Robust output-feedback control of 3D directional drilling systems

Octavio A. Villarreal Magaña

Committee:
Prof.Dr.Ir. Nathan van de Wouw (TUDelft, supervisor)
Prof.Dr.Ir. Emmanuel Detournay (UMN, supervisor)
Dr.Ir. Manuel Mazo Jr. (TUDelft)

Delft University of Technology, The Netherlands

University of Minnesota, USA

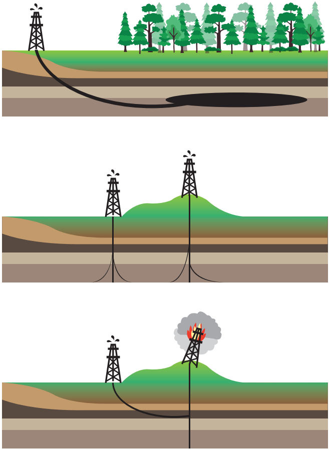
July 12, 2016

Outline

TUDelft
University of Minnesota

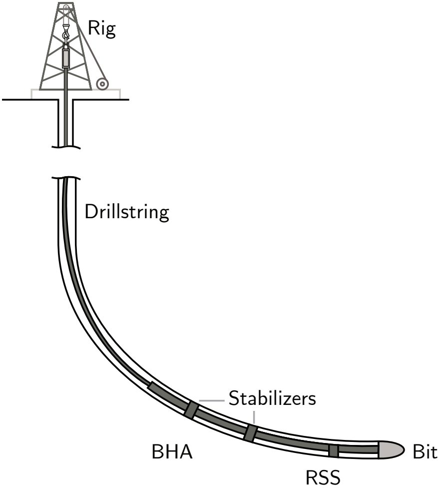
Outline

Applications of directional drilling

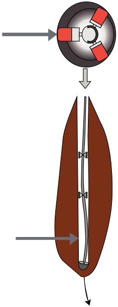


- Extract oil, mineral and thermal energy resources
- Reach targets that need complex geometries such as:
  - Under a city or an ecosystem
  - Far from the drill rig
  - Relief for hazardous situations

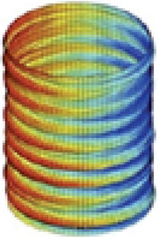
General description of the system



Rotary Steerable System



Context and challenges



- State-of-practice: Constant RSS force
- Negative effects: kinking, rippling and spiraling
- Process consequences of negative effects: reduced ROP and accuracy

TUDelft
University of Minnesota

Research goal

Develop a control strategy for a 3D directional drilling system, that allows to drill boreholes with complex geometries.

Previous works

- PD model of 3D directional drilling systems [Perneder 2013]

- Model-based decoupled control of a 3D directional drilling system [Monsieurs 2015]
  - State-feedback controller
  - Relies on availability of measurements of the states (not possible)
  - Not "a priori" robustly stable

Subgoals

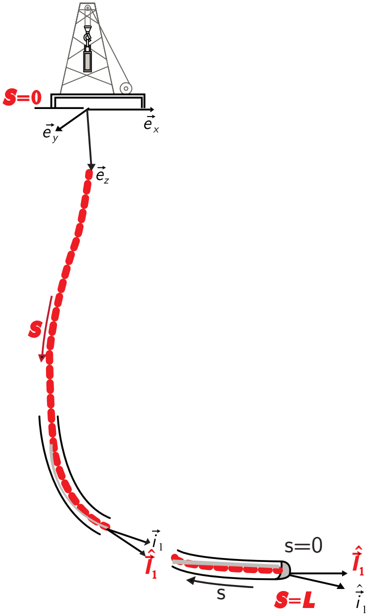
- **Control strategy that relies only in local measurements (observer design)**
- **Robustness against parametric uncertainty**

