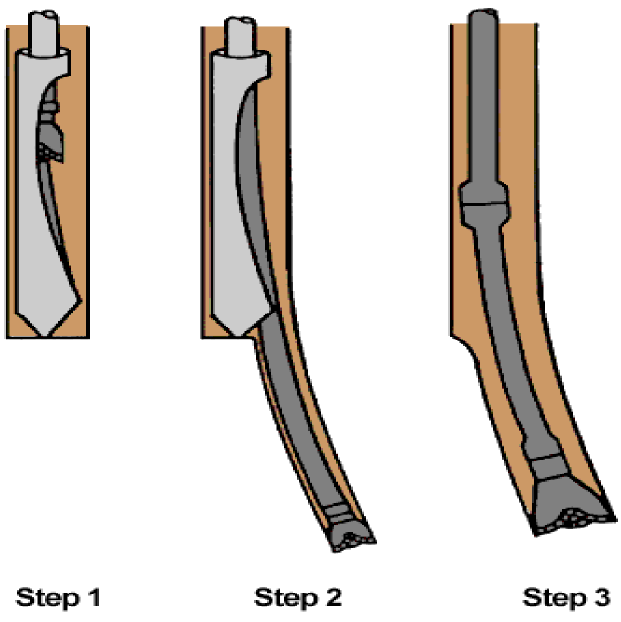

Figure 23 Openhole Whipstocks steps

3.6.2: Jetting

Jetting deflection (Figure 24) is more usably in soft formation. The bit is lowered to bottom, the jet is oriented in the desired direction, and mud flows is initiated with no drill string rotation. After hydraulically gouging a small pilot hole, the driller initiates conventional rotary drilling to open the section to full gauge. The process is then repeated.

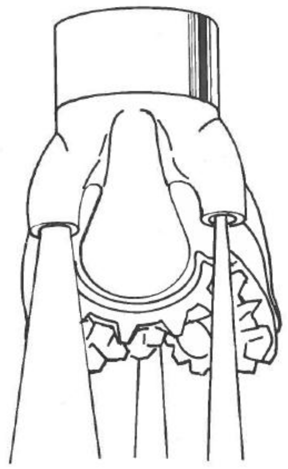

Figure 24 Jetting Deflection [24]

3.6.3: Downhole Motors

The downhole mud motor has replaced the Whipstock as the primary tool to deviate the direction of a wellbore, since it is safer, provides dogsleg control and drills a full gauge hole [25]. It works in a simple way, first the mud motor function is charge to rotate the bit when a bent sub assembly is used. This is able to eliminate drill string rotation and the wellbore is then deviated in the direction of the oriented bent sub.

The deviation assembly is composed with: a non-magnetic collar, a bent sub, a mud motor and the drilling bit. Since the drill string does not rotate, the bent sub is the responsible for control the deviation., thus maintaining the motor and the bit at a fixed angle relative to the non-magnetic drill collar. The angle of the bent sub, the motor size and the hole size are responsible for the radius of the circle.

4: Directional Drilling

Directional drilling is the process of directing the wellbore along some trajectory to a predetermined target [25]. The various types of well and applications of directional well will be explain in this chapter along with well profiles and well planning.

One of the reasons to do directional drilling is to increase production rates. There are many reservoirs which cannot be tapped by vertical well [25] Since the wellbores are normally drilled vertically, many occasion arise that start to make necessary to drill at an angle.

Directional well are drilled straight to a predetermined depth, and then are gradually curved as need it. Since the curvature of each well is gradual –usually between 1º to 4º per 100 feet (30.5 meters) of well depth- the straight and casing can follow the curve of the well without difficulty. Even though the curve is gradual, directional wells can be deflected of vertical to a very high degree, and also horizontally [26].

Knowing that to build and offshore platform involves a lot of expenses, it must make it worthwhile to construct a drilling platform in water. For that reason, operators cannot afford to tap offshore reservoirs unless they can drill several wells from a single platform.

4.1: Directional Well Applications

There are many different reasons for drilling a non-vertical well, directional drilling has several other uses (Figure 25). Some of the most typical used application of directionally controlled drilling are explain below.

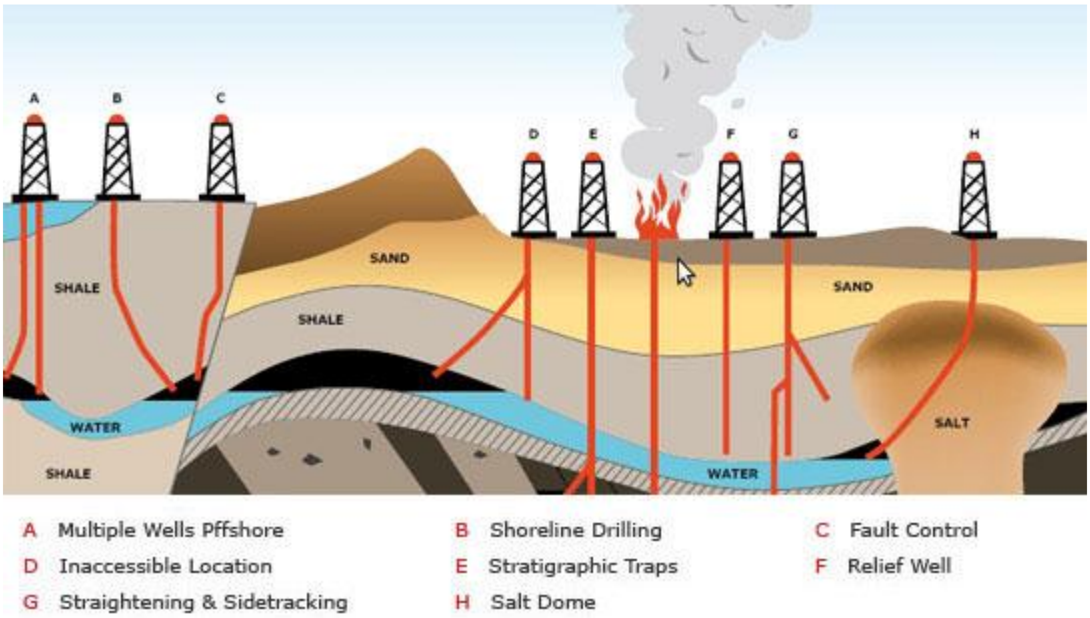

Figure 25 Directional Drilling motivation

4.1.1: Sidetracking

The most common type of sidetracking (Figure 26), are performed when there are unexpected changes geology and obstruction in the path of the wellbore. In most cases, when is intentionally deviated to avoid undrillable material, such as tools, drill pipes, drill collars, known as “Fish”.

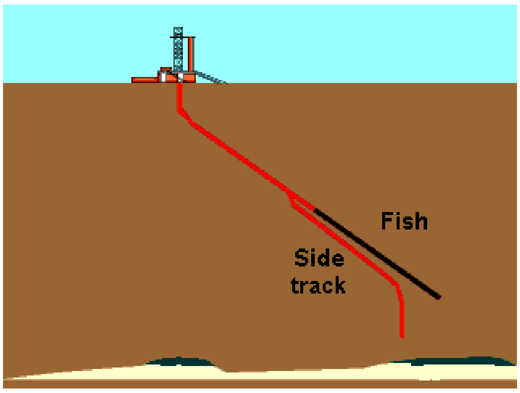

Figure 26 Sidetracking [27]

4.1.2: Inaccessible Locations

It can happen when there is inaccessible locations such as targets located beneath cities, rivers, environmentally sensitive areas or located beneath water.

4.1.3: Relief Wells

Drilling techniques are used to drill wells down to a well suffering a blowout in order to stop the blowout. A carefully planned directional well must be drilled with precision to locate and intercept the blowing well`s borehole. See Figure 27.

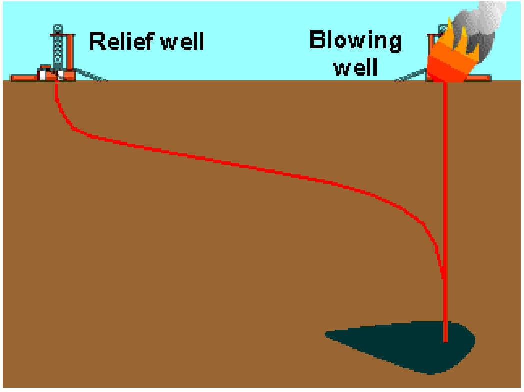

Figure 27 Relief Wells [27]

4.1.4: Multiple Exploration Wells

Multiple wells (Figure 28) are usually drilled from a single location. This is especially seen with offshore rigs, where it is easier to access a range of well from one location. It is more economical way to develop offshore fields, and also in becoming more common on land based rigs, in an attempt to minimize the overall environmental impact.

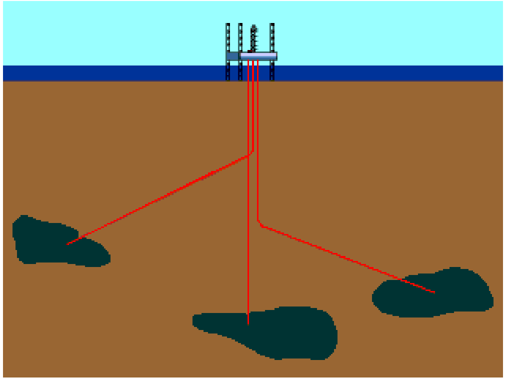

Figure 28 Multiple Exploration Wells [27]

4.1.5: Horizontal Wells

It is used to intersect a producing formation horizontally to better produce the reservoir. Horizontal drilling (Figure 29) increases the surface area of a producing formation, because they offer greater contact area with the productive layer so that the overall production of the well is increased.

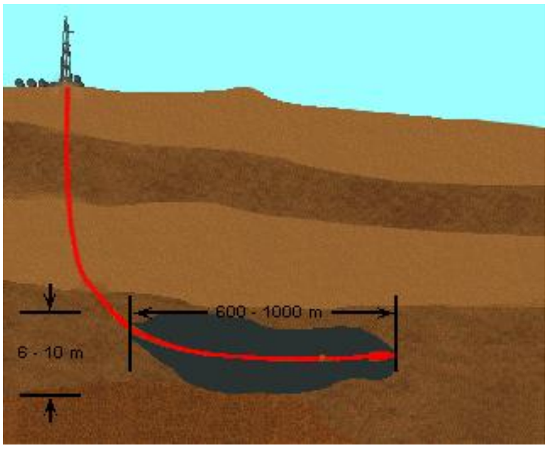

Figure 29 Horizontal Drilling [27]

4.2: Parameters Defining the Wellpath

There are three specific parameter (Figure 30) which must be taken in consideration when planning a well trajectories. They are:

- Kick-off Point
- Buildup and Drop off Section

- Tangent Angle

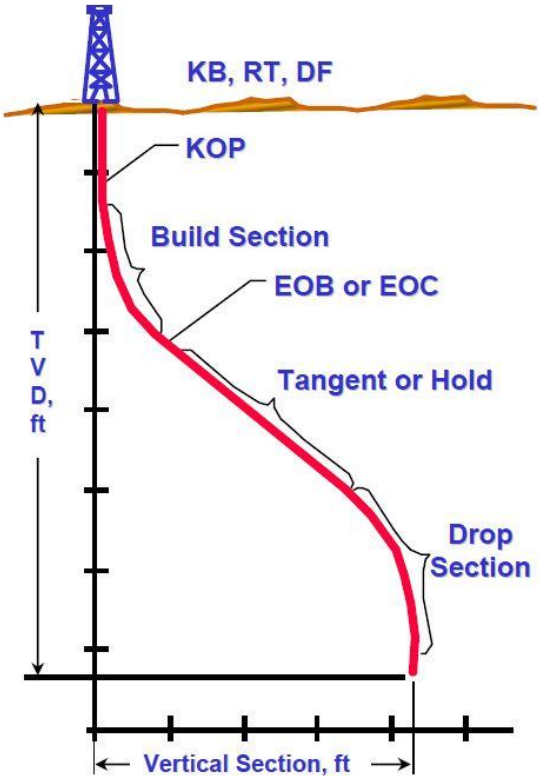

Figure 30 Well planning considerations [23]

4.2.1: Kickoff Point (KOP)

The kick off point is the along hole measured depth at which a change in inclination of the well is initiated and the well begins to orientated in that particular direction. It depends on factors as: hole pattern selected, casing, mud and the maximum angle to be used [25].

4.2.2: Buildup Rate (BUR) and Drop Off Rate (DOR)

The buildup rate and the drop off rate (in degrees of inclination) are the rates at which the well deviates from the vertical, increasing and decreasing respectively. Drop off section is less critical then rate build up section, since there is less tension in the drill pipe run through the deeper dogleg and less time is spent rotating below the dogleg.

