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Machine vision for drill string slip status detection

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ABSTRACT

Slip status of drill string is system generated binary value computed by comparison of sensor generated real time hook load value with a minimum threshold value of hook load stored in measurement system. This research article describes a novel method of slip status detection by machine vision technology which helps overcome the constraints of slip status detection with legacy measurement method. It also helps improve the real time drilling data quality and optimize and automate drilling operations. A method to detect drill string slip status with high-resolution digital camera installed on mast near rig floor is described along with backend vision processing and communication modules, which generate binary values of slip status. The binary values are transferred in real time to drilling measurement system of rig to compute other drilling parameters like bit depth, hole depth and stand counters. This method includes deploying active optical sensors at the rig floor, obtaining 1-D, 2-D, or 3D image data, and processing it to obtain the status of drill string. Reliable measurement of slip status by machine vision helps reduce non-productive time (NPT) by reliable real time surveillance of drilling operations.

1. Introduction

Oil and gas rigs are complex machine, which handle high pressure, temperature and fatigue conditions during construction of oil and gas wells drilled several thousand feet below surface of earth. They operate in land, shallow seawater, deep-sea water and ultra-deep seawater environments.

These rigs are integrated setup, which consists of hoisting, circulatory, rotating and well control systems (Fig. 1). These systems act in sync to drill the well bore, remove rock cuttings from well bore and counterbalance subsurface formation pressure. Driller does the manipulation and control of drilling operation from a console located on rig floor. Support teams provide real time drilling surveillance services from wellsite (mudlogging units) and from remote locations like Real Time Operation Centres (RTOC) and Remote Operation Centres (ROC). Sensors installed by mudlogging, logging while drilling (LWD) and measurement while drilling (MWD) service companies generate the real time drilling data (Li et al., 2011). Rig instrumentation sensors also generate real time drilling data for surveillance and control of drilling operations.

In legacy drilling surveillance system, a set of signals are generated from electronic sensors installed at various location on rig. Due to heavy lifting, vibrations, harsh weather, and climatic condition of operations on rig, it is often difficult to run electronic sensors in optimum condition and maintain the accuracy and quality of real time data generated from them. Sensor failures are common on rigs that leads to down time and non-productive time (NPT) in drilling operations (Emhanna, 2018). Due to excess vibrations and noise associated with drilling operations (Lin et al., 2008), the sensors installed on rig floor, mast, pumps and mud pit are prone to fatigue, wear and tear. High current electrical wires running from generators to Drawworks, mud pumps and pits generate eddy currents, which are potential source of noise in the signals generated by electronic sensors. Therefore, getting constant good quality data from these sensors is a challenge and requires continuous maintenance and replacement of sensors, which may lead to rig down time. Therefore, an alternate technique should complement the real time drilling data generated by electronic sensors. In this paper, we discuss deployment of machine vision technology on oil and gas rigs. This technique works by installation of high resolution, industrial grade digital video camera on rig, which generate digital images and videos that are processed in a vision processing computer to generate meaningful information related to surveillance of drilling operations. The information thus