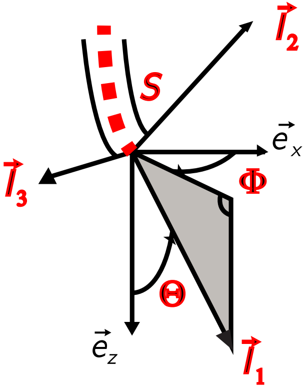
TUDelft
University of Minnesota

Outline

TUDelft
University of Minnesota

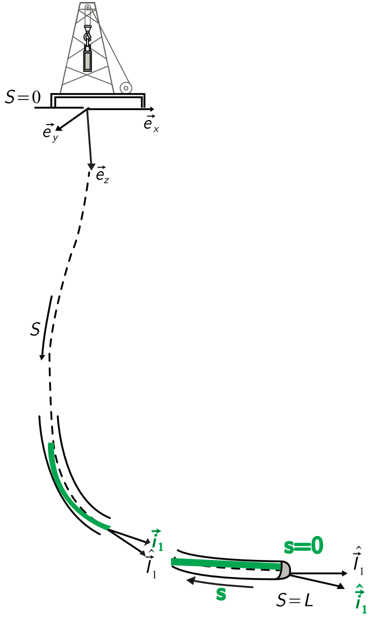
Geometric description

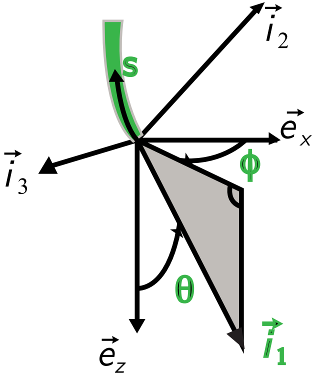




$\Theta(L)$ and $\Phi(L)$: Describe borehole evolution

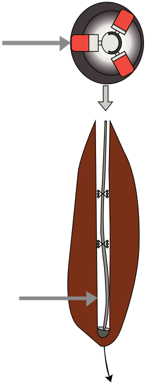
Geometric description

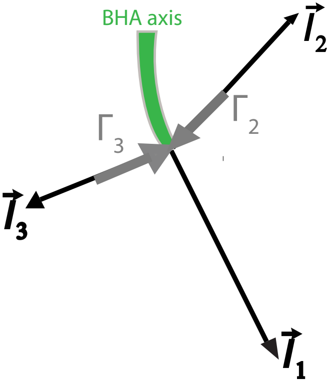




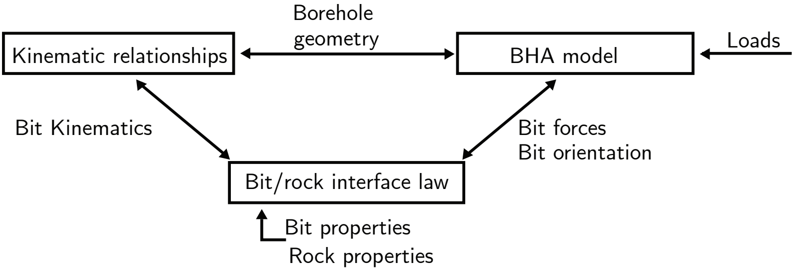
Only measurements of BHA

RSS actuator



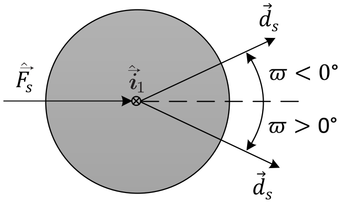


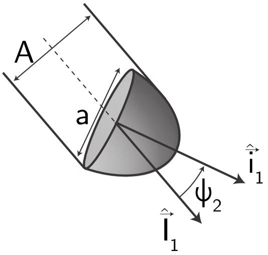
Elements of the model



- Nonlinear delay differential equations (Fit BHA in already drilled borehole)
- Function of length ξ

System parameters



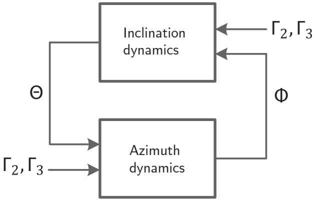


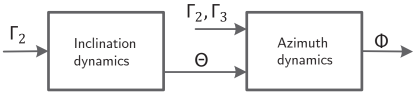
- Constant
  - Angular steering resistance η
  - Lateral steering resistance χ
- Uncertain
  - Active weight on bit Π (Hookload, drag forces, bit sharpness).
  - Bit walk angle ϖ (bit orientation, overgauging).

Borehole evolution equations

$$\Theta'(\xi) = f_\Theta(\Theta, \Phi, \Gamma_2, \Gamma_3, \varpi, \Pi)$$
$$\Phi'(\xi) = f_\Phi(\Theta, \Phi, \Gamma_2, \Gamma_3, \varpi, \Pi)$$

Non-neutral vs neutral bit walk tendency:





$$\varpi \neq 0 \qquad\qquad \varpi = 0$$

Neutral bit walk evolution equations

Two stabilizers case:

$$\begin{aligned}
\chi\Pi\Theta' = &-\mathcal{M}_b(\Theta - \langle\Theta\rangle_1) - \frac{\mathcal{M}_b\mathcal{F}_1 + \mathcal{M}_1(\eta\Pi - \mathcal{F}_b)}{\eta\Pi}(\langle\Theta\rangle_1 - \langle\Theta\rangle_2) \\
&+ \frac{\chi}{\eta}\mathcal{F}_b(\Theta - \Theta_1) - \frac{\chi}{\eta}\mathcal{F}_1\left(\Theta - \Theta_1 - \frac{\Theta_1 - \Theta_2}{\varkappa_2}\right) \\
&- \frac{\mathcal{M}_b\mathcal{F}_r + (\eta\Pi - \mathcal{F}_b)\mathcal{M}_r}{\eta\Pi}\Gamma_\Theta - \frac{\chi}{\eta}\mathcal{F}_r\Gamma'_\Theta + W \\
\chi\Pi\Phi' = &-\mathcal{M}_b(\Phi - \langle\Phi\rangle_1) - \frac{\mathcal{M}_b\mathcal{F}_1 + \mathcal{M}_1(\eta\Pi - \mathcal{F}_b)}{\eta\Pi}(\langle\Phi\rangle_1 - \langle\Phi\rangle_2) \\
&+ \frac{\chi}{\eta}\mathcal{F}_b(\Phi - \Phi_1) - \frac{\chi}{\eta}\mathcal{F}_1\left(\Phi - \Phi_1 - \frac{\Phi_1 - \Phi_2}{\varkappa_2}\right) \\
&+ \left(\frac{\chi}{\eta}\frac{\mathcal{F}_r\Theta'\cos\Theta}{(\sin\Theta)^2} - \frac{\mathcal{M}_b\mathcal{F}_r + \mathcal{M}_r(\eta\Pi - \mathcal{F}_b)}{\eta\Pi\sin\Theta}\right)\Gamma_\Phi - \frac{\chi}{\eta}\frac{\mathcal{F}_r}{\sin\Theta}\Gamma'_\Phi
\end{aligned}$$