The hole deviation intentionally created by directional drilling is known as doglegs. The severity of the dog-legs must be controlled to prevent some future damages, such as: drill string failures, difficulty in logging and surveying below the bend, productions problems, inferior cementing caused by non-centralized casing.

4.2.3: Tangent Angle

It represents the inclination of the long straight section of the well after the buildup section of the well. The tangent angle will generally be between 10 and 60 degrees, because off the difficulty of control the trajectory of the well at angles below 10º and to run wireline tools into wells at angles of greater than 60º.

4.2.4: True Vertical Depth (TVD)

The depth of well measured from the surface straight down to the bottom of the well [28].

4.2.5: Measured Depth (MD)

The depth of the survey station is provided by the driller and is calculated on the basis of the length of drill string in the wellbore and the distance between the drillbit and the survey too [6].

4.2.6: Azimuthal and Inclination of the wellbore

Is the angle in degrees between the horizontal component of the wellbore direction, at a particular point, measured in a clockwise direction from the reference (North). It is generally expressed as a reading on a 0º to 360 º, measured from North. The inclination of the wellbore is the angle in degrees that the wellbore is deviated from the vertical. The Figure 31 bellow shows how to find the MD, TVD and Azimuth in the wellpath.

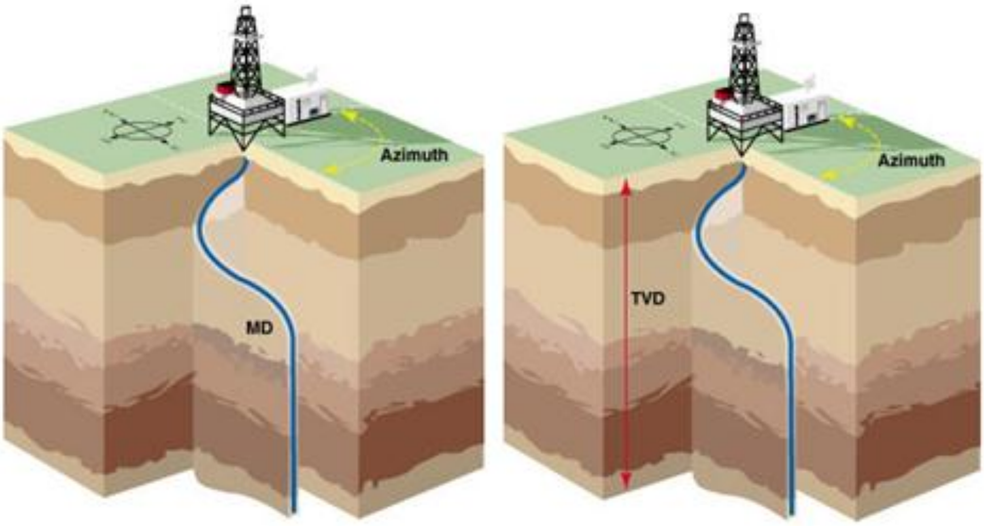

Figure 31 Azimuth, Measured Depth and True Vertical Depth Parameters

4.2.7: Rate o Penetration (ROP)

Rate of Penetration it is the measured of the speed at which the bit drills into formations, usually minutes per foot. It is directly related with the drilling time, consequently influences in the necessary amount of money to drill the well. A wiser way to use the ROP can help the driller to achieve the reservoir in less time.

The ROP is a measure [1] of the drilling speed, defined as the well length L increase over time t, as shown in the equation (5.1).

$$ROP = \frac{\partial L}{\partial t} \tag{5.1}$$

Based in real cases data it was estimated the ROP value of $0.0025\ {}^{m}/_{sec}$, for use in this work.

4.3: Wellpath Calculation

With the advance of directional drilling, trajectory programs are becoming more complicated. When drilling a directional well, surveys are taken at regular intervals in order to ascertain the coordinates to measured inclination and direction at downhole location and then to calculate the trajectory.

At each location, inclination and direction angles are measured as well as the course length between them. Using this data it is possible to calculate North-South (N-S), East-West (E-W) coordinates and TVD of the well. There are several methods that can be used to calculate the survey data. The main difference in the techniques is that one uses straight line approximations and the other assumes the wellbore is more of a curve.

Some of the most common methods used for survey calculation in the industry are:

- Tangential
- Balanced Tangential
- Average Angle
- Radius of Curvature
- Minimum Curvature

Marine Cybernetics has developed a 2-D oil well simulator for testing of control systems, where the main dynamics of the environment and devices involved are captured by the functional HIL simulator. It simulates all the pressures involved (BHP, chocke pressure, etc), equipment (rig mud pump, chocke valve, etc) and behaviors associated to drilling operation. It also takes into account the inclination angle (from vertical axis) to determine the depth of the well.

The objectives of this subchapter is to evaluate and compare some of the survey calculation method available for the industry. In addition, evaluate the actual influence of adding a third dimension (3-D) in the modeling explained above. After evaluation, the company will be able to have a position about what is the real effect of adding a third dimension. In addition, with this numerical will be able to ensure the necessity of or adding an important data for improving quality in the vertical well simulator, or cut irrelevant data for HIL testing and optimized the process

4.3.1: Tangential Method

The Tangential Method is the simplest method among the other directional survey calculation methods. The Tangential Method gives a noticeable error for northing, easting and evaluation which makes it no longer preferred in the industry [25].

In Tangential Method, the greater the build or drop rate, the greater the error. Also, the distance between surveys has an effect on the quantity of the error. See Figure 32 below:

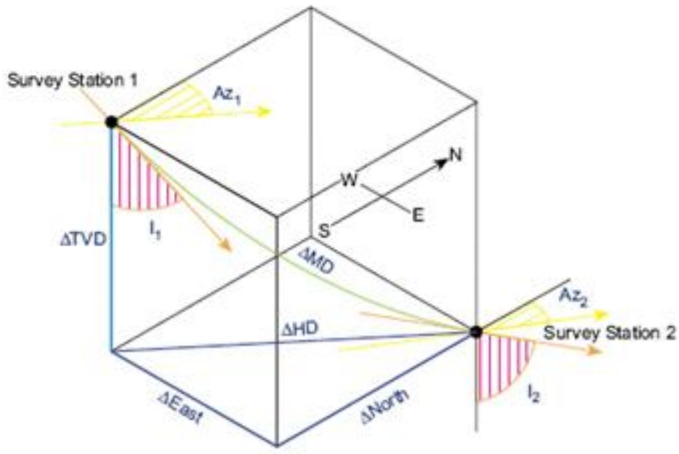

Figure 32 Tangential Method Calculation [29]

The formulas are listed below [19]:

$$North = MD \cdot sin(I_2) \cdot cos(A_2) \quad (4.1)$$

$$East = MD \cdot sin(I_2) \cdot cos(A_2) \quad (4.2)$$

$$TVD = MD \cdot cos(I_2) \quad (4.3)$$

where;

MD = Measured Depth between surveys (ft)
I_1 = Inclination anlge of upper survey (degrees)
I_2= Inclination angle of lower (degrees)
A_2 =Azimuth direction of upper survey
A_2 =Azimuth direction of lower survey

4.3.2: Balanced Tangential Method

This calculation method treats half of the measured distance ($\frac{MD}{2}$) as being tangent to I_1 and A_1 the remainder of measured distance as being tangent to I_2 and A_2. This technique provides a smoother curve which should more closely approximate the actual wellbore between surveys. Although, the longer the distance between survey stations, the greater the possibility of error [23].

The formulas are listed below [29]:

$$North = \frac{MD}{2} \cdot [(sin(I_1)\, cos(A_1)) + (sin(I_2) \cdot cos(A_2))] \quad (4.4)$$

$$East = \frac{MD}{2} \cdot [(sin(I_1)\, sin(A_1)) + (sin(I_2)\, sin(A_2))] \quad (4.5)$$

$$TVD = \frac{MD}{2} \cdot (cos(I_1) + cos(I_2)) \quad (4.6)$$

4.3.3: Average Angle Method

When using the average angle method, the inclination and azimuth at the lower and upper survey stations are mathematically averaged, and then the wellbore course is assumed to be tangential to the average inclination and azimuth [23]. This model if often used at the rig site since the calculations are fairly simple [6].

The formulas for average angle methods are listed below [29]:

$$North = \frac{MD}{2} \cdot [(sin(I_1) \cdot cos(A_1)) + (sin(I_2) \cdot cos(A_2))] \quad (4.7)$$

$$East = MD \cdot \left[sin(\frac{I_1 + I_2}{2}) \cdot sin(\frac{A_1 + A_2}{2}) \right] \quad (4.8)$$

$$TVD = MD \cdot cos(\frac{I_1 + I_2}{2}) \quad (4.9)$$

4.3.4: Radius Curvature

The method assumes the wellbore course is a smooth curve between the upper and lower survey stations. The curvature of the arc is determined by the survey inclinations and azimuths at the upper and lower survey stations as shown in Figure 33 below. John Ford [6] says this method is less sensitive to errors, even if the survey interval is relatively long. The calculations, however, are more complicated and are best handled by programmed software.

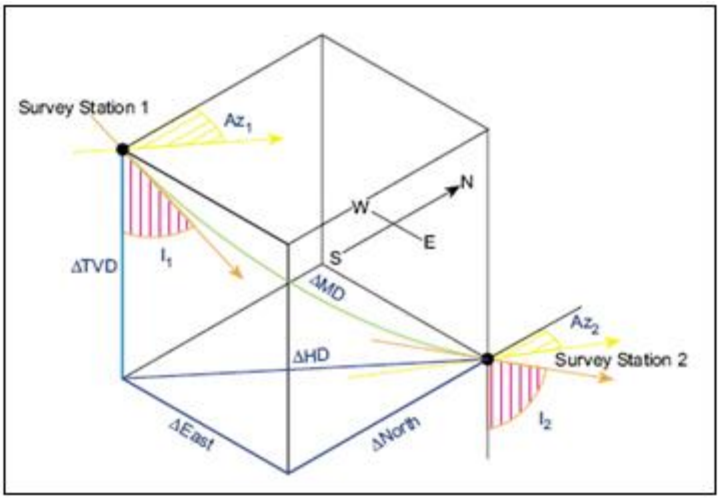

Figure 33 Radius of Curvature Model [29]

The formulas are shown below [29]:

$$North = \frac{MD \cdot (cos(I_1) - cos(I_2)) \cdot (sin(A_2) - sin(A_1))}{(I_2 - I_1) \cdot (A_2 - A_1)} \quad (4.10)$$

$$East = \frac{MD \cdot (cos(I_1) - cos(I_2)) \cdot (cos(A_1) - cos(A_2))}{(I_2 - I_1) \cdot (A_2 - A_1)} \quad (4.11)$$

$$TDV = \frac{MD \cdot (sin(I_2) - sin(I_1))}{I_2 - I_1} \quad (4.12)$$

4.3.5: Minimum Curvature

In this method, two adjacent survey points are assumed to lie on a circular arc. This is done by applying a ratio factor based on the amount of bending in the wellpath between the two stations (dog-leg angle(β)), as shown in the Figure 34 bellow. The dog-leg angle can be calculated from [29]:

$$\beta = cos^{-1}[cos(I_2 - I_1) - (sin(I_1) \cdot sin(I_2) \times (1 - cos(A_2 - A_1))] \quad (4.13)$$

And the ratio factor (RF) can be calculated from [19]:

$$RF = \frac{2}{\beta} \cdot tan(\frac{\beta}{2}) \quad (4.14)$$

The ratio factor is then applied to the results of $North, East\ and\ TVD$. The equations for the minimum curvature method can be summarized as follows [29]:

$$North = \frac{MD}{2} \cdot [sin(I_1) \cdot + sin(I_2) \cdot] \cdot RF \quad (4.15)$$

$$East = \frac{MD}{2} \cdot [sin(\mathrm{I}_1) \cdot + \sin(\mathrm{I}_2) \cdot \cos(\mathrm{A}_2)] \cdot \mathrm{RF} \quad (4.16)$$

$$TVD = \frac{MD}{2} \cdot [\cos(I_1) + \cos(I_2)] \cdot RF \tag{4.17}$$

The minimum curvature method is the one most often adopted for directional surveying calculations [29].

