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A comparison of hazards and efficiencies of conventional and adaptive control algorithms using Systems-Theoretic Process Analysis

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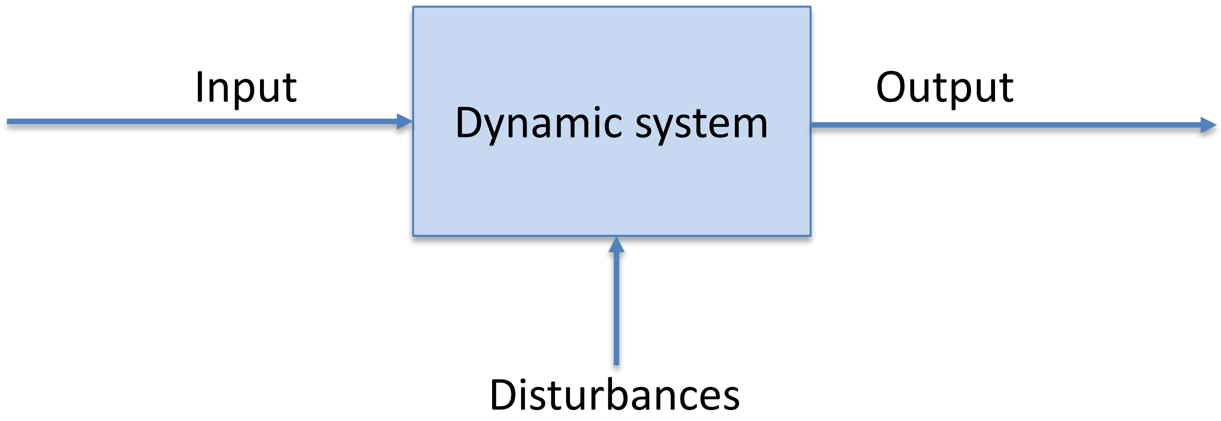
Agenda

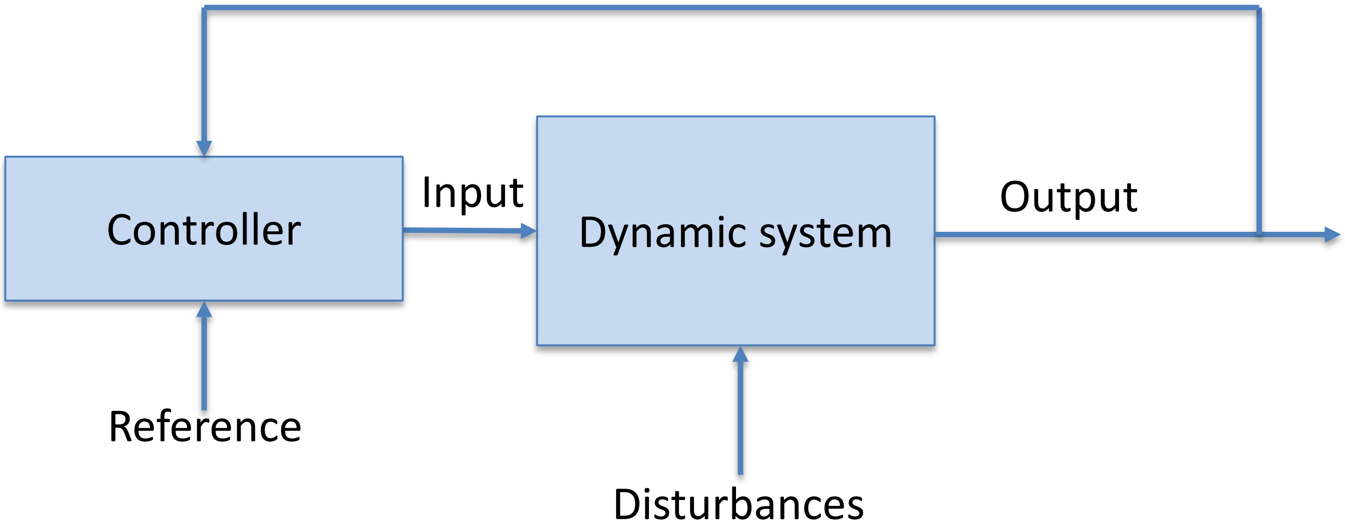
- Introduction
- Control of pipeline-riser system subject to slug flow
- Simulation results
- STPA Results
- Discussion and Concluding Remarks