Neutral bit walk evolution equations

Two stabilizers case:

$$
\begin{aligned}
\chi\Pi\Theta' = &-\mathcal{M}_b(\Theta - \langle\Theta\rangle_1) - \frac{\mathcal{M}_b\mathcal{F}_1 + \mathcal{M}_1(\eta\Pi - \mathcal{F}_b)}{\eta\Pi}(\langle\Theta\rangle_1 - \langle\Theta\rangle_2) \\
&+ \frac{\chi}{\eta}\mathcal{F}_b(\Theta - \Theta_1) - \frac{\chi}{\eta}\mathcal{F}_1\left(\Theta - \Theta_1 - \frac{\Theta_1 - \Theta_2}{\varkappa_2}\right) \\
&- \frac{\mathcal{M}_b\mathcal{F}_r + (\eta\Pi - \mathcal{F}_b)\mathcal{M}_r}{\eta\Pi}\Gamma_\Theta - \frac{\chi}{\eta}\mathcal{F}_r\Gamma'_\Theta + W \\
\chi\Pi\Phi' = &-\mathcal{M}_b(\Phi - \langle\Phi\rangle_1) - \frac{\mathcal{M}_b\mathcal{F}_1 + \mathcal{M}_1(\eta\Pi - \mathcal{F}_b)}{\eta\Pi}(\langle\Phi\rangle_1 - \langle\Phi\rangle_2) \\
&+ \frac{\chi}{\eta}\mathcal{F}_b(\Phi - \Phi_1) - \frac{\chi}{\eta}\mathcal{F}_1\left(\Phi - \Phi_1 - \frac{\Phi_1 - \Phi_2}{\varkappa_2}\right) \\
&+ \left(\frac{\chi}{\eta}\frac{\mathcal{F}_r\Theta'\cos\Theta}{(\sin\Theta)^2} - \frac{\mathcal{M}_b\mathcal{F}_r + \mathcal{M}_r(\eta\Pi - \mathcal{F}_b)}{\eta\Pi\sin\Theta}\right)\Gamma_\Phi - \frac{\chi}{\eta}\frac{\mathcal{F}_r}{\sin\Theta}\Gamma'_\Phi
\end{aligned}
$$

BHA configuration constant coefficients

Neutral bit walk evolution equations

Two stabilizers case:

$$
\begin{aligned}
\chi\Pi\Theta' = &-\mathcal{M}_b(\Theta - \langle\Theta\rangle_1) - \frac{\mathcal{M}_b\mathcal{F}_1 + \mathcal{M}_1(\eta\Pi - \mathcal{F}_b)}{\eta\Pi}(\langle\Theta\rangle_1 - \langle\Theta\rangle_2) \\
&+ \frac{\chi}{\eta}\mathcal{F}_b(\Theta - \Theta_1) - \frac{\chi}{\eta}\mathcal{F}_1\left(\Theta - \Theta_1 - \frac{\Theta_1 - \Theta_2}{\varkappa_2}\right) \\
&- \frac{\mathcal{M}_b\mathcal{F}_r + (\eta\Pi - \mathcal{F}_b)\mathcal{M}_r}{\eta\Pi}\Gamma_\Theta - \frac{\chi}{\eta}\mathcal{F}_r\Gamma'_\Theta + W \\
\chi\Pi\Phi' = &-\mathcal{M}_b(\Phi - \langle\Phi\rangle_1) - \frac{\mathcal{M}_b\mathcal{F}_1 + \mathcal{M}_1(\eta\Pi - \mathcal{F}_b)}{\eta\Pi}(\langle\Phi\rangle_1 - \langle\Phi\rangle_2) \\
&+ \frac{\chi}{\eta}\mathcal{F}_b(\Phi - \Phi_1) - \frac{\chi}{\eta}\mathcal{F}_1\left(\Phi - \Phi_1 - \frac{\Phi_1 - \Phi_2}{\varkappa_2}\right) \\
&+ \left(\frac{\chi}{\eta}\frac{\mathcal{F}_r\Theta'\cos\Theta}{(\sin\Theta)^2} - \frac{\mathcal{M}_b\mathcal{F}_r + \mathcal{M}_r(\eta\Pi - \mathcal{F}_b)}{\eta\Pi\sin\Theta}\right)\Gamma_\Phi - \frac{\chi}{\eta}\frac{\mathcal{F}_r}{\sin\Theta}\Gamma'_\Phi
\end{aligned}
$$

Averages (Distributed delays):

$$
\langle\Theta\rangle_i := \frac{1}{\varkappa_i}\int_{\xi_i}^{\xi_{i-1}}\Theta(\sigma)d\sigma, \qquad \langle\Phi\rangle_i := \frac{1}{\varkappa_i}\int_{\xi_i}^{\xi_{i-1}}\Phi(\sigma)d\sigma
$$

$\varkappa_i$: Length between stabilizers, for $i = 1, 2$

Neutral bit walk evolution equations

Two stabilizers case:

$$
\begin{aligned}
\chi\Pi\Theta' = &-\mathcal{M}_b(\Theta - \langle\Theta\rangle_1) - \frac{\mathcal{M}_b\mathcal{F}_1 + \mathcal{M}_1(\eta\Pi - \mathcal{F}_b)}{\eta\Pi}\left(\langle\Theta\rangle_1 - \langle\Theta\rangle_2\right) \\
&+ \frac{\chi}{\eta}\mathcal{F}_b(\Theta - \boldsymbol{\Theta}_1) - \frac{\chi}{\eta}\mathcal{F}_1\left(\Theta - \boldsymbol{\Theta}_1 - \frac{\boldsymbol{\Theta}_1 - \boldsymbol{\Theta}_2}{\varkappa_2}\right) \\
&- \frac{\mathcal{M}_b\mathcal{F}_r + (\eta\Pi - \mathcal{F}_b)\mathcal{M}_r}{\eta\Pi}\Gamma_\Theta - \frac{\chi}{\eta}\mathcal{F}_r\Gamma'_\Theta + W \\
\chi\Pi\Phi' = &-\mathcal{M}_b(\Phi - \langle\Phi\rangle_1) - \frac{\mathcal{M}_b\mathcal{F}_1 + \mathcal{M}_1(\eta\Pi - \mathcal{F}_b)}{\eta\Pi}\left(\langle\Phi\rangle_1 - \langle\Phi\rangle_2\right) \\
&+ \frac{\chi}{\eta}\mathcal{F}_b(\Phi - \boldsymbol{\Phi}_1) - \frac{\chi}{\eta}\mathcal{F}_1\left(\Phi - \boldsymbol{\Phi}_1 - \frac{\boldsymbol{\Phi}_1 - \boldsymbol{\Phi}_2}{\varkappa_2}\right) \\
&+ \left(\frac{\chi}{\eta}\frac{\mathcal{F}_r\Theta'\cos\Theta}{(\sin\Theta)^2} - \frac{\mathcal{M}_b\mathcal{F}_r + \mathcal{M}_r(\eta\Pi - \mathcal{F}_b)}{\eta\Pi\sin\Theta}\right)\Gamma_\Phi - \frac{\chi}{\eta}\frac{\mathcal{F}_r}{\sin\Theta}\Gamma'_\Phi
\end{aligned}
$$