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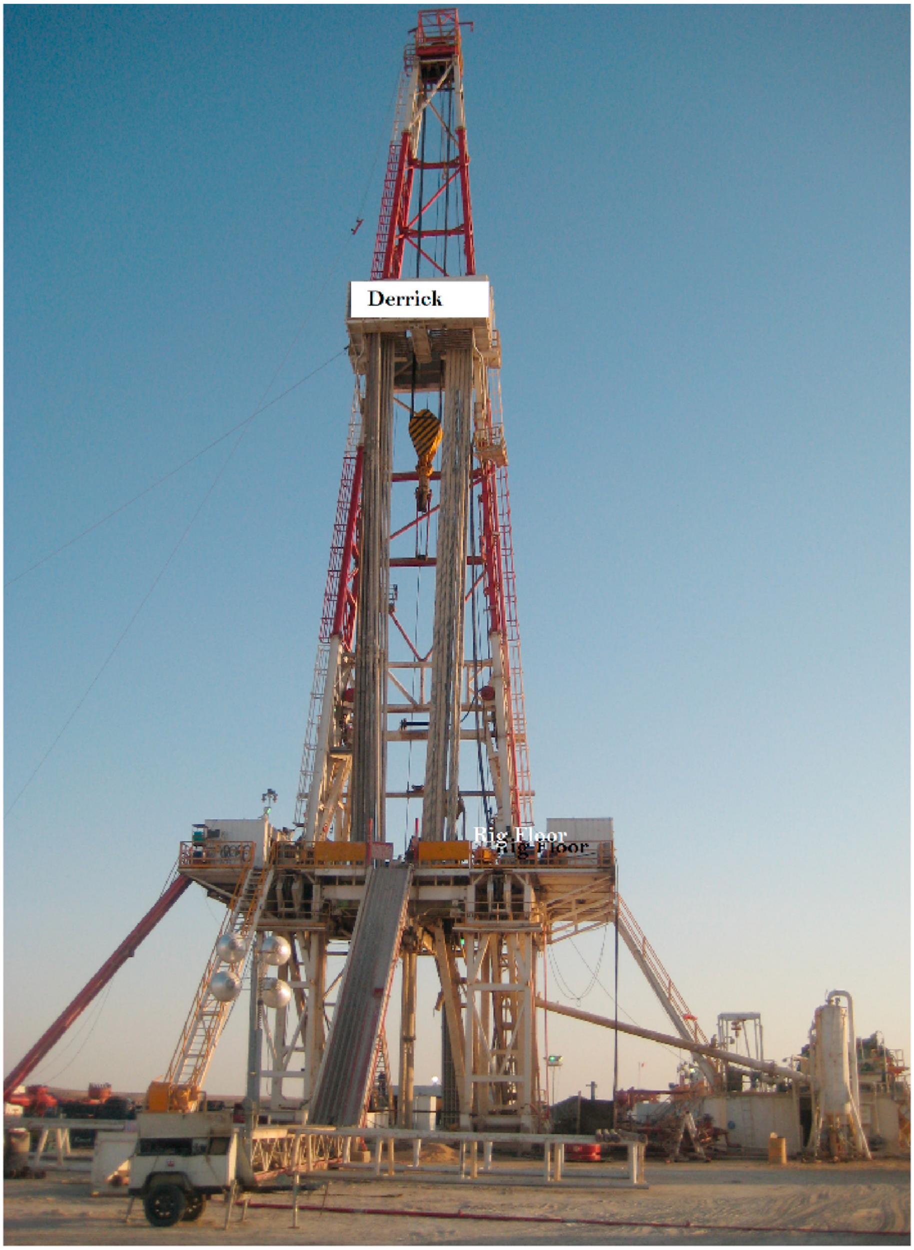

Fig. 1. Image of an oil rig on land location. It consists of hoisting, circulatory, rotating and well control systems.

generated is transferred in real time to drilling measurement system of rig, and it complements data generated from real time electronic sensors, during drilling and completion of wells. There are prerequisites to obtain good quality data for machine vision, which are discussed in detail in later sections. This machine vision enabled surveillance of drilling operations can enable drilling optimization and automation.

This research article describes method of measurement of slip status using machine vision technology, and then compute critical real time variables like bit depth, hole depth and stand counters from slip status data. The real time images of rotary table, rig floor, drill string/tubular hanging from travelling block or supported by rotary slips are such data sets, which enable precise measurement of slip status, hook height and bit depth. This technology is easy to deploy and use due to advanced video capture and storage, streaming, analytics and computer vision technologies available in market. Such measurements can enable drilling efficiency optimization and automation.

2. Screening of variables

During drilling operations, we monitor several real time drilling variables, broadly divided into hoisting, drilling fluid and subsurface formation pressure related variables. Formation pressure, gases trapped in formation and Petrophysical properties of rocks are subsurface formation related variables (Li et al., 2011) while mud volumes and their rheology and specific gravity etc. are drilling fluid related variables (Lysyannikov et al., 2016). Standpipe pressure, pump rate and returns are dependent on subsurface pressure and pressure rating of equipment. The drill string related real time variables are hook load, hook height, slip status, bit depth, hole depth and stand counters etc. In this research paper, we optimize quality of some drill string related variables using alternate machine vision technique deployed to detect slip status of drill string/tubular present in the well bore.

3. Slip status problem statement

The slip status (SS) of drill string is a critical variable, which helps measure other critical variables like bit depth, hole depth and stand counter etc. The SS of drill string has binary value, either 0 or 1 (Fig. 2). While 0 value implies in-slip status, the 1 numerical value is out of slip status of drill string. These values are quantized and discrete i.e. only these two integral values are possible for SS of drill string.

In-slip status (SS = 0) implies that the rotary slips are put into rotary hole and string load is borne by them, which implies the string load is not borne by hoisting system of rig. The out of slip status (SS = 1) implies that there is no rotary slip in rotary hole, the string is attached to hoisting system, and its load is borne by hoisting system. Any drill pipe, bottom-hole assembly (BHA) component, casing, liner, Measurement while drilling (MWD), logging while drilling (LWD) tool etc. when in rotary hole with a slip in rotary hole wrapped around it will have SS = 0 value, while when any of them in hole without slip wrapped around it will have SS = 1 binary value.