Introduction



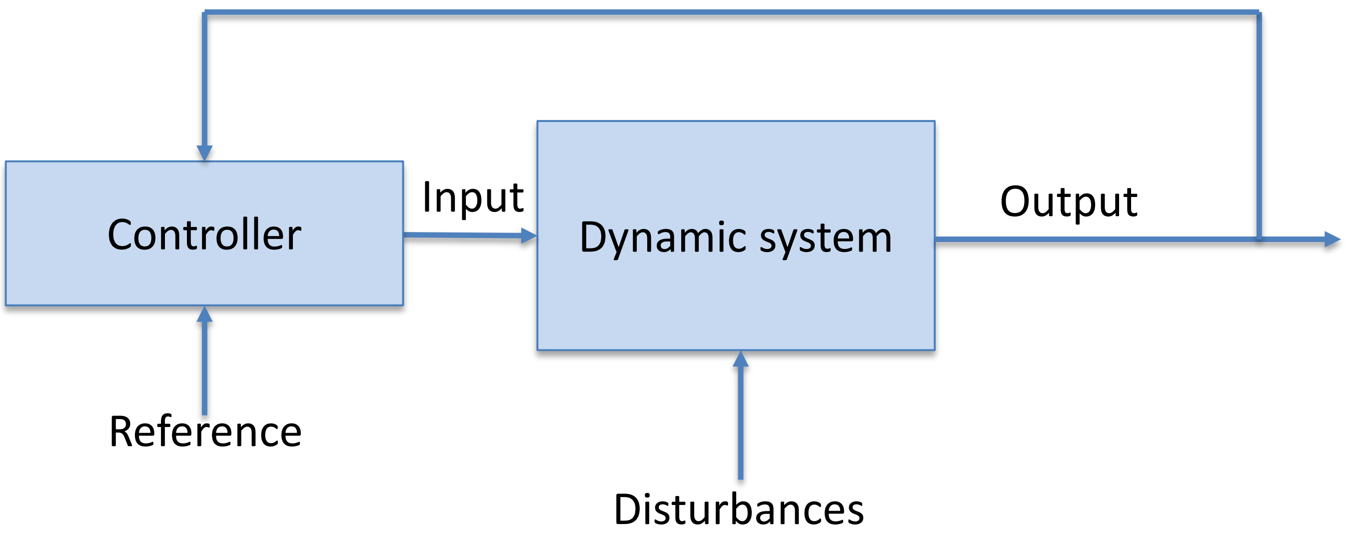
- Dynamic system:
  - Robots, cars, process plants, economical and biological systems.
- Automatic control:
  - Manipulate the input such that the output behaves in a predictable and desired way, subject to external disturbances.

Introduction



- Controller:
  - Compares output to reference value
  - If deviation, apply input such that deviation reduces
  - Feedback Control

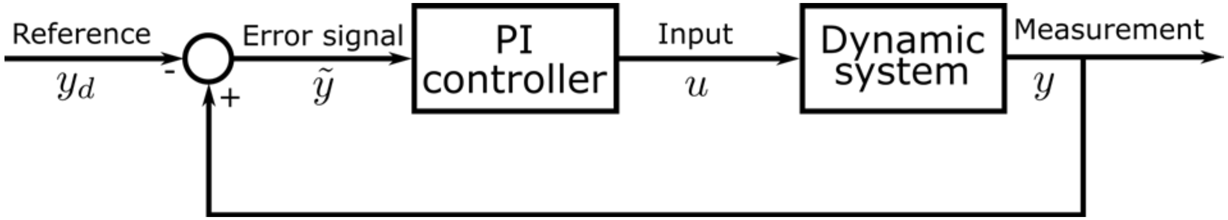
Introduction



- All dynamic systems are nonlinear and time-varying by nature
  - Can linearize or assume time-invariant
- Simplifies controller design

Introduction

- The PI controller is used in over 90% of control loops
  - Proportional part (P) corrects immediate errors
  - Integral part (I) corrects past deviations
- Fixed controller parameters must be selected
  - Many tuning procedures exist
- Works very well on linear systems



Introduction

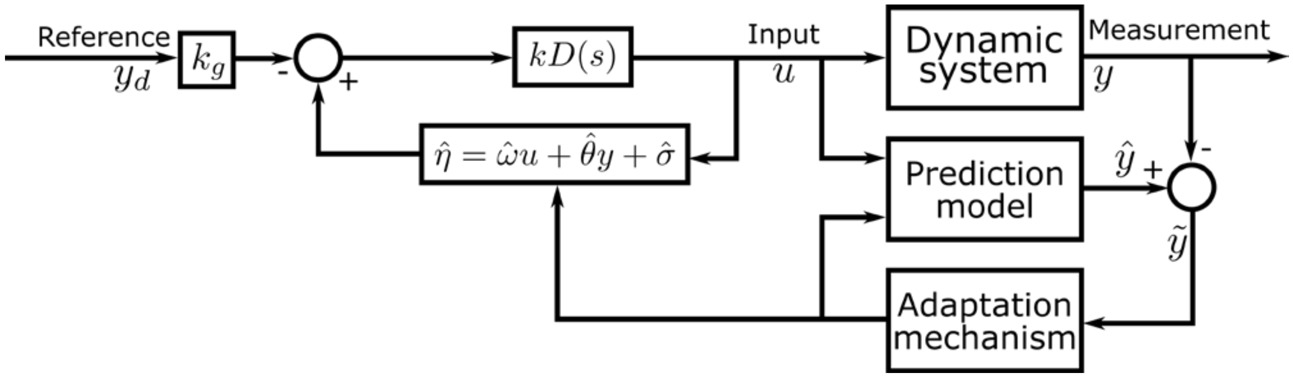
- If the system is highly nonlinear the PI controller would need constant re-tuning
- PI controller has the form

