Multivariate nonlinear model predictive controller for managed drilling processes

Reza Asgharzadeh Shishavan, Hector Perez and John D. Hedengren, Chemical Engineering, Brigham Young University, Provo, UT

This paper details a comprehensive control structure and the application in managed pressure drilling (MPD). The goal of this controller is to regulate the downhole pressure and rate of penetration (ROP) at desired values and attenuate any unwanted gas influx. For this purpose, a moving horizon estimator (MHE), an Extended Kalman Filter (EKF) and a nonlinear model predictive controller (NMPC) are designed to estimate and regulate the process. MHE and EKF provide the estimated unmeasured variables values to the controller to update the NMPC model and enable the controller to capture varying dynamics of the drilling process.

During MPD, the main pump sends the drilling mud into the middle of the drill string pipe. This mud travels downward through the drill bit and into the annulus and upward to the choke valve. Mud is used to remove the drilling cuttings and also to maintain a hydrostatic pressure at the drill bit against reservoir pore pressure. Rotation speed of the drill string (RPM) and weight on the bit (WOB), the amount of downward force placed on the drill bit, are two of the main factors that affect the drilling rate. Drill string rotation is adjusted with a top drive and WOB is adjusted by actuation above ground. As a result of hydraulic forces, torsional spring characteristics of the drill string, frictional losses, non-Newtonian mud flow, and other effects, the downhole WOB and RPM may be dynamically different than those applied topside.

While process automation and control has found many applications in the downstream industry, it is still immature in the upstream processes. The prior incidents while drilling have motivated research in drilling automation [1, 2]. One of the principle reasons that automation has not been progressed in drilling industry is lack of a high speed data communication network. Mud pulse telemetry has been the dominant technology available to send the data from sensors to topside equipment. However, mud pulse telemetry has limited bandwidth that is not capable, in many circumstances, for high-speed automated control systems.

Recently, a new high speed technology system has been developed and introduced that sends the data with a high bandwidth (57,600 bits/sec) to the surface. In this technology, electrical wires and conductors are used to transfer signals through drill pipe and across each threaded pipe to the next segment. Therefore the controller designed in this work is based on the wired pipe technology [3].

Two main goals in most drilling operations are safety and economics. In relation to safety, kick attenuation is vital to minimize operational risks. Kicks are the unexpected intrusion of formation gas into the drilling annulus due to a higher formation pressure. Kick attenuation can be achieved through annulus pressure regulation [2].In relation to economics, a higher ROP will lower the drilling cost. Therefore, ROP maximization is a motivating factor [4].

It is known that ROP depends on many factors including RPM, WOB, and downhole pressure. Previous research has attempted control and real-time optimization of ROP by only changing RPM and WOB, choosing to approach downhole pressure as a disturbance variable [4-6]. On the other hand, downhole pressure depends on the mud pump flow rate, choke valve opening, ROP and RPM (through an effect on the friction factor). Among all prior work, only mud pump flow rate and choke valve opening have been considered as manipulated variables in designing the pressure controllers [1, 7-10] for kick attenuation, while ROP and RPM have been considered as disturbance variables.

Prior research has focused on designing separate independent controllers and optimizers to regulate either pressure or ROP and excluded the effect of the multivariate nature of the control. This research offers a comprehensive controller that considers the interactions between ROP and pressure, regulating both in a single application. This multivariate controller uses pump flow rate, choke valve opening, rotation speed and WOB as manipulated variables and seeks to maintain ROP and downhole pressure.

Annulus density, friction factor and unwanted gas influx flow rate are not directly measured during drilling and therefore are considered as estimated variables. For this purpose, an MHE was designed to estimate annulus friction factor and density, and an EKF was designed to estimate unwanted gas influx flow rate.The nonlinear model predictive controller (NMPC) designed for this application uses a novel l1-norm with a dead band structure in the objective function. This is known to improve robustness of the controller while rejecting data outlier, noise and drift [11]. The NMPC uses both interior point and active set point optimization methods.