In legacy measurement system, the SS of drill string is a derived parameter obtained by comparison of instantaneous hook load value with a threshold hook load (THL) value. The THL is the hook load value when no load is borne by hook and is the minimum value of hook-load measurement system. The empty hook weight value (THL) is fixed value for a hook, which is fed into the measurement system. To compute in and out SS of drill string, the instantaneous hook load is compared to THL by rig measurement system. If the instantaneous value of hook load is more than THL, the system generates out of slip (SS = 1) status of drill string. Vice versa, if the instantaneous hook load value is less than or equal to THL, the measurement system generates in slip (SS = 0) status of drill string.

Bit depth is a critical variable, which gives the length of drill string present in the well bore measured from top of rotary hole. Bit depth changes happen due to run in and pull out of drill string or during drilling of wellbore when bit drills through the rock formation. The lifting up or lowering down of drill string by rig hoisting system results in change of bit depth. The lifting up or lowering down of drill string is done by travelling block attached to hook, which is hanging from crown of the rig. The change in bit depth values is measured from hook height or travelling block height change, only when the drill string is out of slip (SS = 1). In legacy measurement system, an electric pulse sensor installed in Drawworks shaft measures movement of hook. The out of slip (SS = 1) downward movement of hook is measured as increase in bit depth while upward out of slip (SS = 1) movement is measured as decrease in bit depth. If the drill string is held by hook during its upward and downward movement i.e. when the drill string is out of slips (SS = 1), the hook movement value is respectively subtracted or added to original bit depth value to get its new value. When the drill string is detached from hook i.e. when drill string is in slips (SS = 0), its load is borne by rotary slips. Movement of travelling block/hook when string is in slip (SS = 0) causes no changes in the bit depth values.

Due to rapid downward movement of the empty hook during beginning and end of tripping operation, the instantaneous empty hook weight values are subject to rapid fluctuation and change by several tons, which can lead to error in estimation of SS. While the string is actually in slip (SS = 0), the measurement system makes a false estimation of SS as out of slip (SS = 1), thereby leading to erroneous change in bit depth values. Therefore, drillers keep THL value a few kilo pounds higher than empty hook weight to counterbalance hook weight fluctuations due to its rapid movements. However, this approach also has its own set of problems. When the weight of drill string is minimum during beginning and end of tripping operations, higher THL values lead to constant in slip status of drill string (SS = 0), thereby no changes in bit depth are obtained, leading to erroneous measurements displayed to driller. The chances of error are more when the THL value is close to drill string plus hook weight in beginning and end of tripping. Any fluctuation in hook weight measurements due to rapid movement of hook can cause flip-flop in the values of SS. Any flip-flop measurement of SS will lead to jumps in bit depth values.

Therefore, the manual THL setting and slip status measurement suffers from several handicaps mentioned below.

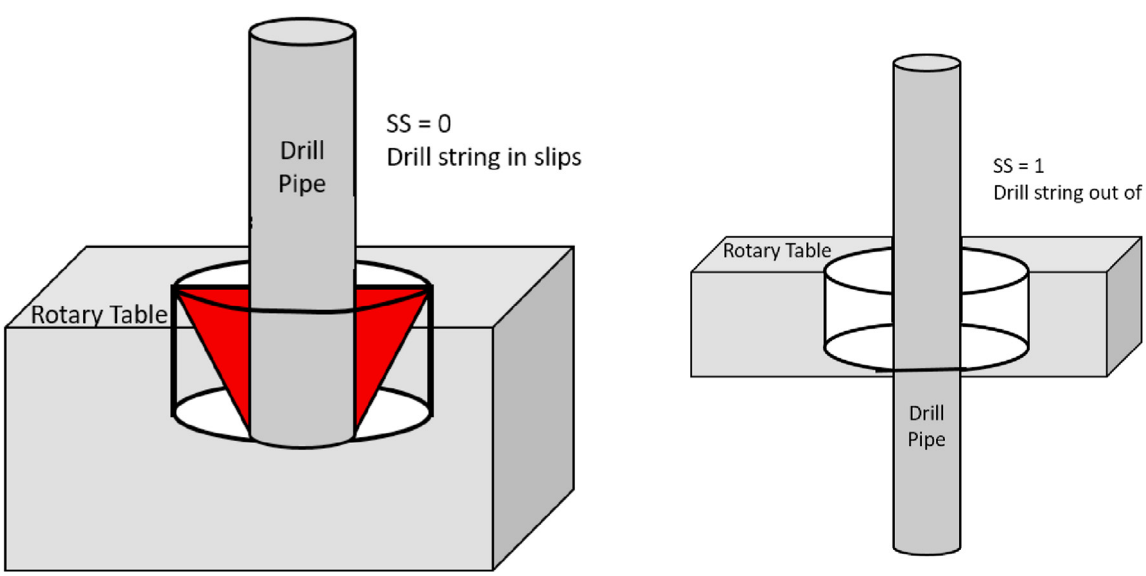

Fig. 2. In slip (SS = 0) and out of slip (SS = 1) state of drill string explained with suitable drawings. In left drawing, weight of drill string is borne by slips shown in red while in right drawing, weight of drill string is borne by hoisting system of the rig.