Borehole orientation variables at the first and second stabilizers (point-wise delays)

Neutral bit walk evolution equations

Two stabilizers case:

$$
\begin{aligned}
\chi\Pi\Theta' =& -\mathcal{M}_b(\Theta - \langle\Theta\rangle_1) - \frac{\mathcal{M}_b F_1 + \mathcal{M}_1(\eta\Pi - \mathcal{F}_b)}{\eta\Pi}(\langle\Theta\rangle_1 - \langle\Theta\rangle_2) \\
&+ \frac{\chi}{\eta}\mathcal{F}_b(\Theta - \Theta_1) - \frac{\chi}{\eta}\mathcal{F}_1\left(\Theta - \Theta_1 - \frac{\Theta_1 - \Theta_2}{\varkappa_2}\right) \\
&- \frac{\mathcal{M}_b\mathcal{F}_r + (\eta\Pi - F_b)\mathcal{M}_r}{\eta\Pi}\Gamma_\Theta - \frac{\chi}{\eta}\mathcal{F}_r\Gamma'_\Theta + W \\
\chi\Pi\Phi' =& -\mathcal{M}_b(\Phi - \langle\Phi\rangle_1) - \frac{\mathcal{M}_b F_1 + \mathcal{M}_1(\eta\Pi - F_b)}{\eta\Pi}(\langle\Phi\rangle_1 - \langle\Phi\rangle_2) \\
&+ \frac{\chi}{\eta}\mathcal{F}_b(\Phi - \Phi_1) - \frac{\chi}{\eta}\mathcal{F}_1\left(\Phi - \Phi_1 - \frac{\Phi_1 - \Phi_2}{\varkappa_2}\right) \\
&+ \boxed{\left(\frac{\chi}{\eta}\frac{\mathcal{F}_r\Theta'\cos\Theta}{(\sin\Theta)^2} - \frac{\mathcal{M}_b\mathcal{F}_r + \mathcal{M}_r(\eta\Pi - \mathcal{F}_b)}{\eta\Pi\sin\Theta}\right)\Gamma_\Phi - \frac{\chi}{\eta}\frac{\mathcal{F}_r}{\sin\Theta}\Gamma'_\Phi}
\end{aligned}
$$

Coupling terms

State definition

To have a set of first order DDE's with point-wise delays:

$$x_\Theta = \begin{bmatrix} \Theta \\ \langle\Theta\rangle_1 \\ \langle\Theta\rangle_2 \end{bmatrix} \qquad x_\Phi = \begin{bmatrix} \Phi \\ \langle\Phi\rangle_1 \\ \langle\Phi\rangle_2 \end{bmatrix}$$

Derivatives of the average states:

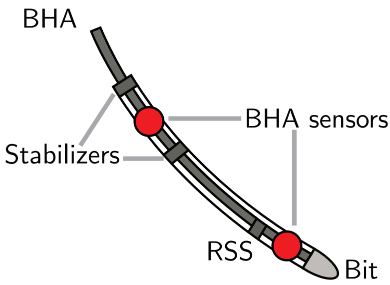
$$\langle\Theta\rangle_i{}' = \frac{1}{\varkappa_i}\left(\Theta_{i-1} - \Theta_i\right) \qquad \langle\Phi\rangle_i{}' = \frac{1}{\varkappa_i}\left(\Phi_{i-1} - \Phi_i\right)$$

State-space description:

$$\begin{bmatrix} x'_\Theta \\ x'_\Phi \end{bmatrix} = \begin{bmatrix} A_0 & 0 \\ 0 & A_0 \end{bmatrix} \begin{bmatrix} x_\Theta(\xi) \\ x_\Phi(\xi) \end{bmatrix} + \begin{bmatrix} A_1 & 0 \\ 0 & A_1 \end{bmatrix} \begin{bmatrix} x_\Theta(\xi_1) \\ x_\Phi(\xi_1) \end{bmatrix} + \begin{bmatrix} A_2 & 0 \\ 0 & A_2 \end{bmatrix} \begin{bmatrix} x_\Theta(\xi_2) \\ x_\Phi(\xi_2) \end{bmatrix}$$
$$+ \begin{bmatrix} B_{0\Theta} & 0 \\ 0 & \boxed{B_{0\Phi}} \end{bmatrix} \begin{bmatrix} \Gamma_\Theta \\ \Gamma_\Phi \end{bmatrix} + \begin{bmatrix} B_{1\Theta} & 0 \\ 0 & \boxed{B_{1\Phi}} \end{bmatrix} \begin{bmatrix} \Gamma'_\Theta \\ \Gamma'_\Phi \end{bmatrix} + \begin{bmatrix} BW \\ 0 \end{bmatrix}$$

$$\xi_1 = \xi - \varkappa_1, \qquad \xi_2 = \xi - \varkappa_1 - \varkappa_2$$

Output equations



- Only measurements of the BHA orientation

- Equation for sensor location:

$$y_\theta = [\theta_0(\xi, s_{m,1}),\ \theta_2(\xi, s_{m,2})]^T$$
$$y_\phi = [\phi_0(\xi, s_{m,1}),\ \phi_2(\xi, s_{m,2})]^T$$

- Output explicit expressions:

$$y_\Theta = C_\Theta x_\Theta + D_\Theta \Gamma_\Theta + W_y$$
$$y_\Phi = C_\Phi x_\Phi + D_\Phi \frac{\Gamma_\Phi}{\sin\Theta}$$