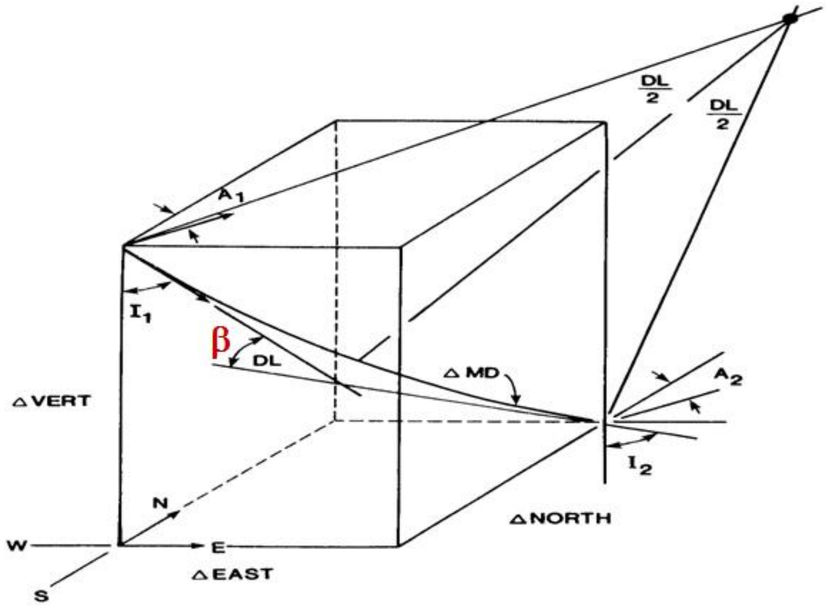

Figure 34 Minimum curvature Method [29]

4.3.6: Methods Comparison

It is notable that the tangential method shows considerable error. This is why the tangential method is no longer used. The differences among radius of curvature, minimum curvature and balanced tangential methods are so small that any of the methods could be used for calculating trajectory. But with the advent of programmable hand calculator, the minimum curvature method has become the most common in industry [25].

As shown in the Figure 35 the vertical (true vertical depth) profile plots of Matlab Program results using Ullrigg`s well data.

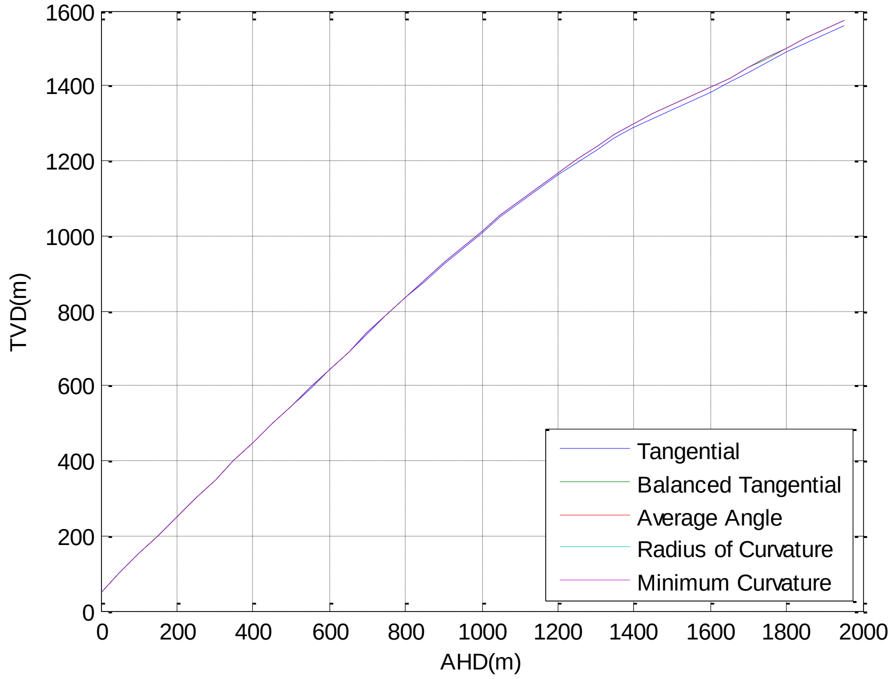

Figure 35 Vertical Profile

The two Figure 36 and 37 below shows a zoomed vertical plot of Matlab program results, where clearly sees the great difference between tangential method and the others.

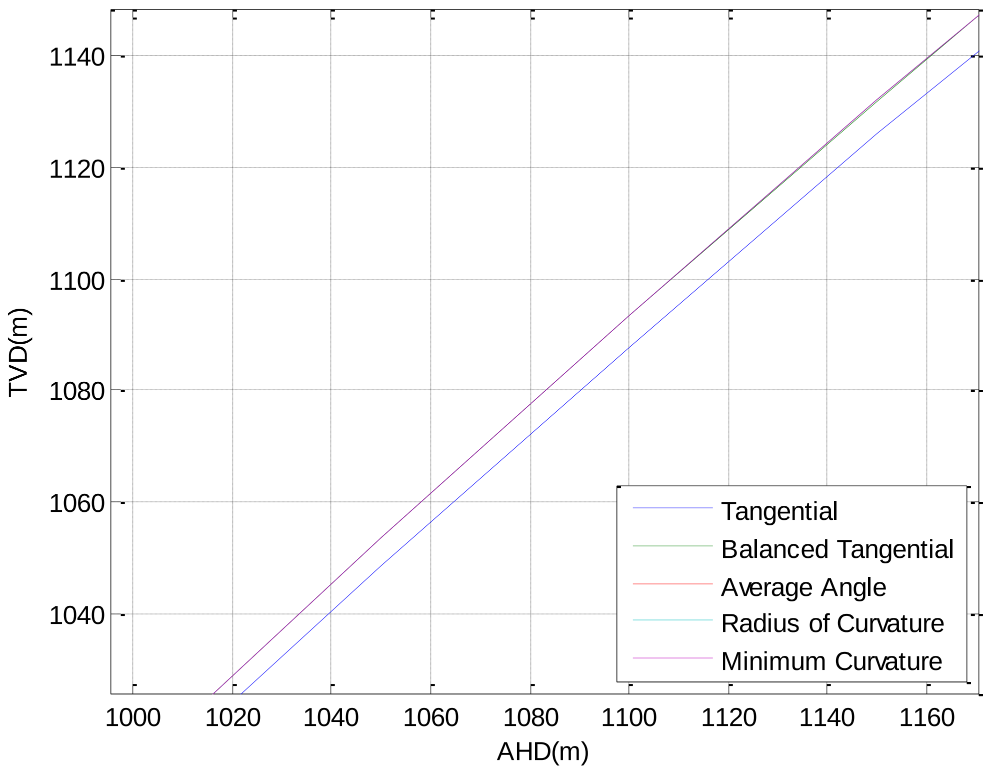

Figure 36 A zoomed vertical plot of Vertical profile

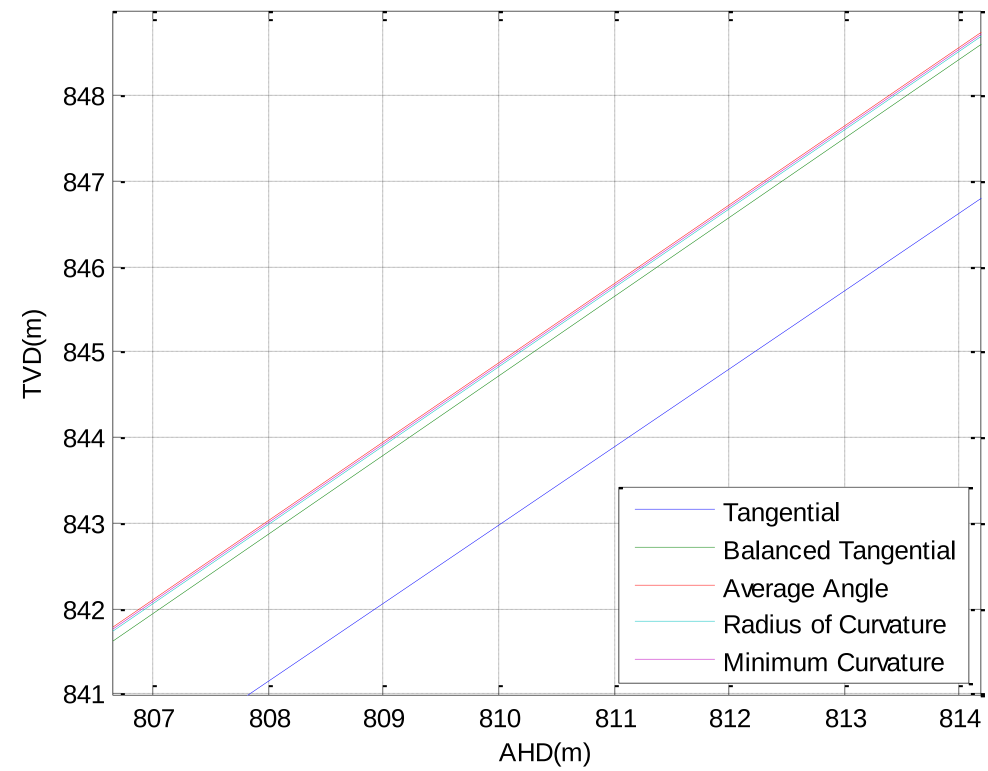

Figure 37 zoomed vertical plot of Vertical profile

As shown in the Figure 38 the horizontal profile plots of Matlab Program results using Ullrigg well data.

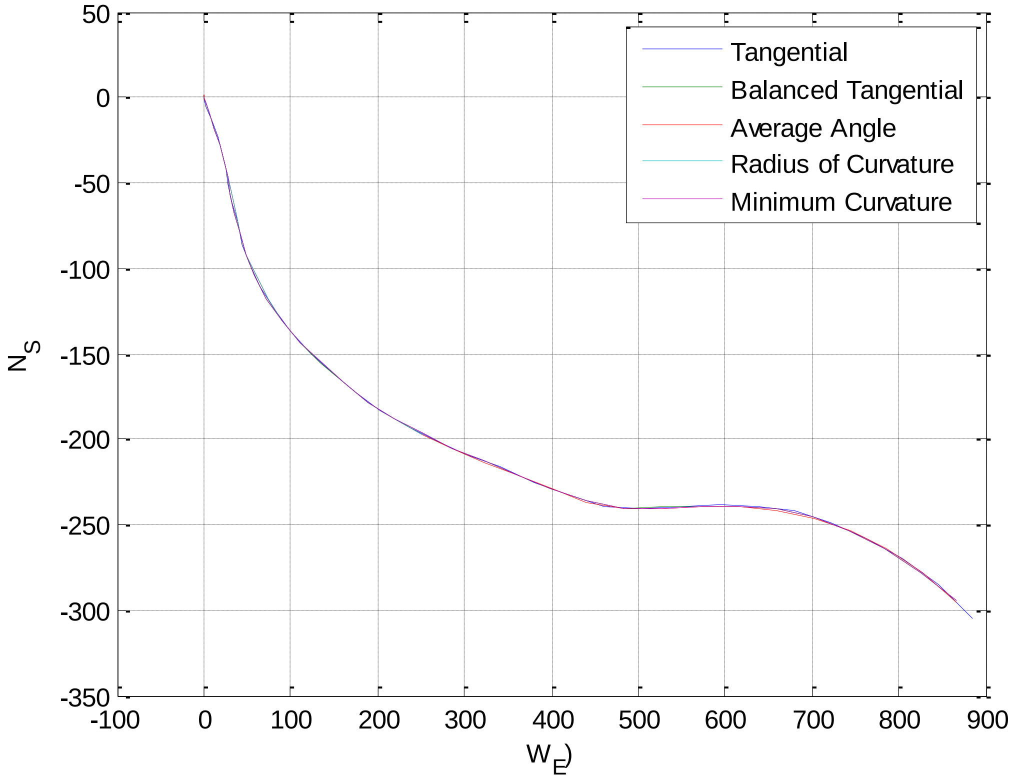

Figure 38 Horizontal Profile

The Figure 39 shows a zoomed horizontal plot of Matlab program results, where sees the major problem when applying the tangential method, mainly for moment of bend the well. Also the Average Angle Method shows some difference in the path comparing with others curvature methods. It didn`t follow the path perfectly, as the others methods, but still is a good method for calculating the well trajectory.

In the Figure 40 it is visible that the 3 methods: Balanced tangential, Radius of Curvature or Minimum Curvature follows the path almost in the same line, showing a good approximation. On the other hand, is noticeable the error on Tangential method and Average Angle method. The first because it uses straight line to calculate the path, and the second the equations are fairly simple, in order to have equations that can easily be calculated by hand, in case of the need to calculate the path at the rig.