a. If THL is set higher than empty hook weight, continuous in slip status is obtained (SS = 0) and the bit depth and related stand counter changes are not obtained while actually they change.
b. If THL is set lower than empty hook weight, in slip status (SS = 0) is never obtained and bit depth will move even during movement of empty hook.
c. If THL is too close to empty hook weight, then while moving empty hook, variations in bit depth may be recorded, as there is flip-flop change of slip status.

In summary, legacy method has inherent accuracy and reliability issues in measurement of SS and bit depth during drilling operations. Another method of SS detection by obtaining pressure data and hook load data for the drill string was invented by Castel et al. (2016). Drilling operations generate vibrations and shocks (Lin, 2008), which generate hook load spikes. Another method to detect SS of drill string is invented where algorithms are there to train machine to recognize drill string slip status from rate of change of hook load (Khare, 2019).

These methods depend on hook load data obtained from electronic sensor installed on rig. However, there are eddy currents present on rig due to power transmission lines, which can cause deflection in sensor pulse measurement values. Besides, draw works sensor needs frequent calibrations and is prone to frequent wear and tear. Therefore, there is a need of an alternate method to compute SS of drill string with machine vision technology.

4. Machine vision

Machine vision is a next gen technology to enable the machine with visual perception system (Rahmatov et al., 2019). It is an assembly of hardware and software integrated to recognize and manipulate the activities done by machines. It is an enabler of automation where image based process control and surveillance of industrial operations can be performed (Heras and Blanke, 2020). Machine vision has several applications in industrial surveillance (Cho and Kwon, 2021), traffic monitoring and control system, automated inspection, driver less cars, vehicle guidance and interpretation of remotely sensed images (Hannan et al., 2009). One common application of camera-enabled surveillance is fixed installation roadside cameras used for smart traffic management with real time analysis (Jacob et al., 2019) that capture image of registration number of over speeding and signal jumping vehicles (Fig. 3).

Several scientists have addressed the problems in recognizing 3D objects and images in image sequences (Park and Inoue, 1997). Workers have done work on pattern recognition on 3D CAD objects (George, 1996). In upstream oil and gas operations, 3-D computer vision and pattern recognition technology can help in operation surveillance. The need is to understand the essential theory and practicalities to design algorithms and systems for surveillance of drilling operations. Case studies to demonstrate specific techniques for drilling surveillance should be designed with pattern recognition, computer vision and machine vision systems.

Rig surveillance systems should analyze image recordings captured by cameras to detect state of systems operating on rig. Detection of such states leads to detection of rig activity. High-resolution rugged cameras installed at critical locations on rig capture real time images. These cameras are connected to a system database and a processing unit for assigning a state to a machine. Various states that are assigned to drill string, mud pump, travelling block, shale shakers and return line are given below in Table 1.

Machine vision technology can help detect states of each of these machines and rig components with reliable accuracy. A logical diagram of steps in getting information from machine vision technique in given in Fig. 4. The image captured by camera undergoes preprocessing to remove noise, blurs and poor resolution. Only good quality, undistorted, high-resolution pictures are considered for next step detection of machine state.

Fig. 3. Roadside radar and camera inside housing for road surveillance. Camera captures picture and registration number of over speeding and signal jumping vehicles and stores in a database.

These preprocessed set of images of rig floor, slips, drill string, rotary table are sent in database, where algorithms are applied to images for SS detection. The more the processed images, the better is learning of the system and better detection of SS. The binary SS value is transferred to rig data acquisition and instrumentation system (Fig. 4). This data helps compute other derived real time variables and to compute rig states. For rig surveillance, images obtained from multiple cameras should detect machine status concurrently.

5. Rig specific machine vision technology

Machine vision has wide industrial applications where operational surveillance is done by a combination of hardware and software based on the capture and processing of images. The similar system is proposed on oil and gas rigs for surveillance of drilling, completion and well testing operations. However, rig specific machine vision systems should have greater robustness, reliability, and stability compared to other industrial setups due to harsh environments and operating conditions on oil and gas rigs. Depending on connectivity bandwidth, the software system can be located on the rig, in the base, or in cloud.

The machine vision system has several components, which should be compatible to rig environments. Machine vision systems will generate high quality digital images from industrial cameras with specialized optics, suitably located at several locations on rig. The computer hardware and software systems should process and

Table 1
Possible system states of critical machines of an oil and gas rig.