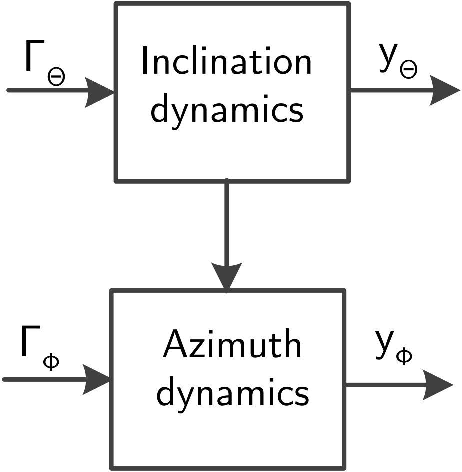
Outline

TUDelft
University of Minnesota

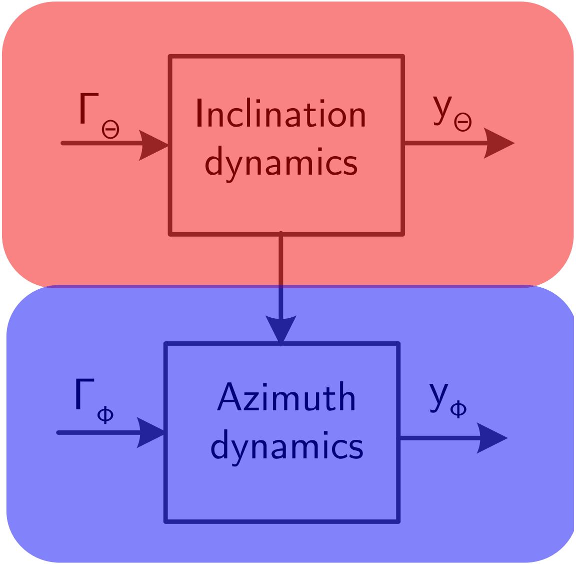
Control objectives

- Track a desired reference trajectory corresponding to a complex borehole geometry
- The response of the system should have favorable transient behavior (avoid kinking, rippling and spiraling)

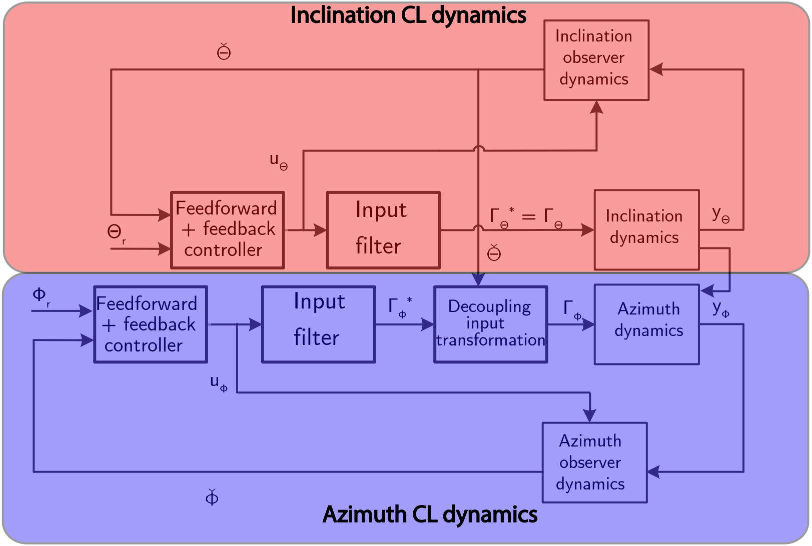
Plant definition



Plant definition

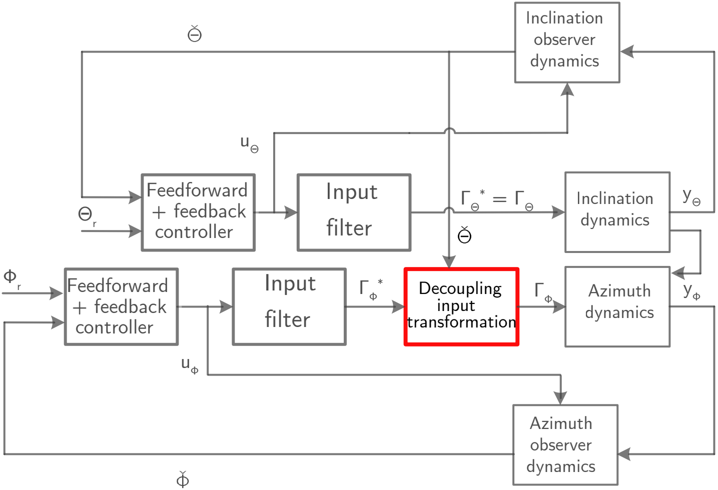


Plant definition



Control structure

Input decoupling transformation



Control structure

Input decoupling transformation

- Coupling terms:

$$\left(\frac{\chi}{\eta}\frac{\mathcal{F}_r \boldsymbol{\Theta}' \cos \boldsymbol{\Theta}}{\left(\sin \boldsymbol{\Theta}\right)^2} - \frac{\mathcal{M}_b \mathcal{F}_r + \mathcal{M}_r \left(\eta \Pi - \mathcal{F}_b\right)}{\eta \Pi \sin \boldsymbol{\Theta}}\right) \boldsymbol{\Gamma_\Phi} - \frac{\chi}{\eta}\frac{\mathcal{F}_r}{\sin \boldsymbol{\Theta}} \boldsymbol{\Gamma'_\Phi}$$

- Fully decouples system[Monsieurs 2015]:

$$\begin{bmatrix} \Gamma_\Theta^* \\ \Gamma_\Phi^* \end{bmatrix} := \begin{bmatrix} 1 & 0 \\ 0 & \frac{1}{\sin \Theta} \end{bmatrix} \begin{bmatrix} \Gamma_\Theta \\ \Gamma_\Phi \end{bmatrix}, \qquad \text{for } \Theta \in (0,\ \pi).$$