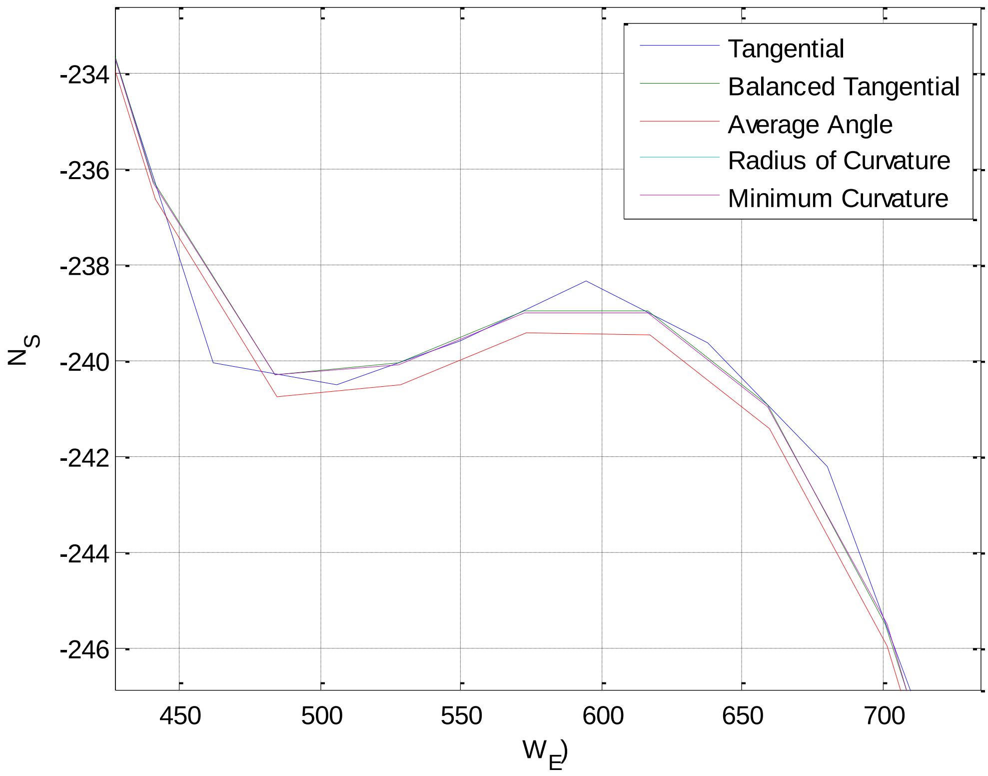

Figure 39 A zoomed Horizontal Profile with inclination

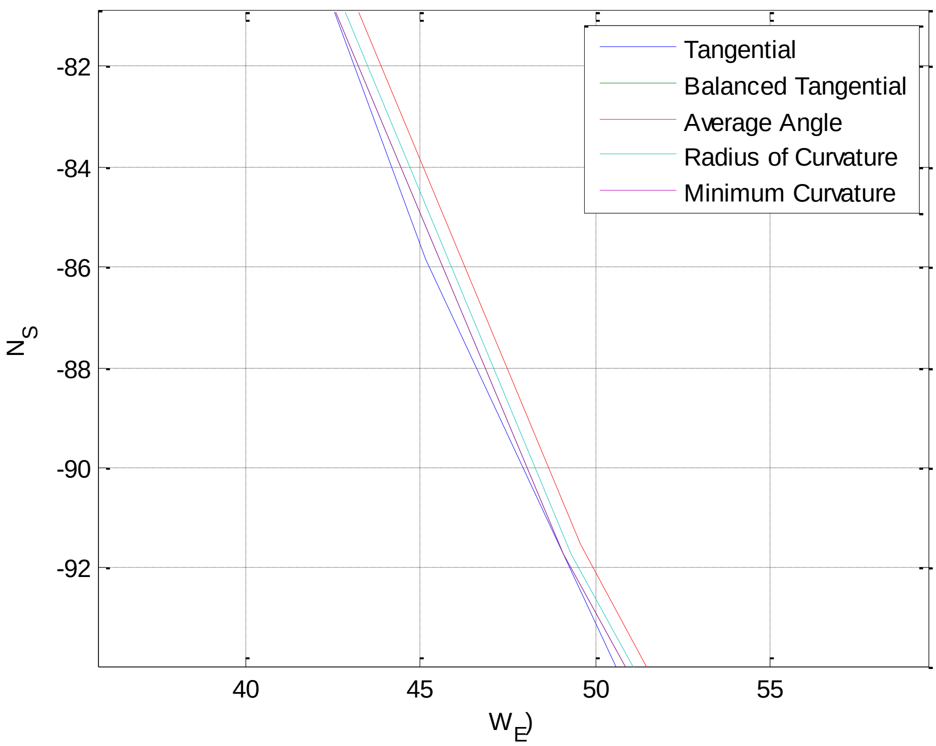

Figure 40 A zoomed Horizontal Profile of a straight line

Figure 41 and 42 shows a 3-D view of the Ullrigg wellpath.

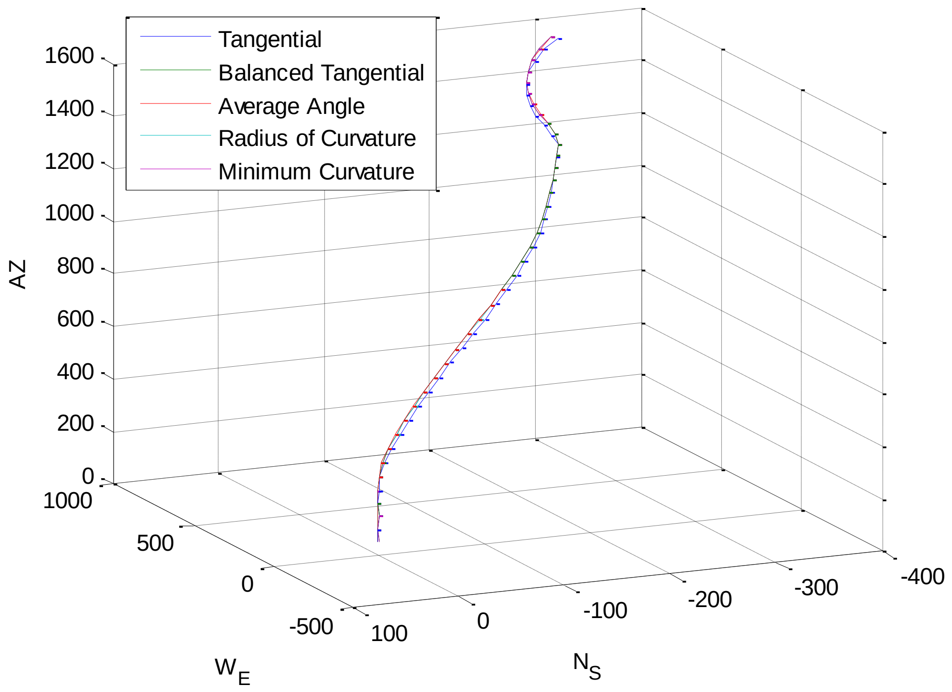

Figure 41 3D profile

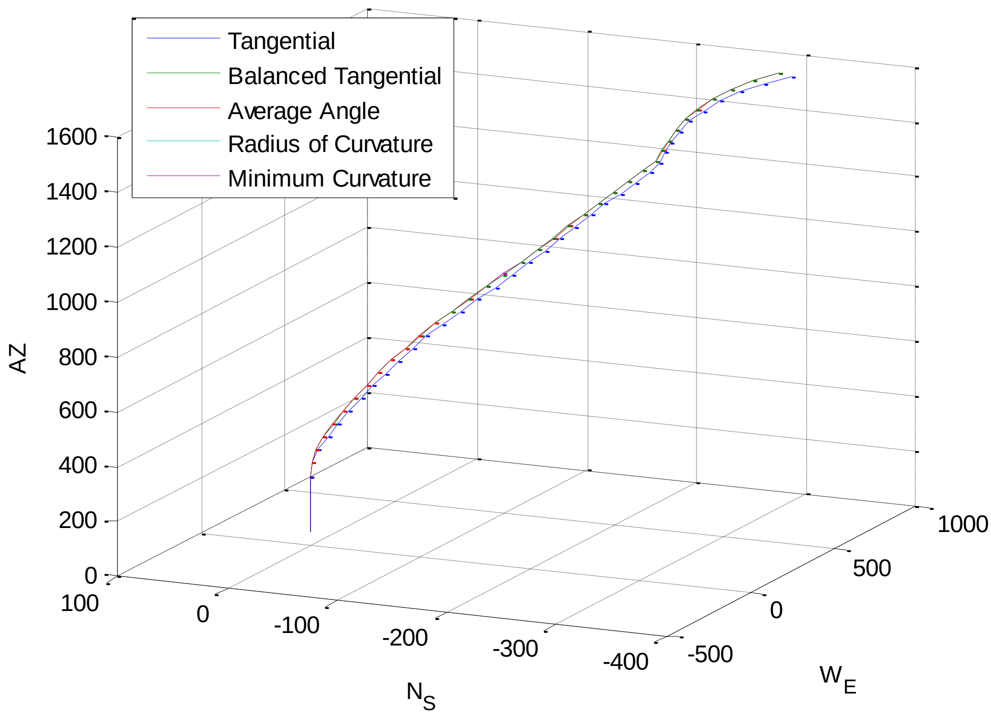

Figure 42 3D profile

Table 1 show a comparative wellbore trajectory from Matlab results using Ullrigg`s well data.

Trajectory Methods	True Vertical Depth (TVD)(ft)	Ullrigg survey data TVD(ft)	Difference
Tangential	1561.9	1575.0	13.1
Balanced Tangential	1574.9	1575.0	0.1
Average Angle	1575.2	1575.0	0.2
Radius of Curvature	1575.1	1575.0	0.1
Minimum Curvature	1575.3	1575.0	0.3

Table 1 Wellbore trajectory comparation

4.4: Conclusion

The fourth of five tested methods to calculate the wellpath provide satisfactory results, even without considering the dog-leg angle.

5: Implementation

This chapter presents the HIL simulator for 3D modeling of drill string and well for directional drilling. The methodology employed in the development of HIL simulator is briefly introduced. The implementation approach used in the simulator is explained, as well as its modular structure. Finally, the simulator modules are individually described.

The simulations were performed using the developed simplified well simulator emulating Ullrigg`s well data, for more details regarding the validation of the simulator, see Appendix A.

5.1: Simulator Development

The HIL well simulator was developed using Matlab-Simulink platform. The 3D directional drilling control system presented was implemented in a modular and configurable manner, in order to facilitate the individual testing and debugging.

All modules were verified individually with the purpose of testify the implementation and the performance of the mathematical models. After all the models which compose the HIL simulator are implemented and tested, they are loaded in the CyberSea application in order to constitute the HIL simulator. The connection among subsystems could then be established, and the parameters for all modules easily set according to the real control system configuration.

Thus, the simulator is capable to run using virtual inputs (control signals and user interface) in different scenarios and test sequences in order to testify the HIL simulator performance before employ it in an official HIL testing.

5.2: Implementation Approach

The approach employed in the development of the simulator, based on the modeling data presented in the Schlumberger paper [19] about PowerDrive X5, follows a common development philosophy used in modeling.

The main objective of this implementation is to simulate the directional drilling tool when directional drilling is needed, to verify how does a rotary steerable system operates when directional drilling is needed. Based on Hardware-In-the-Loop testing, where the focus is to test the control system, this work focus on the implementation of the tool, however the control system was also develop in order to test the tool. Since there was no industrial controller available in the market for the specific tool.

The implementation was divided in 3 main Systems: Driller Setup, Control System and PowerDrive X5 tool, see figure 44 for better understanding of the modeling scheme. The first one is in charge of defining the references, the control is responsible for control the operation of a specific tool.

The input data: inclination and azimuth values were extracted from Ullrig`s well data, as mention before. Since the well has 2000 meters, to facilitated the simulation the well was divided in 40 sections of 50 meters each one. So that the simulation is capable to trip all the wellpath until the target point. In every section there is a new value for inclination and azimuth.

5.3: HIL Directional Drilling Simulator Structure

The purpose of this HIL testing simulator is to simulate the directional drilling events during the steerable operations in order to test DD control systems.

The organization of the simulator is illustrated in the Figure 43. As might be seen, the HIL Directional Drilling simulator was developed in modules in order to have separated subsystems for each main part of PDX5, this imply the simulation of the real world might be easily comprehended.