Drill string			
With RPM Without RPM	Moving Up Moving down No movement	*In slips* ***Out of slip***	*In hole* ***No string in hole***
Mud Pumps			Shale Shakers
Pumping Not pumping Repair work			Mud flowing No mud In motion/No motion
Travelling Block			Mud returns
Moving up Moving down Stationery			Mud flowing back No mud in returns

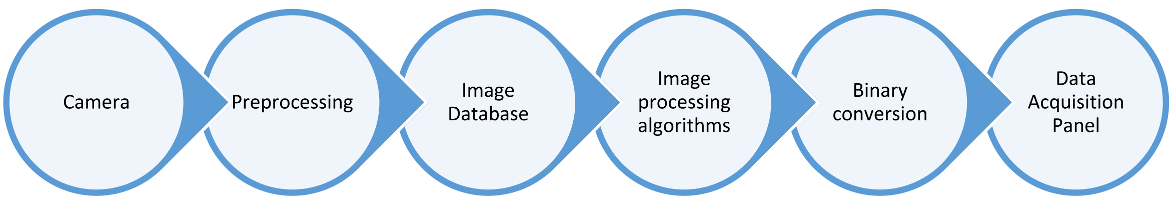

Fig. 4. A logical dataflow chart for image capture, screening and identification of equipment state.

analyze these images in real time for decision-making. The critical components of machine vision system are light, lenses, vision sensors, image processing module, vision-processing module and communication module.

6. Lighting

In machine vision applications, good illumination of object is mandatory for image capture (Fig. 5). For safe operation, rig areas run on bright light 24 $\times$ 7, provided by halogens and other light sources. Bright light illumination of rig floor and drill string is mandatory for safe operations. For slip status detection, back lighting is mandatory to detect the drill string outline. The camera and light source should be located on opposite sides of drill string for better detection of edges, shape and dimensions of the drill string. Since there are no shiny or reflective surfaces on rig floor or drill string, bright field illumination of the drill string and rig floor is also suitable for image capture.

7. Machine vision lens and image sensors

It is the most critical component of machine vision system meant to capture and transfer image to camera sensor. The lenses installed on machine vision camera must have wide angle, zoom features, minimal radial and perspective distortion. Radial distortion leads to differential magnification whereas parallax leads to image size reduction. High-resolution lenses with good contrast are required to get better object details. High resolution produces better pixel images. Vibration and shock resistant lenses are better option for rig installations. Fog resistant lenses are suitable for offshore and high humidity environments. Anti-scratch coating is preferred for long life of lens. 3-D cameras are widely used in industry to provide perception of depth in images, as obtained by binocular human vision. It uses more than one lenses for simultaneous capture of image and then processing of image done to obtain depth perspective of object under observation. They are of wide use in face detection, biometric authentication and face expression recognition (Ulrich et al., 2020), and must be used for machine vision enablement on drilling rigs.

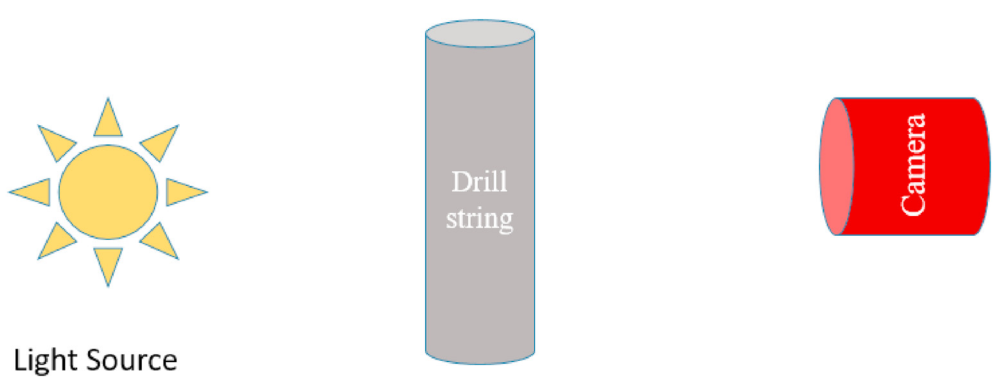

Fig. 5. An illustration of relative location of light source vis. a vis. camera for a drill string object.

8. Rig floor installations

CCTV cameras with rugged rig installation are now available and widely used across all types of rigs. Closed circuit systems transmit real time video footage at shale shakers, rig floor, doghouse, and mud pits etc. is now common on rig site. They are used for video surveillance of rig. In offshore rigs, Remote Operating Vehicles (ROV) cameras are used for underwater operations. 3D imaging systems offer state of the art stereoscopic HDTV images from subsea, for the ROV pilot and the end user. Such systems come with self-light source, which provides clear 16:9 high definition images viewed through circular polarized glasses. Umbilical Solutions provide control line systems and managed services that reduce risk and help use resources more efficiently.