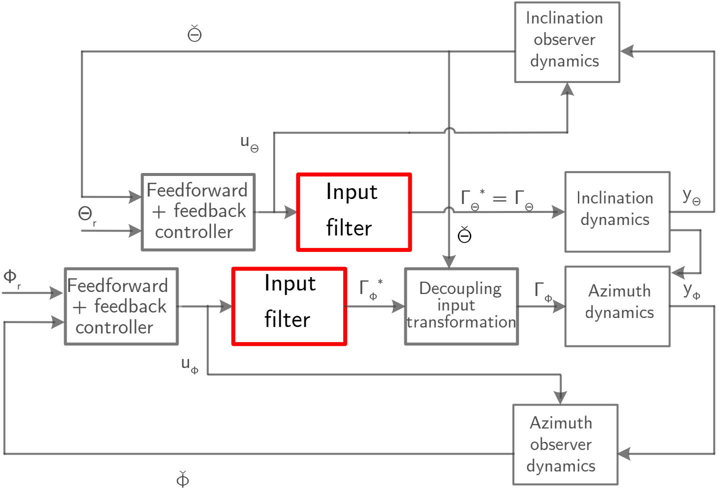
- Problem: no access to Θ

$$\begin{bmatrix} \Gamma_\Theta^* \\ \Gamma_\Phi^* \end{bmatrix} := \begin{bmatrix} 1 & 0 \\ 0 & \frac{1}{\sin \check{\boldsymbol{\Theta}}} \end{bmatrix} \begin{bmatrix} \Gamma_\Theta \\ \Gamma_\Phi \end{bmatrix}, \qquad \text{for } \check{\Theta} \in (0,\ \pi).$$

- Decouples system providing proper observer

Control structure

Input filter



Control structure

Input filter

- Terms with derivative of the input

$$\begin{bmatrix} B_{0\Theta} & 0 \\ 0 & \boxed{B_{0\Phi}(\Theta, \Theta')} \end{bmatrix} \begin{bmatrix} \Gamma^*_\Theta \\ \Gamma^*_\Phi \end{bmatrix} + \begin{bmatrix} B_{1\Theta} & 0 \\ 0 & \boxed{B_{1\Phi}(\Theta, \Theta')} \end{bmatrix} \begin{bmatrix} \Gamma^{*'}_\Theta \\ \Gamma^{*'}_\Phi \end{bmatrix}$$

- New control input for $i = \Theta, \Phi$

$$Bu_i = B_{0i}\Gamma^*_i + B_{1i}\Gamma^{*'}_i, \qquad B = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}$$

- Solve ODE

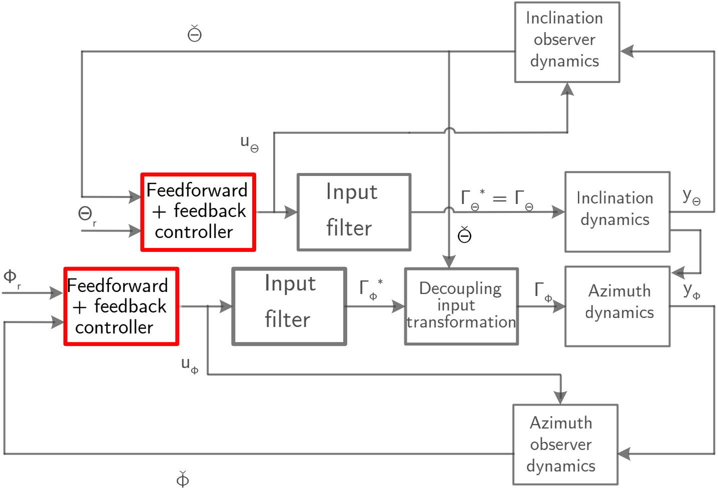
$$\Gamma^{*'}_i = B^+_{1i} Bu_i - B^+_{1i} B_{0i} \Gamma^*_i$$

- Problem $\Theta \neq \check{\Theta}$, include Γ_i in states

$$\begin{bmatrix} x_\Theta(\xi) & \Gamma^*_\Theta(\xi) & x_\Phi(\xi) & \Gamma^*_\Phi(\xi) \end{bmatrix}^T$$

Control structure

Feedback + feedforward controller



Control structure

Feedback + feedforward controller

- Control input:

$$u_i = v_i + u_{ri}, \text{ for } i = \Theta, \Phi.$$

- Feedforward:

$$u_{ri} = B^T(x'_{ri}(\xi) - A_0 x_{ri}(\xi) - A_1 x_{ri}(\xi_1) - A_2 x_{ri}(\xi_2)).$$

- Feedback (with $e_i := x_{ri} - x_i$):

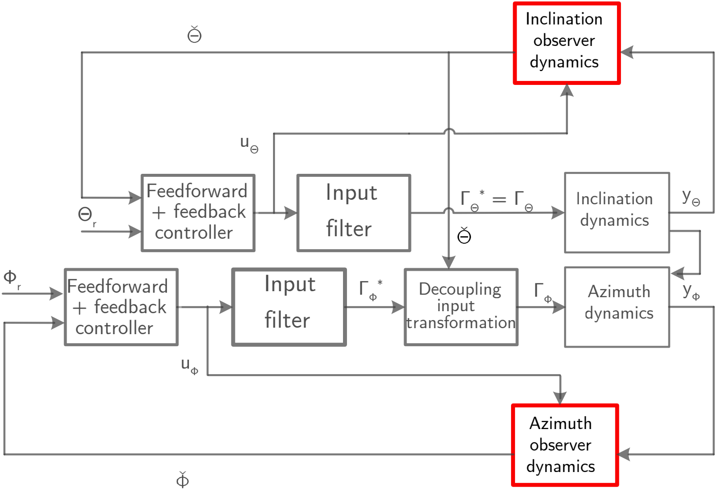
$$\begin{aligned} z'_{1i} &= \zeta \begin{bmatrix} k_{1i} & 0 & 0 \end{bmatrix} e_i \\ z'_{2i} &= -\gamma z_{2i} + \gamma(z_{1i} + K_i e_i) \\ v_i &= z_{2i}. \end{aligned}$$