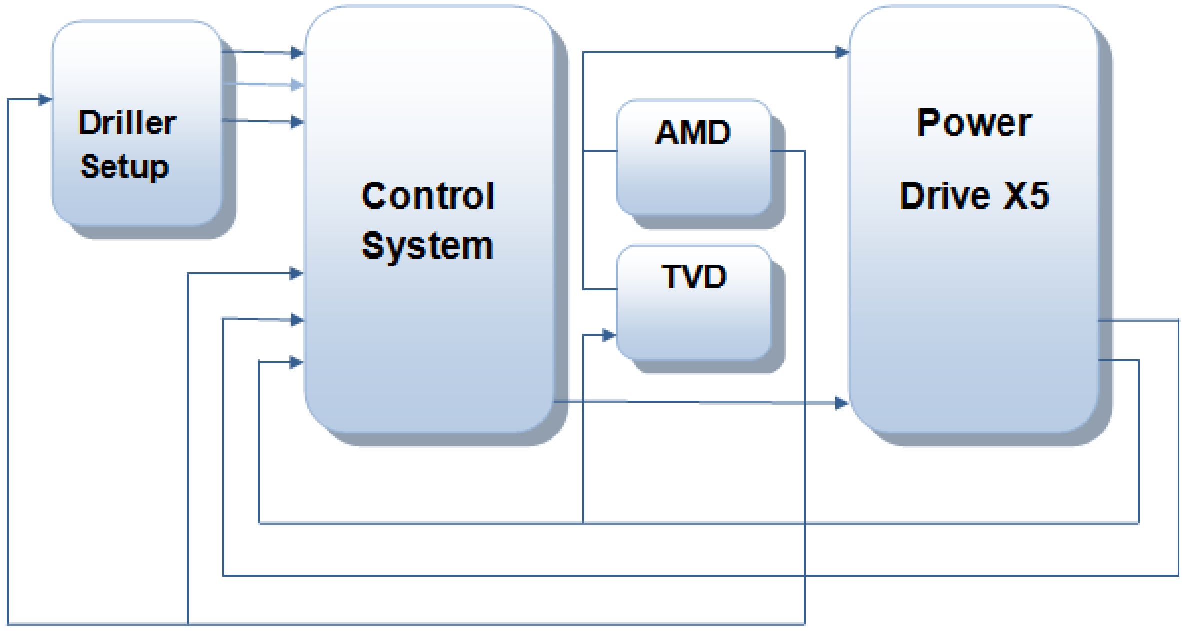

Figure 43 HIL DD simulator arrangement connected with the control system

5.3.1: Driller Setup

The driller setup module defines the configuration of the references to be tested according to the real planning for the well. The outputs are the references for the control system to be able to compare what the tool is modeling with the real data. The Inclination, Azimuth and AMD references came from Ullrigg`s well data. An illustration of the module structure is given in the Figure 44. The main blocks are represented in order to explain the implementation approach adopted.

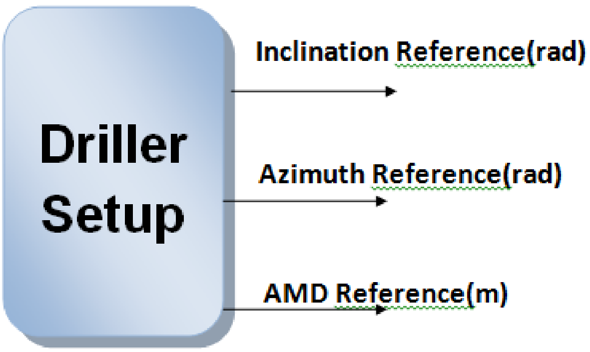

Figure 44 Define References (Driller Setup)

5.3.2: Control System

The Control System is responsible for the selection of the right mode depending of what input data it is entering. The liability of this block is providential for achieving the good results . As input this block receives inclination, azimuth and AMD parameters such as from reference as well as from the PowerDrive X5 output. With those two data the control is in charge to make the comparison and make the decision of each mode the simulation must use to continue on the wellpath.

The control system prioritized the inclination data, since it was not possible to correct both at the same time –azimuth and inclination– using the controller approach chosen. Thereby, the control is capable to decide each mode must use depending on the input. The controller starts to work on the mode selection.

- If the inclination output is higher than inclination reference, use mode 1;
- If not, use mode 3;

After the simulation achieve the inclination set point, then it starts to work on azimuth parameters.

- If the azimuth need to decrease use mode 3;
- If not, use mode 2;

Otherwise, the control will switch to mode 0, where the system will work as a neutral mode, using the last angle value, running as hold angle mode.

The mode selection is held inside the PowerDrive X5 system, in the disk position subsystem, which will be explain in the subchapter 5.3.5. The module structure is given in the Figure 45.

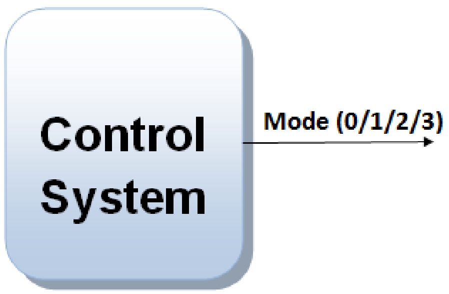

Figure 45 Control System

5.3.3: Along Measured Depth

Along Measured Depth module is shown in the Figure 46. It demonstrate how the tool is drilling the well, showing the path that the drill string is doing according to the commands received by the controller. The output AMD is responsible for showing if the wellpath is going in the right pre-determined direction. The input is the Rate of Penetration (ROP).

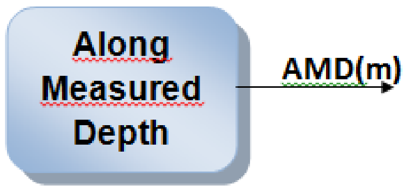

Figure 46 AMD System

5.3.4: True Vertical Depth

True Vertical Depth module works similar as de AMD module, to show the position in the vertical depth the drill string is drilling. It also helps to verify if the tool is drilling according to the commands. It has as input the ROP and the Inclination angle, and as output TVD. The module structure is given in the Figure 47.

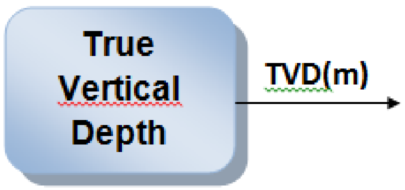

Figure 47 TVD System

5.3.5: PowerDrive X5

The PowerDrive X5 events are being represented in this module. This was the tool has been choosen to model the 3D directional drilling performance for this work. This block (Figure 48) received as an input the ROP and the 4 different types of Mode selected by the control system. It is capable to calculate through the disk position the correctly value of azimuth and inclination depending where the bit is in the wellpath.

Inside this bock there are 3 other subsystems responsible to simulate the activity of the tool during drilling. The Disk position, Angle variation and Disk which will be explain with more details in the subchapter below.

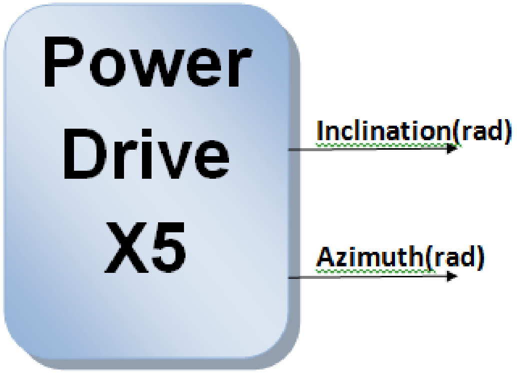

Figure 48 PowerDrive X5 System

5.3.5.1: Angle Variation

The Angle Variation Subsystem works as a random variation angle tax. Calculation how many degrees per meters does the bit drill. Those values are taken in consideration to calculate the bit direction on the disk block (subchapter 5.3.8). The module structure is given in the Figure 49.

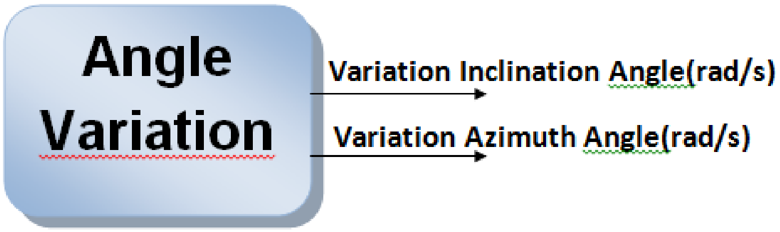

Figure 49 Angle Variation Subsystem

5.3.5.2: Disk Position

The DiskPosition Subsystem (Figure 50), is part of the Power Drive X5 System block, it is responsible for giving the right position of the disk valve to the Disk Subsystem. It provides the maximum and the minimum value of the disk position so that, to have the exactly position of the pads, and where they will act.

The outputs of this block are the DiskPosition maximum and minimum, according to the 360º circle division. Through this, help the model to recognize the exactly position of the pads, consequently knows the position of the drill string and from that get the azimuth and inclination value.

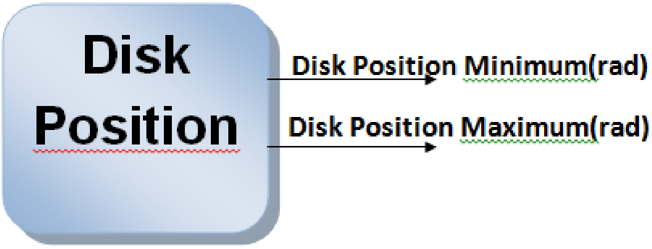

Figure 50 Disk Position Subsystem

5.3.5.3: Disk

The Disk Subsystem is the most important block inside the PowerDrive X5 System for the final result of the simulation. It is responsible for the selection of the mode in operation. The 4 modes works as a boolean to direct the bit. Since the bit is constantly pushed in one direction, the direction opposite to the push point. And there are three constantly moving pads and one disk valve, charge of leave an space open for only one pad per time be able to touch the formation.

For this work it was assumed that the disk valve has three sections, each one of 120º , in this way it lets available a work space for the pads of 120º. After that, it was assigned a specific direction for each one to actuate. For simplicity it was adopted only three positions for the disk, resulting in only three directions that the bit can drill, restricting the tool range of actuation. The Figure 51 bellows shows how the disk moves inside the control shaft, in order to steer correctly the tool for the predetermined direction.

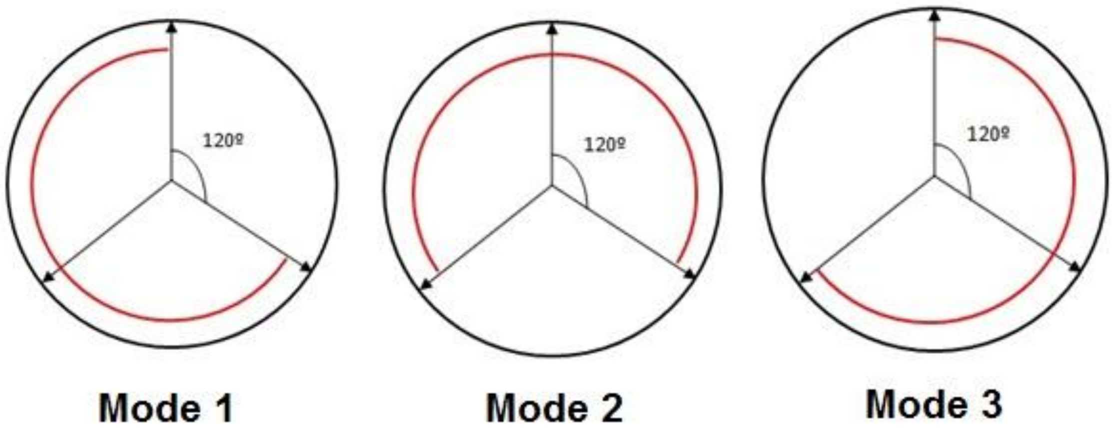

Figure 51 Modes Selection

Since the inputs have values positive and negative it was determined that azimuth as the x axis, and inclination as the y axis. As shown in the Figure 52. In order to get better results in the simulation, it was also determined inclination as the most important parameter to evaluate the tool performance. For that reason, as a simplification, the model gives the preference to fix first the inclination angle, and after fix the azimuth.

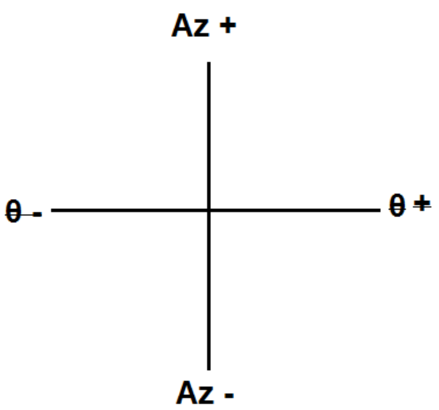

Figure 52 XY inclination and azimuth values

The modes works as follows:

- Mode 0: all pads are activated at the same time so the mud flows continuously and the drill string will drill straight, working as a "hold angle" mode;
- Mode 1: the pads will be activated between 0º to 120º, pushing the bit to the opposite side, inclination and azimuth are negatives;
- Mode 2: 120º to 240º, there is only azimuth contribution;
- Mode 3: 240º to 360º, inclination is positive and azimuth is negative;

The outputs of this block (Figure 53) are the inclination and azimuth.

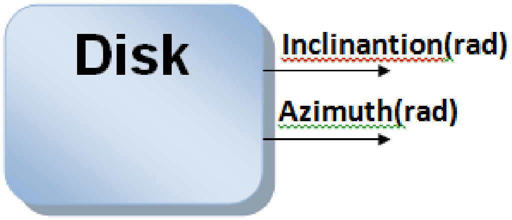

Figure 53 Disk SubSystem

6: Simulations

In the following the simulation results are presented and discussed. The simulator was able to simulate faster than reality, with a 0:05 seconds fixed-step size. Different simulations were performed and the data from the developed model is compared to real data from Ullrigg. Some common drilling operational scenarios are in addition simulated and analyzed in order to verify the functionality of the developed simulator.