Several companies provide live streaming video services to drilling contractors. The cameras and housings must be robust to withstand heat and dust. Video cameras offer both fixed position and pan tilt zoom systems with motors. The rig floor camera should have following features.

a. Should be digital video camera with HD image quality even during night or bad weather.
b. Internet capability, even over mobile data, to enable real-time view and fast security response.
c. Camera housing that protects outdoor camera from harsh weather.
d. Equipment functionality in places where crew cannot reach safely.
e. Camera maintenance can be done by remote video monitoring, making cameras virtually tamperproof.
f. Always online, driver software stays up to date.
g. Analytics on video streams.
h. Unlimited cloud storage of video footage for a well.

For machine vision detection of slip status, install a rugged stereoscopic 3-D HD camera with suitable features mentioned above at a suitable location near rotary table. Install multiple cameras to overcome occlusion (Keck and Davis, 2011). The camera should be on lower side of mast and with rugged fixtures to absorb vibration and rig rolling, pitching and heave in offshore locations. Multiple installations have advantage of image capture from another direction even if one side has obstruction. Non-stop image capture continues even if one camera is under maintenance.

9. Vision processing

It's a PC based system equipped with algorithms to calculate in slip (SS = 0) and out of slip (SS = 1) status of drill string. The system can be standalone located on rig or can be on cloud managed by an oil field service provider. The image captured by camera sensor undergoes preprocessing prior to analysis. Bad quality images with blur and distortion are not suitable for SS detection. An algorithm calculates the SS from measurements done on good quality image.

A schematic diagram (Fig. 6) shows the data flow related to machine-vision drill-string/tubular slip status detection. In this figure, R is actual diameter of rotary hole while D is the actual outer diameter of tubular hanging in the well bore. The slip is a tool, which can be inserted in rotary hole between rotary hole inner surface and outer surface of tubular. When slip is inserted, the slip status of tubular is in slip (SS = 0) while when there is no slip in rotary hole, the slip status of tubular is out of slip (SS = 1).

The actual diameter of rotary hole opening is R, which is a fixed value for a rig. The rotary hole diameters vary from around 30 to 60 inches in most rigs. The rotary hole diameter value is fed into the vision-processing computer. To begin the slip-status detection, a system calibration is mandatory, where a camera captures a high-resolution good quality image of rotary table hole and adjacent area, and transfers it to vision processing module. This computer system measures distance between extreme edges of circular rotary hole R_m in the image received by camera. A unit less coefficient α is calculated where

$$\alpha = R/R_m$$

where R is actual diameter of rotary hole.

Next, a drill pipe of diameter D inches is run into rotary hole and its image is captured by camera. The computer now measures in image, the perpendicular distance D_m between extreme edges of rill pipe\ perpendicular to rotary hole and passing through it. When D_m multiplied with α, the system gets the diameter of drill pipe. The nominal diameter of common drill pipe is 5 inches. The system generated and actual drill pipe diameter values are compared. Good calibration of system will give same values of system generated and actual diameter of drill pipe. These calibration values are stored in the vision processing system. The flow chart for slip status calculation is shown in Fig. 7.

There are three scenarios of rotary hole and drill pipe/tubular interaction.

a. No string in hole (which is in slip state SS = 0)
b. String in slip (SS = 0).
c. String out of slip (SS = 1).

In first scenario, there is no tubular perpendicular to rotary hole, therefore $D_m = 0$. In this scenario, vision processing module (VPM) transmits SS = 0 to communication module against the time stamp for which data was captured.

In second scenario, computer, from the image supplied by camera, measures a tubular edge distance value $D_m > 0$. It implies that there is a drill string or its components present in the well bore. It then multiplies D_m with α to get the D which is actual distance between edges of tubular (tubular diameter). In this case, computer makes a measurement of D_m values at several points from 2 to 3 feet above to nearest point on the rotary hole opening and converts it to D values by multiplying with α, and stores it against the same time stamp in its database. It then subtracts D from R for all table rows for this timestamp image. If R − D values remains >0 and almost constant for all data points then drill string is out of slip and SS = 1 value is transferred to communication module. However, if the D value increases towards the rotary table hole and at one point D and R become equal (R − D = 0), then it implies that tubular SS = 0. This value is then transmitted to communication module. The R − D value will be zero, when rotary hole diameter and slip wrapped around tubular diameter, as measured in image are same, which is the case when slip is in rotary hole and string is in slip.

10. Communication module

Communication system (Fig. 8) is a server to transfer time series SS data to rig measurement system. This module may or may not store SS data. If stored, SS binary values are indexed against time stamp.