- Integral (ζ) and low-pass filter (γ) gains fixed

TUDelft
University of Minnesota

Control structure

Observer



Control structure

Observer

- Only available measurements of the BHA orientation

- Model-based observer with output-injection part

- Gravity-related terms in the output rejected using integral action:

$$q_i' = \zeta[l_1, l_2](y_i - \check{y}_i), \qquad \text{for } i = \Theta, \Phi.$$

Control structure

Observer

$$\begin{bmatrix} \check{x}'_\Theta \\ q'_\Theta \\ \check{x}'_\Phi \\ q'_\Phi \end{bmatrix} = \begin{bmatrix} A_0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & A_0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \check{x}_\Theta(\xi) \\ q_\Theta(\xi) \\ \check{x}_\Phi(\xi) \\ q_\Phi(\xi) \end{bmatrix} + \begin{bmatrix} A_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & A_1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \check{x}_\Theta(\xi_1) \\ q_\Theta(\xi_1) \\ \check{x}_\Phi(\xi_1) \\ q_\Phi(\xi_1) \end{bmatrix}$$

$$+ \begin{bmatrix} A_2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & A_2 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \check{x}_\Theta(\xi_2) \\ q_\Theta(\xi_2) \\ \check{x}_\Phi(\xi_2) \\ q_\Phi(\xi_2) \end{bmatrix} + \begin{bmatrix} L_\Theta(y_\Theta - \check{y}_\Theta) \\ \zeta[l_{1\Theta}, l_{2\Theta}](y_\Theta - \check{y}_\Theta) \\ L_\Phi(y_\Phi - \check{y}_\Phi) \\ \zeta[l_{1\Phi}, l_{2\Phi}](y_\Phi - \check{y}_\Phi) \end{bmatrix}$$

$$+ \begin{bmatrix} Bq_\Theta \\ 0 \\ Bq_\Phi \\ 0 \end{bmatrix} + \begin{bmatrix} B(u_{r\Theta} + v_\Theta) \\ 0 \\ B(u_{r\Phi} + v_\Phi) \\ 0 \end{bmatrix},$$

TU Delft
University of Minnesota

Control approach

- Tune K_i and L_i, such that the reference trajectory is the solution of the closed-loop dynamics

- Tracking error dynamics and observer error dynamics:

$$e_i := x_{ri} - xi, \qquad \delta_i := x_i - \hat{x}_i, \text{ for } i = \Theta, \Phi.$$

- **Linearize system around**:

$$e_i = 0, \qquad \delta_i = 0.$$

- Linearized closed-loop system: ξ-**dependent**

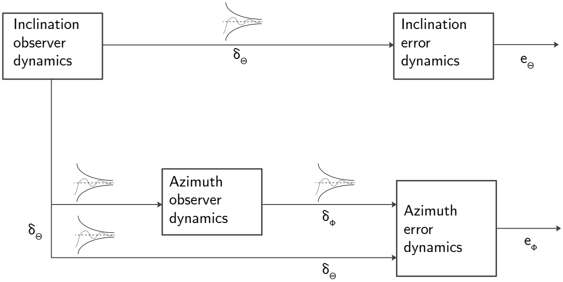
Controller synthesis

Analysis of the structure of closed-loop matrices:

- K_i and L_i separation principle for both Θ and Φ
- ξ-dependent terms present in coupling terms
- Isolated dynamics of e_i and δ_i are ξ-independent (bounded)

Controller synthesis

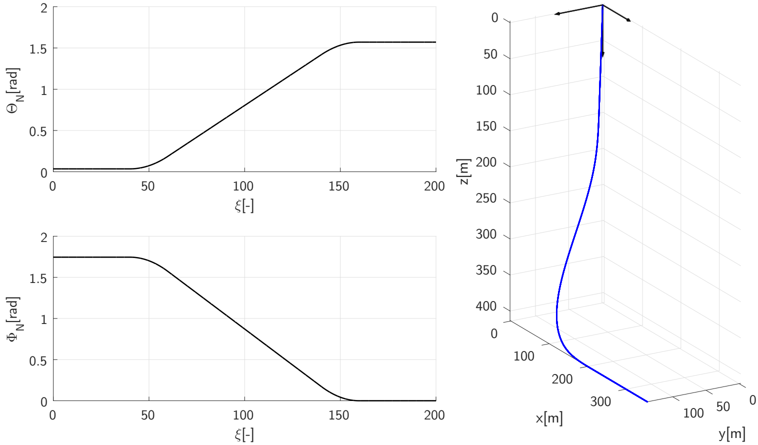
- Synthesize K_i and L_i for isolated systems
- Favorable transients, with proper order of convergence
- Due to infinite number of poles in delay systems, optimize location of right-most pole over K_i and L_i