6.1: Ullrigg well data Evaluation

The Ullrigg Drilling and Well Center is a division of the International Research Institute of Stavanger (IRIS), Norway, which includes a full-scale offshore drilling facility with a set of drilling and completion equipment and access to seven wells. The offshore rig has been updated and modified in order to be used for different research activities, testing and development of new technology [31].

Figure 54 illustrates the well structure where the data was collected. The real testing data used to evaluate the current HIL directional drilling simulator was collected in tests performed at well U2 in November 2009 by Statoil. The design of the well U2 was simplified in order to easily set the HIL simulator`s models accordingly. The original U2 well planning is presented in the Appendix A. The simulator models were set up based on the U2 well planning.

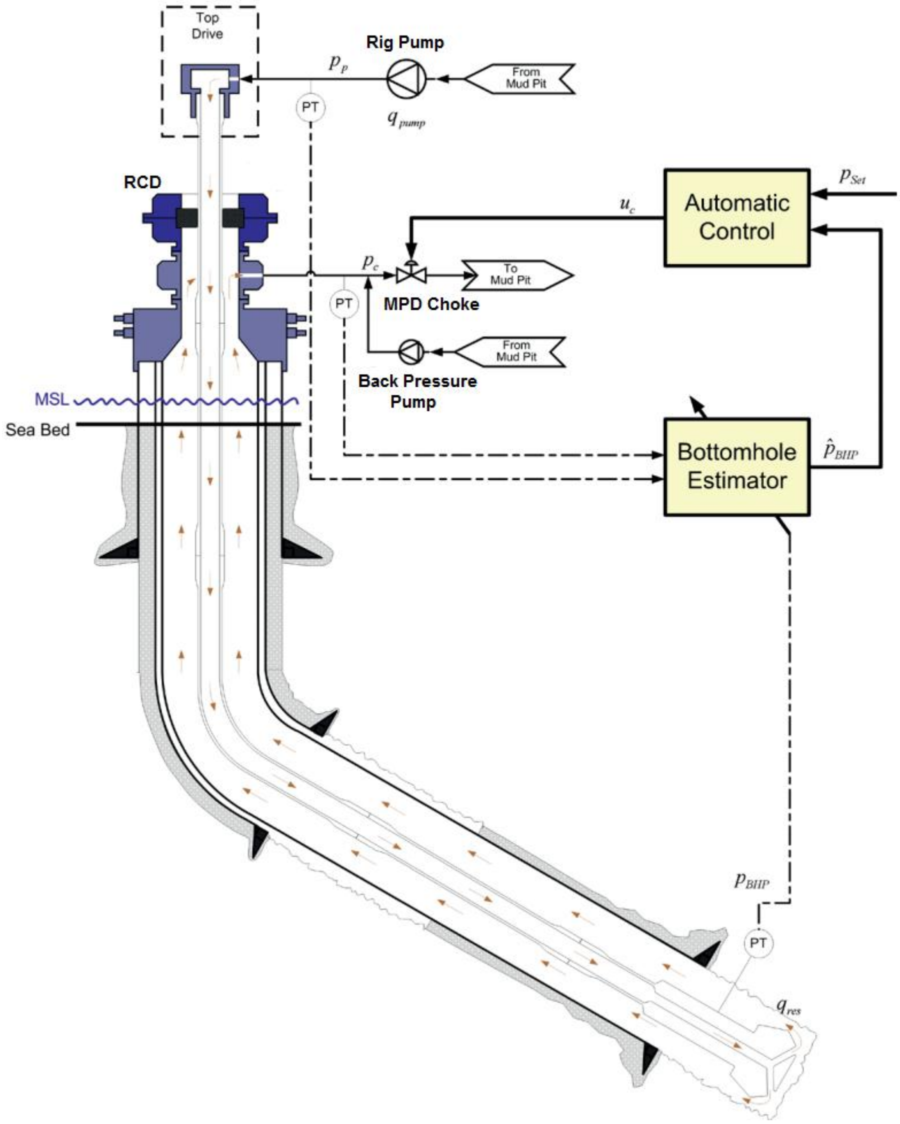

Figure 54 Ullrigg well U2 MPD control system schematic [30]

6.2: Inclination Angle

The simulation realized regards the comparison of the inclination angle acquired with the PowerDrive X5 implementation results and with the Ullrig`s reference data.

Inclination and azimuth values are obtained in a complementary way, see Figure 55 and 56 for a better view of the angles complementarity. As long as the inclination is increasing, azimuth is decreasing. Since the controller prioritized the inclinations data to achieve better results in the simulations, azimuth simulation was left as second priority.

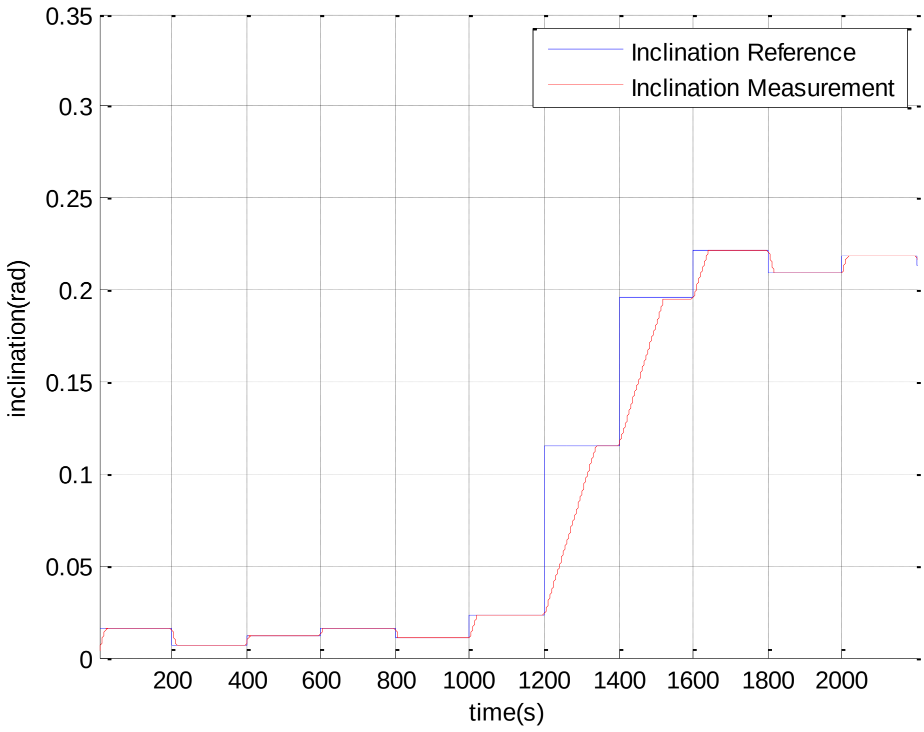

Figure 55 Inclination zoon in

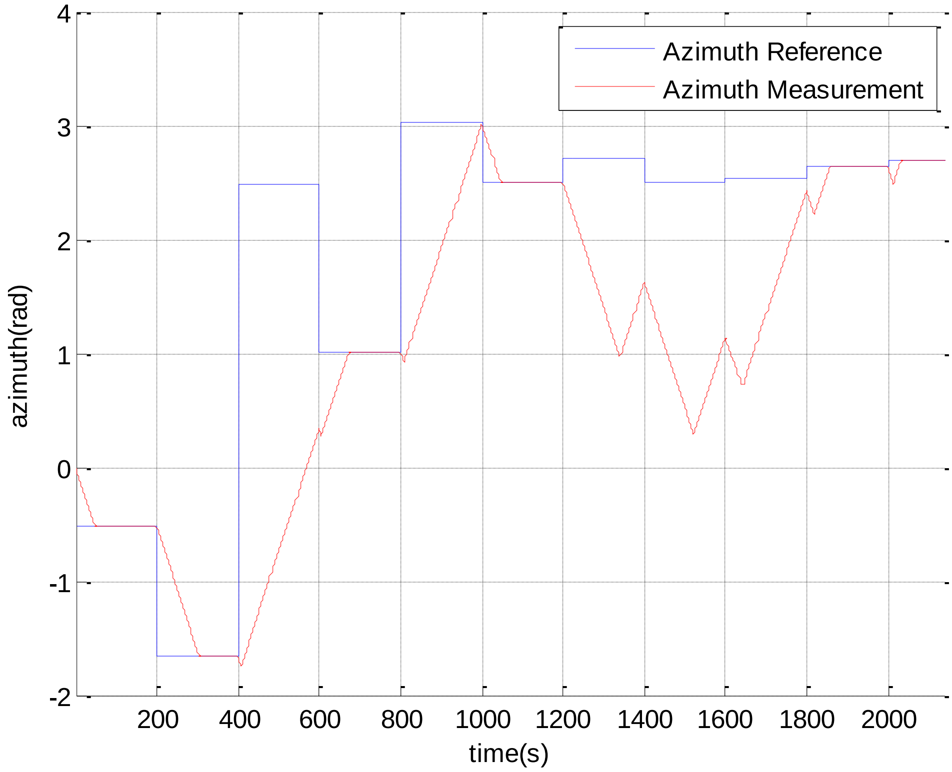

Figure 56 Azimuth zoom in

The graphic below (Figure 57) shows the behavior of the controller acting on the PowerDrive X5 model tool, achieving corrects modes according to the necessity.

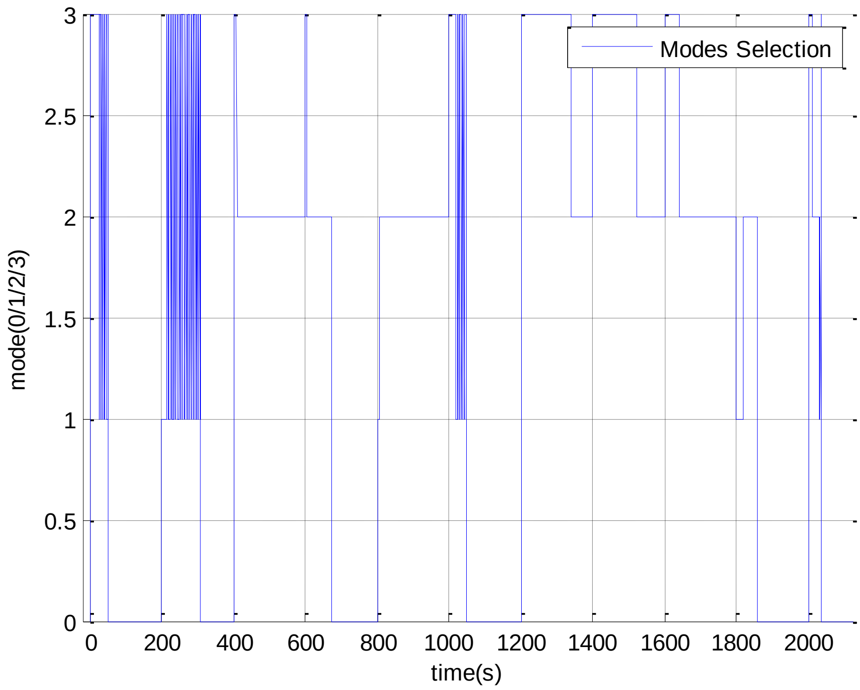

Figure 57 Mode Selection

The graphic below (Figure 58) shows the behavior of the controller acting on the PowerDrive X5 model tool, achieving the input inclination and showing the good results achieved.

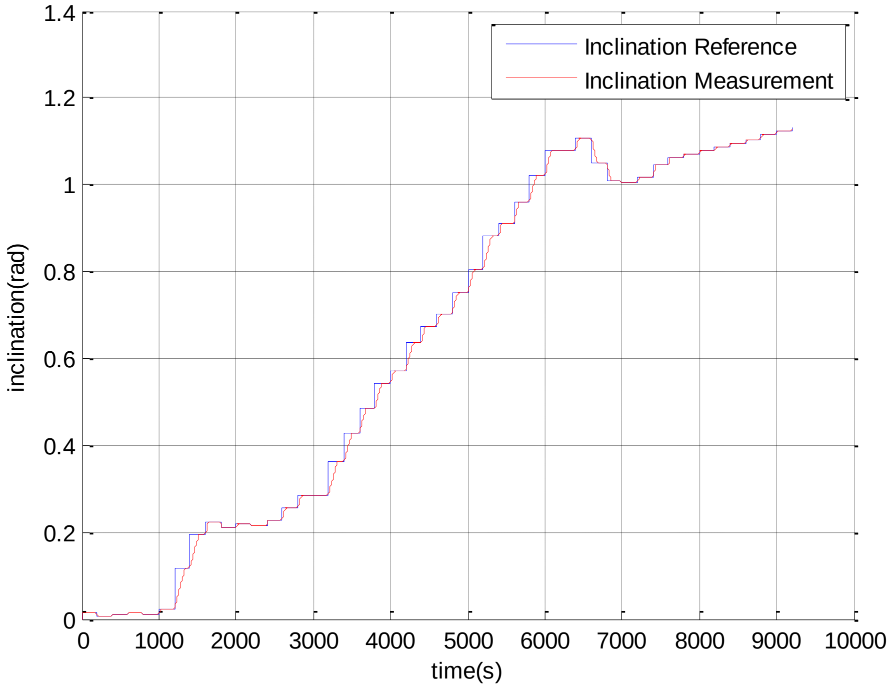

Figure 58 Inclination Comparison

6.3: Azimuth Angle

The simulation realized regards the comparison of the Azimuth Angle acquired with the PowerDrive X5 implementation results and with the Ullrigg`s reference data.