The communication system constantly relays time stamp SS data to Data Acquisition System (DAS) of rig. This server pushes the time stamp SS value to client. The client DAS system merges SS data with other high frequency data acquired from rig sensors, indexed against time stamp. The SS value becomes input variable to derive other critical drilling variables like bit depth, stand counter and hole-depth.

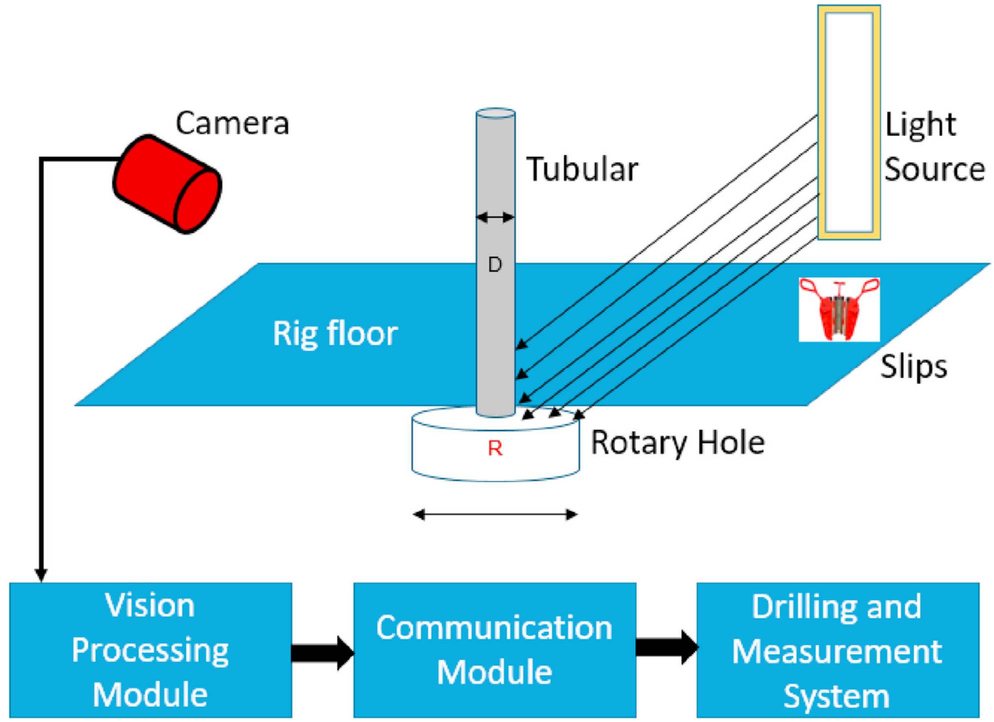

Fig. 6. A schematic diagram to illustrate rotary hole and tubular image capture on rig floor and then the pathway of data flow to rig drilling and measurement system via vision processing and communication modules.