The control methods during normal drilling or kick conditions are detailed as follows: During normal drilling conditions, the goal is to maximize the ROP while maintaining the downhole pressure within a specified range. Therefore the controller calculates the required downhole RPM, WOB and downhole pressure values that lead to highest possible ROP. Next, it manipulates the pump flow rate and choke valve opening to regulate the downhole pressure to specified set points and changes topside WOB and RPM until the required WOB and RPM are achieved at the Bottom Hole Assembly (BHA).

During a kick event, the primary goal is to attenuate the kick while maintaining the ROP constant. First, the controller detects the kick condition through a rise in the downhole pressure and estimated unwanted gas influx value. Second, the application switches the controlled variable from downhole pressure to choke valve pressure and sets a new set point as the current value plus the desired change observed in the downhole pressure. Third, the controller calculates the optimum pump flow rate, choke valve opening and downhole RPM that lead to the new choke valve pressure set point. Finally, the controller adjusts the choke valve opening and pump flow rate and topside rotation speed to target values. This increases the pressure of the upper parts of the annulus that have not been affected by the kick and results in kick attenuation. WOB only affects ROP. Therefore, the controller also changes the topside WOB to compensate for the effect of the change in RPM to maintain a constant ROP. While attenuating the kick, the new reservoir pore pressure is estimated using the available topside and along-string measurements. When the unexpected gas influx is suppressed, the controlled variable is switched back to downhole pressure with the new set point calculated based on the new reservoir pore pressure.

Case study results show that integrated multivariate ROP and downhole pressure have superior performance compared to the case where each ROP and pressure have separate independent controllers. The benefits are faster and more effective kick attenuation along with a higher ROP leading to more efficient drilling operations.

References:

1. Hauge, E., et al., *A novel model-based scheme for kick and loss mitigation during drilling.* Journal of Process Control, 2013. **23**(4): p. 463-472.

2. Godhavn, J.-M., et al. *Drilling seeking automatic control solutions*. in *18th IFAC World Congress, August 28, 2011 - September 2, 2011*. 2011. Milano, Italy: IFAC Secretariat.
3. Reeves, M., et al. *High-speed drillstring telemetry network enables new real-time drilling and measurement technologies*. in *2006 IADC/SPE Drilling Conference - Achieving our Goals: People, Planning and Performance, February 21, 2006 - February 23, 2006*. 2006. Miami Beach, FL, United states: Society of Petroleum Engineers (SPE).
4. Arabjamaloei, R. and B. Karimi Dehkordi, *Investigation of the most efficient approach of the prediction of the rate of penetration.* Energy Sources, Part A: Recovery, Utilization and Environmental Effects, 2012. **34**(7): p. 581-590.
5. Eren, T., *Real-Time-Optimization of drilling parameters during drilling operations*, in *Petroleum and natural gas engineering,* 2010, Middle east technical university.
6. Irawan, S., A.M. Abd Rahman, and S.Q. Tunio, *Optimization of weight on bit during drilling operation based on rate of penetration model.* Research Journal of Applied Sciences, Engineering and Technology, 2012. **4**(12): p. 1690-1695.
7. Carlsen, L.A., G. Nygaard, and M. Nikolaou, *Evaluation of control methods for drilling operations with unexpected gas influx.* Journal of Process Control, 2013. **23**(3): p. 306-316.
8. Gravdal, J.E., et al., *Improved Kick Management During MPD by Real-Time Pore-Pressure Estimation.* SPE Drilling & Completion, 2010. **25**(4): p. 577-584.
9. Zhou, J., et al. *Adaptive observer for kick detection and switched control for bottomhole pressure regulation and kick attenuation during managed pressure drilling*. in *2010 American Control Conference, ACC 2010, June 30, 2010 - July 2, 2010*. 2010. Baltimore, MD, United states: IEEE Computer Society.
10. Zhou, J., et al., *Switched control for pressure regulation and kick attenuation in a managed pressure drilling system.* IEEE Transactions on Control Systems Technology, 2011. **19**(2): p. 337-350.
11. John D. Hedengren, R.A.S., Kody M. Powell, Thomas F. Edgar, *Nonlinear Modeling, Estimation and Predictive Control in APMonitor.* Computers & Chemical Engineering, 2014. In Press, Accepted Manuscript.