The restriction applied in the controller to test the performing of the simulation became insufficient to achieve good results for the azimuth angle. After some analysis, the error found came from the sharply change in the azimuth value between section 3 to 4, in the Ullrigg well data used to test the model.

This proof that, the tool implemented in this work to perform a 3D directional drilling well it is not capable to drill Ullrigg`s well, due to the incompatibility of azimuth growth in a such small period of time. PD X5 it is unable to drill 273º azimuth in only 50 meters with the implementation approach used in this work. The build rate of PowerDrive X5 varies from 0º to 8º, depending which version of the PD X5 it is used, see Appendix B for more details. For this work the tool bend section used was 0º to 3º, which leads to a build rate angle of 3º per 30 meter, as used in the [19].

There is a big metric difference between one section and other in the beginning of the simulation, this happens because the tool is not able to reach the stipulated plan. See Figure 59.

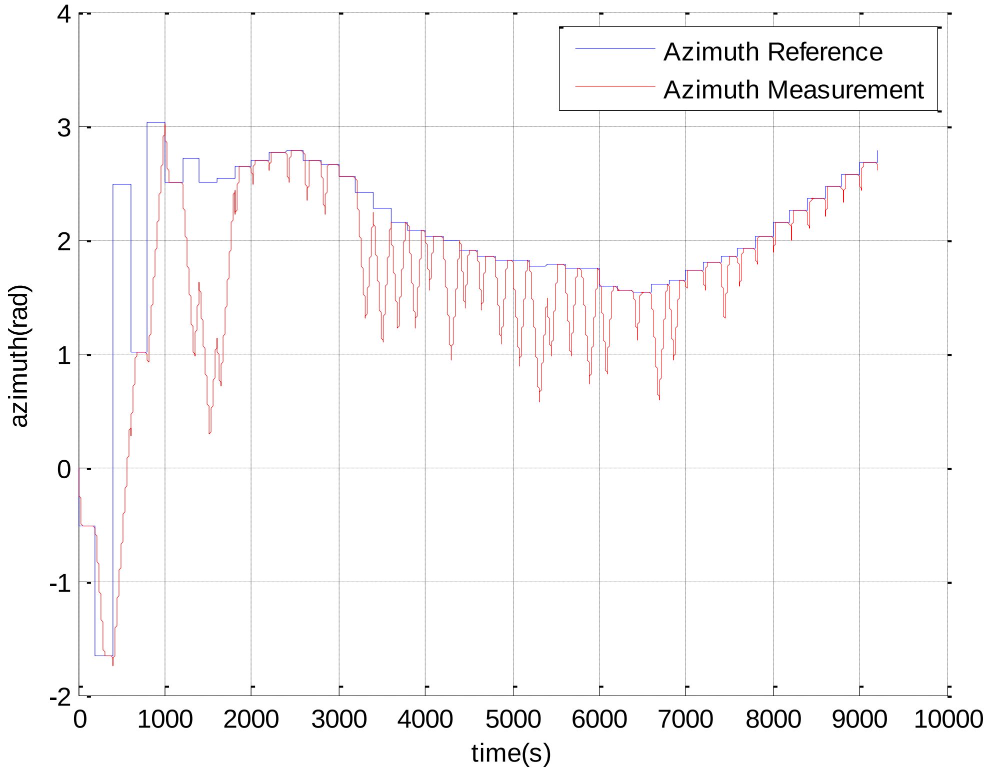

Figure 59 Azimuth Comparasion

6.4: Mode

This scope shows how the controller is working and switching the modes as the input data requires. Unfortunately there was just the Ullrig`s data available to test the performance of the control system.

The Figure 60 below show the effort of the controller to keep the azimuth and inclination angle in the right line, according to reference data. Once the specific angle is achieved in the section, the controller automatically changes to mode 0 and “hold” the last angle that was used to drill before. It keeps in mode 0 until change for the next section, and receive a new input data.

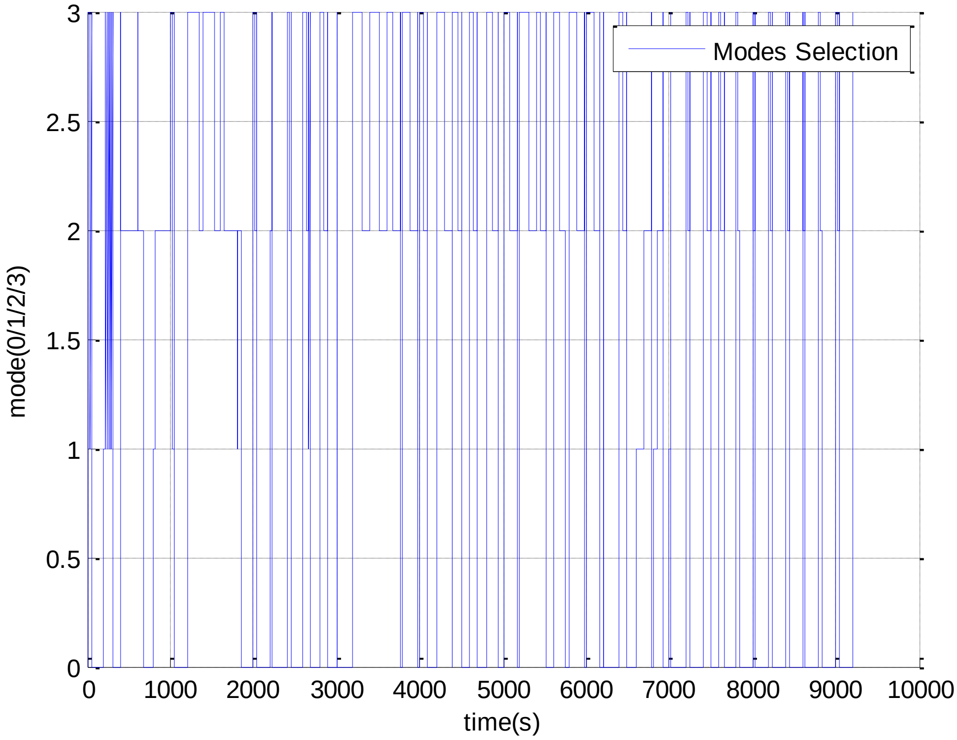

Figure 60 Mode Selection

It is also visible, the performance of the controller when it is switching modes. It is easily seen that, the control works in the correct way. The graphic shows that the controller does not switch sharply. Since the control acts on a mechanical device it should not switch the disk position so often in a small period of time, resulting in damage for the equipment. It has a pre-determinate behavior, staying in the same mode for as long as it is necessary and then changes smoothly for the next mode, with a period of time in between.

6.5: Along Measured Depth x True Vertical Depth

The simulation realized regards the comparison of the Along Measured Depth and True Vertical Depth acquired with the PowerDrive X5 implementation results and with the Ullrig`s reference data.

The simulation obtained the same wellpath as the reference data, performing the right way of the well until reach the target (Figure 61). The results achieved shows the same TVD x time graphic from all 5 wellpath calculations methods, from the PD X5 tool simulation and the Ullrigg`s well data. Drilling 2000 meters results in 1600 meters of true vertical depth, due to inclination angle.

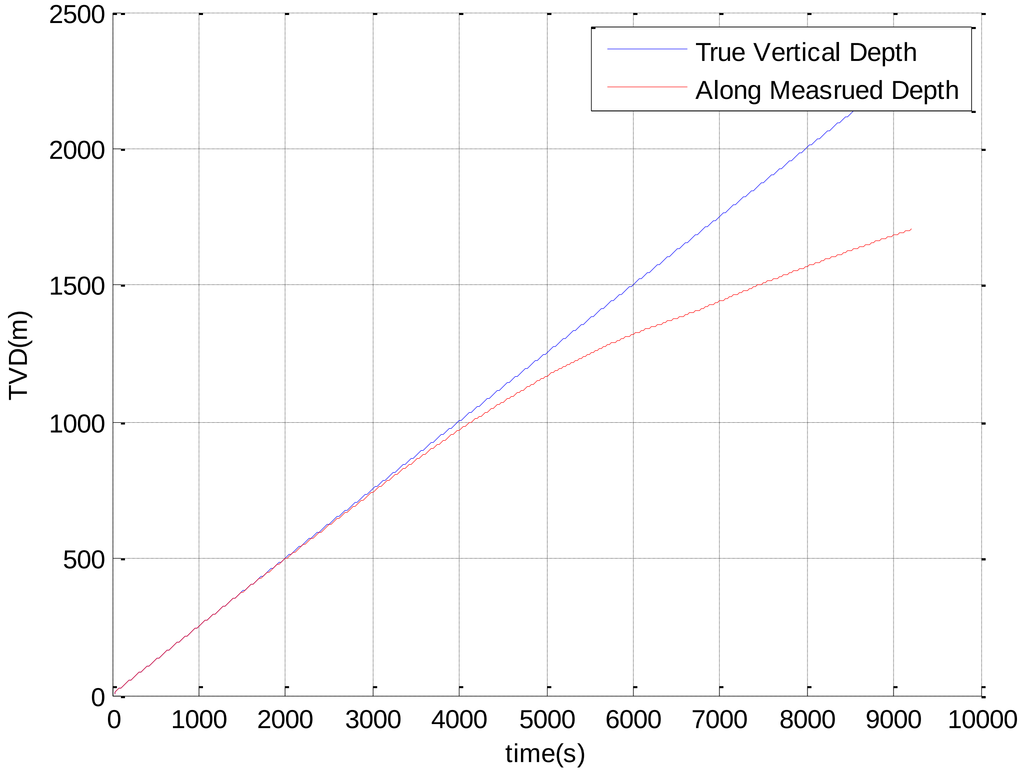

Figure 61 Simulation wellpath

7: Conclusion

This thesis has presented the development of a commercial HIL well simulator to be employed in HIL functional testing of 3d Directional Drilling Systems. A simplified modeling approach was thereby implemented in a modular manner using Matlab/Simulink. The simulator was evaluated against real testing data and also had its functionality verified by simulating operational scenarios.

Different planning techniques and tools enables the well to be drilled as close as possible to the planned path and active the target correctly. Directional drilling is used to reach complex reservoir though an accurate control of the deflection of a wellbore in a specific direction. To optimized the drilling operation Rotary Steerable Systems tools are well suited to the application of DD helping to improve performance. They are capable to control the inclination, azimuth and direction in which a well is drilled using a steering mechanism that continually rotates.

The HIL testing technology is a suitable and well-proven testing methodology widely used in the automotive and aerospace industries. Its concept of replacing the controlled system for a virtual environment enables the verification of failure handle capability, integration, and functionality of control systems, by inducing several scenarios which would be dangerous, costly, or even impossible to be tested in the real world.

The implementation approach employed in the development of the simulator, based on a simplified well and equipment modeling, presented satisfactory results when compared to the Ullrigg`s well U2 real testing data. The main dynamic could be captured in real time.

The modular implementation allows an easy configuration of the subsystems, and also a future replacement of simplified modules by complex ones, in case of a more accurate response is needed. Different well designs might be simulated using the current simulator by setting the modules according to the well planning desired.

The simulation requirements to be solved using fixed step solver (step size: 0.05 seconds), to simulate faster than reality and to have parameters easy to tune were achieved. The parameters are loaded in a .m file from Matlab and simplified models of the downhole dynamics were used to simulate as fast as possible.

Marine Cybernetics has performed several HIL testing on vessel systems and drill floor equipment, however never involving directional drilling models. This developed of a 3D directional drilling simulator is thereby part of a new project of the company with aim of provide HIL testing for DD systems.

7.1: Future work

Suggestions for further improvement of the simulator are listed below:

- Improve the pads dynamics for different formation scenarios;
- Improve the disk position performance allowing to positioned in all 360º of the disk valve;
- Since, at low inclinations the azimuth cannot be measured accurately due to the limitations of the magnetometers in the MWD tool. Implement the control system to start actuate from 3º of inclination;
- Include the mud circulation dynamics inside the piston;
- Include sensors acquisition data for inclination, azimuth, shock and thermal sensors;
- Include the LWD and MWD tool, in order to have a Power Pulse communication system for a later retrieval at surface;
- Include sensors in the control unit, for more data acquisition testing such as: record the instantaneous speed of the drill string with respect to the formation;
- integrate the PowerDrive X5 model with Marine Cybernetics AS models;

According to Schlumberger white paper [19] this information would help to diagnose drilling problems, and coupled with the MWD, mud logging and formation records, it would be an extremely valuable in optimizing future runs. Since, at low inclinations the azimuth cannot be measured accurately due to the limitations of the magnetometers in the MWD tool. For future work it would be better to implement the control system to start actuate from 3º of inclination.