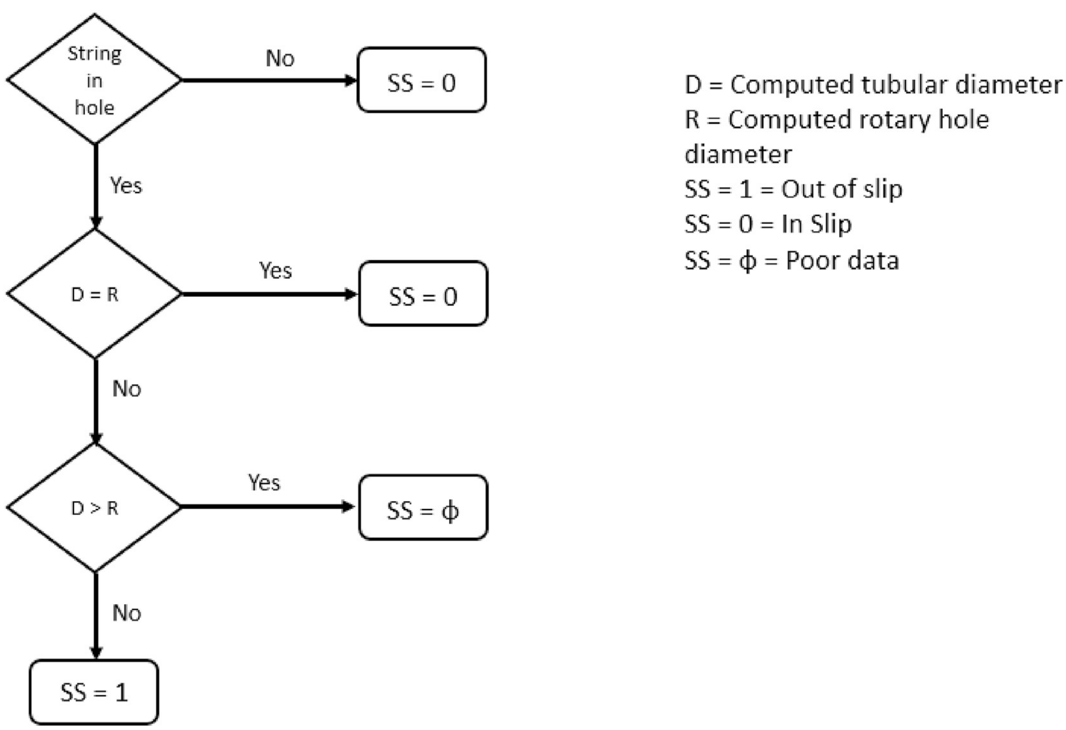

Fig. 7. Flow chart for calculation of drill string slip status.

11. Limitations and challenges

As with any system, this method also suffers from some limitations and challenges in accurate measurement of slip status, which are mentioned below.

a. The camera may not provide good quality images during rains, fog and other adverse weather conditions. The images may be blurred, distorted and vague due to these reasons.
b. Cleaning and maintenance of lens should be done on regular basis. The offshore environment is humid which may lead to

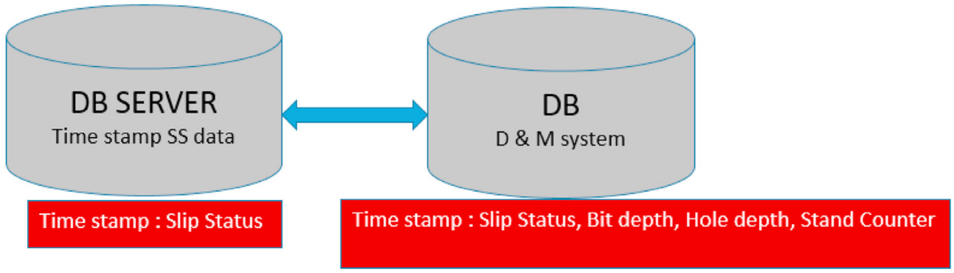

Fig. 8. The storage and communication of SS values from communication module to Data acquisition panel of rig system. The communication server on left side transfers SS value to database of rig measurement system.

frequent deposition of water vapor on lens. This fogging may lead to blurred images.

c. Continuous bright light source is required for good quality images.
d. There should be uninterrupted view of rotary table and drill string from camera.
e. Vibrations, bit bouncing and whirl motion of drill string may give erroneous results.
f. Severe rolling, pitching and heave of drill ships in offshore environment may give erroneous results.
g. Calibration may be tedious process. Several images are required for calibration to get correct values of coefficient. Verify D values with actual string diameter after calibration.

12. Conclusion

Drilling of oil and gas wells is a high-risk activity done in hazardous environment where safety of people and assets is a prime concern of an oil and gas company. It is a capital-intensive activity with high NPT and down time, which is close to average 30 percent of total time. Therefore, there is a need and challenge to optimize and automate drilling operations (Sircar et al., 2021). The low-oil price regime has led to shrinking revenues of oil and gas companies and further put pressure on operators to cut their exploration and production costs. Therefore, research scientists focus on leveraging emerging next gen computing technologies to improve operation efficiency (Khare et al., 2019) and reduce overall operation cost of well construction and completion.

Machine vision is one such next gen technology, which provides an alternate method of accurate slip status detection of drill string/tubular in rotary hole, thereby improving overall quality of real time drilling data. The legacy slip status detection method suffers from several constraints, which often leads to incorrect measurement of critical drilling variables like bit depth, hole depth, stand counter and weight on bit etc. The proposed method uses machine vision optical video camera and a backend storage and computing system to infer slip status of drill string. The inferred slip status is transmitted in real time to rig data acquisition panel which then uses this input to generate accurate value of several other related drilling parameters like bit depth, stand counter etc. Stereo camera sensor is a good alternative solution to legacy hook load sensor based string slip detection. In the beginning and end of tripping of drill string, when probability of getting correct slip status from legacy hook-load method is poor due to operational mechanical constraints, this method helps overcome these constraints and enables accurate measurement of slip status from beginning to end of trip job. Driller will not make manual adjustment to threshold hook-load values and need not reset these values several times while tripping. The system can be switched over from machine vision method to legacy method when reasonable length of string is run in and the string load is enough to estimate slip status from legacy method. Similarly, legacy system can be switched over to machine vision system during the last phase of pull out of string when there is minimal weight of the string. Since machine vision method computes correct slip status, bit depth, hole depth and stand counter values in the beginning and last phase of tripping, which is a challenge with legacy method, there is an overall improvement of operations surveillance and monitoring. The accurate drilling variable datasets will further enable drilling optimization and automation.

Declaration of competing interest

There are no actual or potential conflict of interest.

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