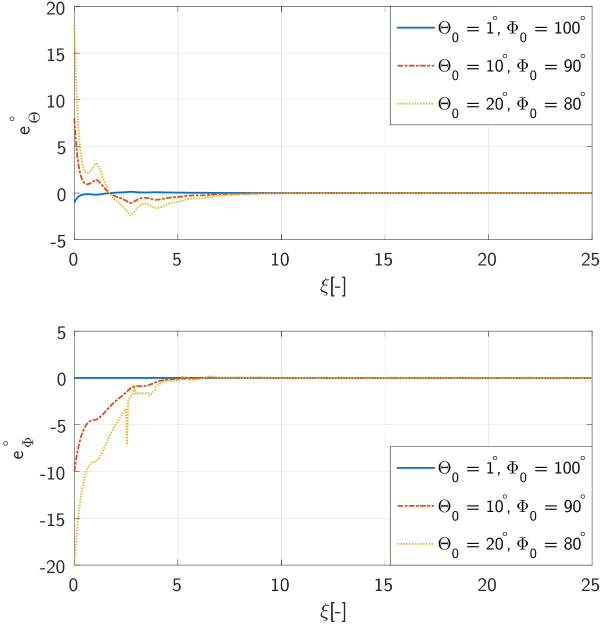
Outline

TUDelft
University of Minnesota

Reference trajectory

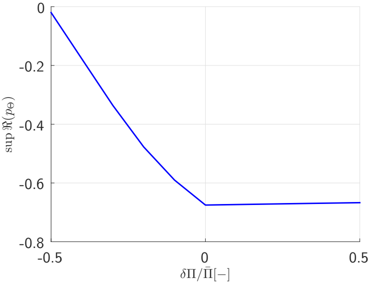


"Time" domain simulation

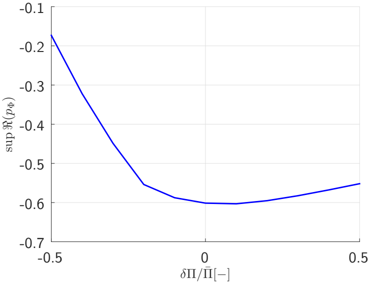


Robust stability analysis, uncertainty in Π

Closed-loop right-most pole of the system for $\Pi \in [0.5\bar{\Pi}, 1.5\bar{\Pi}]$

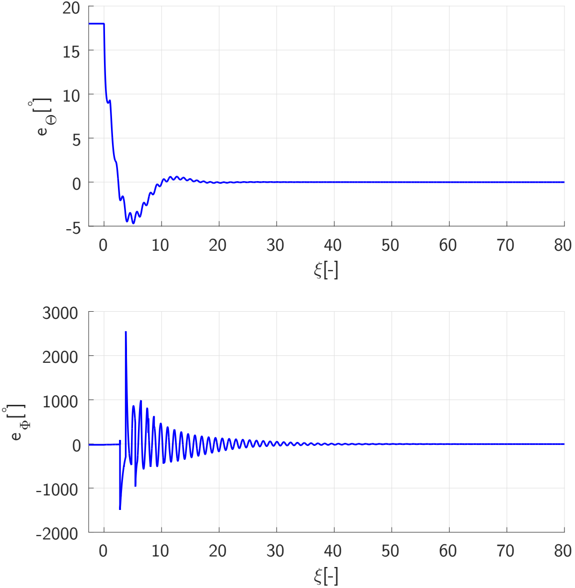


Inclination



Azimuth

"Time" domain simulation, $\Pi = 0.5\bar{\Pi}$



Robust controller synthesis

- Optimize location of right-most pole of closed-loop system for a grid of values of $\Pi \in [0.5\bar{\Pi}, 1.5\bar{\Pi}]$

- Interval of Π

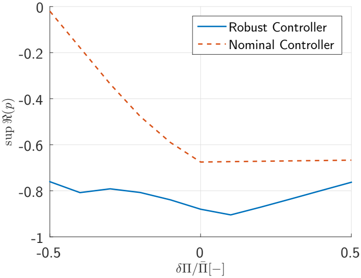
$$\delta\Pi_i = -\delta\Pi_{max} + \frac{i-1}{m-1} 2\delta\Pi_{max}, \qquad \text{for } i \in \{1, 2, ..., m\}.$$

(this case m = 7)

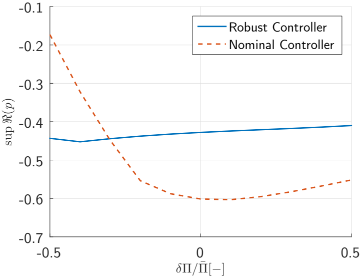
$$\Pi = \bar{\Pi} + \delta\Pi$$

Robustness comparison

Closed-loop right-most pole of the system for $\Pi \in [0.5\bar{\Pi}, 1.5\bar{\Pi}]$

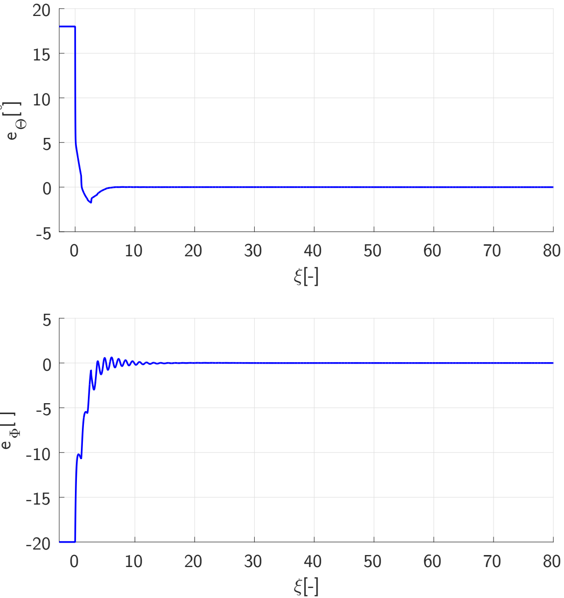


Inclination



Azimuth

"Time" domain simulation for $\Pi = 0.5\bar{\Pi}$



Outline

TUDelft
University of Minnesota

Conclusions

- A controller that only relies on local measurements of the BHA orientation was developed by means of an observer
- The strategy yields robustness against uncertainty in the active weight on bit Π
- Negative effects are greatly reduced even under extreme conditions of low weight on bit

Recommendations

- Extend current design to non-neutral bit walk tendency
- Study alternative angle parameterization
- Analyze use of the developed strategy for models with non-linear effects (bit-tilt saturation, non-ideal stabilizer contact)

Thank you for your attention. Any questions?

TUDelft
University of Minnesota