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Appendix A – Ullrigg U2 Well Planning

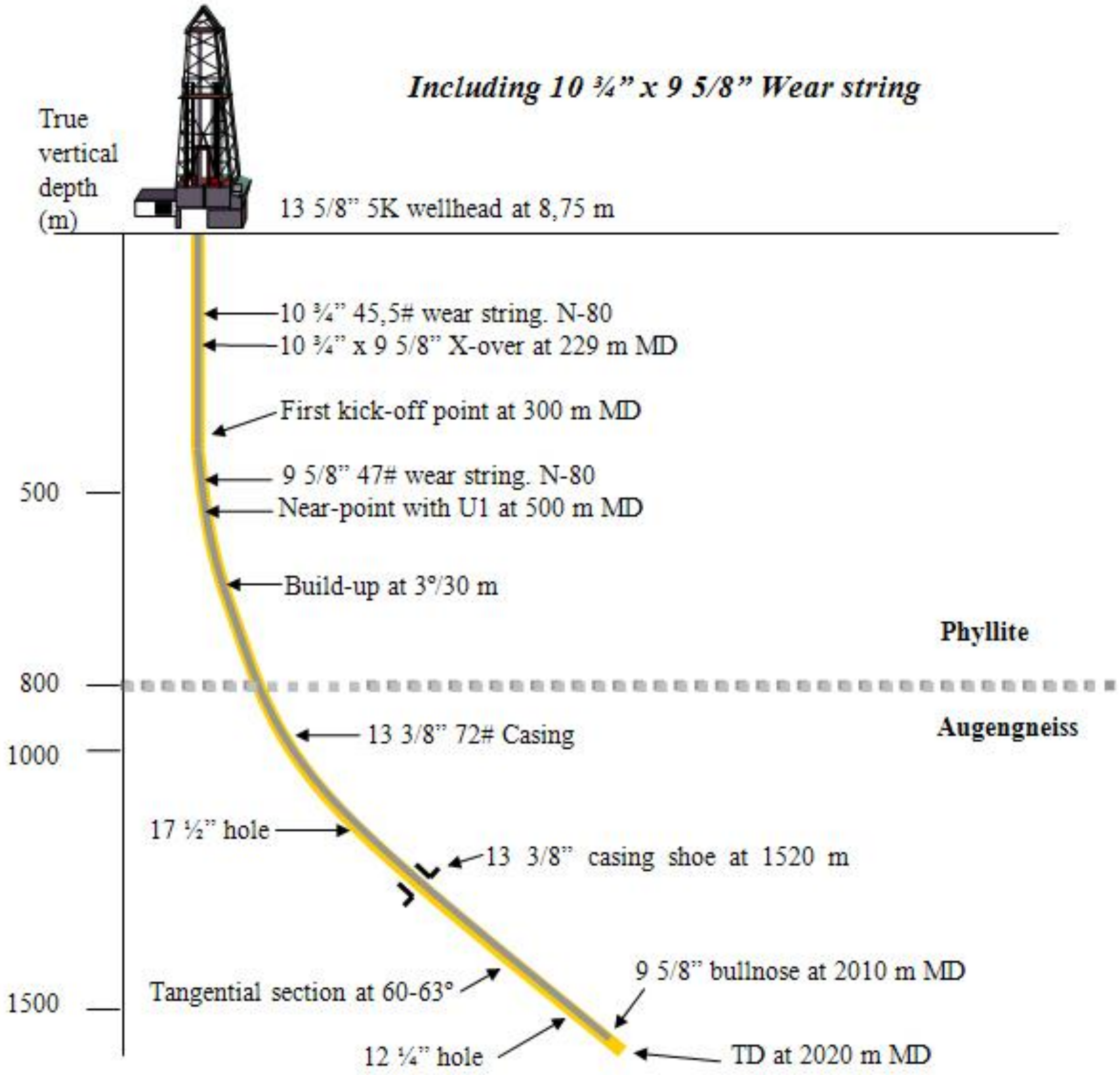

Figure 62 Figure A.1: U2 well planning [30]

		SURVEY DATA (MWD) WELL U2	
AHD (M)	INC (DEG)	AZ (DEG)	TVD (M)
0.0	0.0	0.0	0.0
50.0	0.9	-29.7	50.0
100.0	0.4	-95.1	100.0
150.0	0.7	142.5	150.0
200.0	0.9	58.2	200.0
250.0	0.6	173.2	250.0
300.0	1.3	143.6	300.0
350.0	6.6	155.6	349.8
400.0	11.2	143.7	399.2
450.0	12.7	145.2	448.0
500.0	12.0	150.8	496.9
550.0	12.5	154.7	545.8
600.0	12.2	158.4	594.6
650.0	13.1	159.0	643.4
700.0	14.6	153.9	692.0
750.0	16.2	152.2	740.3
800.0	16.4	146.1	788.3
850.0	20.7	138.2	835.7
900.0	24.6	129.8	881.8
950.0	27.8	123.2	926.6
1000.0	31.0	119.2	970.2
1050.0	32.8	115.6	1012.7
1100.0	36.5	113.7	1053.8
1150.0	38.5	109.1	1093.3
1200.0	40.3	106.5	1132.1
1250.0	43.0	104.0	1169.3
1300.0	46.2	104.0	1204.9
1350.0	50.5	100.6	1238.0
1400.0	52.3	102.4	1269.0
1450.0	55.1	100.5	1298.8
1500.0	58.6	100.2	1326.4
1550.0	61.8	90.6	1351.2
1600.0	61.9	88.8	1374.6
1650.0	63.4	88.4	1397.3
1700.0	60.1	91.7	1420.9
1750.0	57.8	93.5	1446.9
1800.0	57.6	98.9	1473.9
1850.0	58.2	102.7	1500.1
1900.0	59.9	105.8	1526.1
1950.0	60.8	110.5	1550.9
2000.0	61.3	116.6	1575.0

Table A.1: U2 survey data [30]

Appendix B – PowerDrive X5 Specifications

PowerDrive X5

PowerDrive X5 Specifications

	PowerDrive X5 475	PowerDrive X5 675	PowerDrive X5 825	PowerDrive X5 900	PowerDrive X5 1100
Nominal OD (API)	4.75 in [120.7 mm]	6.75 in [171.5 mm]	8.25 in [209.6 mm]	9.00 in [228.6 mm]	9.50 in [241.3 mm]
Hole size	5¾ in to 6½ in	8½ in to 9⅞ in	10⅝ in	12¼ in to 14¾ in	16 in to 22 in
Overall length	14.95 ft [4.56 m]	13.48 ft [4.11 m]	14.60 ft [4.45 m]	14.60 ft [4.45 m]	15.10 ft [4.60 m]
Max. collar dogleg	20°/100 ft [20°/30 m] sliding, 10°/100 ft [10°/30 m] rotating	20°/100 ft [20°/30 m] sliding, 10°/100 ft [10°/30 m] rotating	20°/100 ft [20°/30 m] sliding, 10°/100 ft [10°/30 m] rotating	20°/100 ft [20°/30 m] sliding, 10°/100 ft [10°/30 m] rotating	20°/100 ft [20°/30 m] sliding, 10°/100 ft [10°/30 m] rotating
Build rate	0°– 8°/100 ft	0°– 8°/100 ft	0°– 6°/100 ft	0°– 5°/100 ft	0°– 3°/100 ft
Max. operating torque	4,000 ft.lbf [5,420 N.m]	16,000 ft.lbf [21,700 N.m]	16,000 ft.lbf [21,700 N.m]	48,000 ft.lbf [65,000 N.m]	48,000 ft.lbf [65,000 N.m]
Max. operating load	340,000 lbf [1,500,000 N]	1,100,000 lbf [4,900,000 N]	1,100,000 lbf [4,900,000 N]	1,400,000 lbf [6,200,000 N]	2,280,000 lbf [10,140,000 N]
Max. weight on bit	50,000 lbf [223,000 N[	65,000 lbf [290,000 N]	65,000 lbf [290,000 N]	65,000 lbf [290,000 N]	65,000 lbf [290,000 N]
Weight of assembly in air	754 lbf [3,300 N]	1,700 lbf [7,500 N]	1,900 lbf [8,455 N]	2,370 lbf [10,500 N]	2,584 lbf [11,490 N]
Max. lost circulation material	35 lbm/bbl nut plug	50 lbm/bbl nut plug	50 lbm/bbl nut plug	50 lbm/bbl nut plug	50 lbm/bbl nut plug
Flow range	220–400 galUS/min [830–1,500 L/min]	320–650 galUS/min [1,200–2,460 L/min]	480–1,500 galUS/min [1,800–6,800 L/min]	480–1,900 galUS/min [1,800–7,200 L/min]	480–1,900 galUS/min [1,820–7,200 L/min]
Lateral vibrations	Shock level 3 [50-g_n threshold], 30-min limit	Shock level 3 [50-g_n threshold], 30-min limit	Shock level 3 [50-g_n threshold], 30-min limit	Shock level 3 [50-g_n threshold], 30-min limit	Shock level 3 [50-g_n threshold], 30-min limit
Stick/slip	± 100% mean rotational speed, 30-min limit	± 100% mean rotational speed, 30-min limit	± 100% mean rotational speed, 30-min limit	± 100% mean rotational speed, 30-min limit	± 100% mean rotational speed, 30-min limit
Max. rotational speed	250 rpm	220 rpm	220 rpm	200 rpm	200 rpm
Max. temperature	300 degF [150 degC]	300 degF [150 degC]	300 degF [150 degC]	300 degF [150 degC]	300 degF [150 degC[
Max. hydrostatic pressure	20,000 psi [138 MPa]	20,000 psi [138 MPa]	20,000 psi [138 MPa]	20,000 psi [138 MPa]	20,000 psi [138 MPa]
Pressure drop across tool	Density [in lbm/galUS] × Flow² [in galUS/min] / 14,500	Density [in lbm/galUS] × Flow² [in galUS/min] / 56,000	Density [in lbm/galUS] × Flow² [in galUS/min] / 56,000	Density [in lbm/galUS] × Flow² [in galUS/min] / 259,000	Density [in lbm/galUS] × Flow² [in galUS/min] / 337,500
Recommended pressure drop across bit	600–800 psi [4.1–5.5 MPa]	600–800 psi [4.1–5.5 MPa]	600–800 psi [4.1–5.5 MPa]	600–800 psi [4.1–5.5 MPa]	600–800 psi [4.1–5.5 MPa]
Mud sand content	1% by volume	1% by volume	1% by volume	1% by volume	1% by volume
Rotary Connections					
Collar upper connection	3½ IF box	4½ IF box	6⅝ Reg box	6⅝ Reg box	7⅝ Reg box
Bit box	3½ Reg	4½ Reg	6⅝ Reg	6⅝ Reg	7⅝ Reg
Sensors					
Bit box to gamma ray	5.86 ft [1.79 m]	6.40 ft [1.95 m]	7.56 ft [2.30 m]	7.56 ft [2.30 m]	7.97 ft [2.43 m]
Bit box to inclination	6.73 ft [2.05 m]	7.27 ft [2.21 m]	8.43 ft [2.57 m]	8.43 ft [2.57 m]	8.83 ft [2.69 m[
Bit box to azimuth	8.83 ft [2.69 m]	9.37 ft [2.85 m]	10.53 ft [3.21 m]	10.53 ft [3.21 m]	10.93 ft [3.33 m]
Inclination accuracy	± 0.4° [0.05° resolution]	± 0.4° [0.05° resolution]	± 0.4° [0.05° resolution]	± 0.4° [0.05° resolution]	± 0.4° [0.05° resolution]
Azimuth accuracy	± 0.8° [0.10° resolution]	± 0.8° [0.10° resolution]	± 0.8° [0.10° resolution]	± 0.8° [0.10° resolution]	± 0.8° [0.10° resolution]
Gamma ray accuracy, azimuthal 4-quadrant	± 5% [30-s averaging window]	± 5% [30-s averaging window]	± 5% [30-s averaging window]	± 5% [30-s averaging window]	± 5% [30-s averaging window]
Shock detector threshold, radial	50 g_n ± 5 g_n [± 500 g_n max. peak]	50 g_n ± 5 g_n [± 500 g_n max. peak]	50 g_n ± 5 g_n [± 500 g_n max. peak]	50 g_n ± 5 g_n [± 500 g_n max. peak]	50 g_n ± 5 g_n [± 500 g_n max. peak]

Figure 63 PD X5 Specification [21]