$$u = -k_p \tilde{y} - \frac{k_p}{\tau_i} \int_0^t \tilde{y} \, dt$$

- Deciding k_p and τ_i is not trivial if the system is nonlinear

Introduction

- Adaptive control has self-adjusting parameters, but is more complex
- Introduced in the 50s, but lack of knowledge and tools and bad hardware caused it to enter a hiatus.
- Today, mathematical proofs of stability exist and adaptive control is a broad field of research.



Introduction

- One adaptive method is known as the $\mathcal{L}_1$ adaptive controller
- Fast adaptation and guaranteed robustness

$$u = -kD(s)(\widehat{\omega}u + \hat{\theta}y + \hat{\sigma} - k_g y_d)$$

- Here, $\widehat{\omega}$, $\hat{\theta}$ and $\hat{\sigma}$ are estimated system parameters, continuously updated by

$$\dot{\widehat{\omega}} = \gamma Proj(\widehat{\omega}, -\tilde{y}pbu)$$

$$\dot{\hat{\theta}} = \gamma Proj(\hat{\theta}, -\tilde{y}pby)$$

$$\dot{\hat{\sigma}} = \gamma Proj(\hat{\sigma}, -\tilde{y}pb)$$

Introduction

- Summary:

PI controller

- Parameter tuning done by operator
- Several tuning rules
- Not trivial for nonlinear systems

Adaptive controller

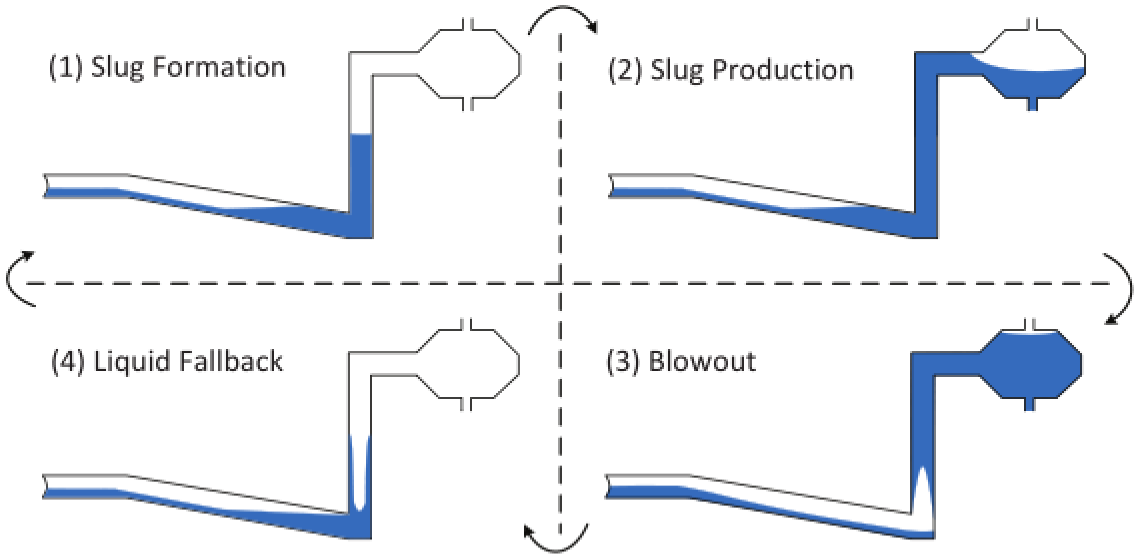
- Requires some initial tuning
- Parameters automatically updated
- More complex / lack of tuning rules

Introduction

- Both methods have pros and cons
- From a control perspective, it is not trivial to decide which solution is better
  - Trade-off between complexity and stability
- Can the safety perspective help us decide?

Control of pipeline-riser system

- Multiphase pipeline-riser systems may be subject to slug flow



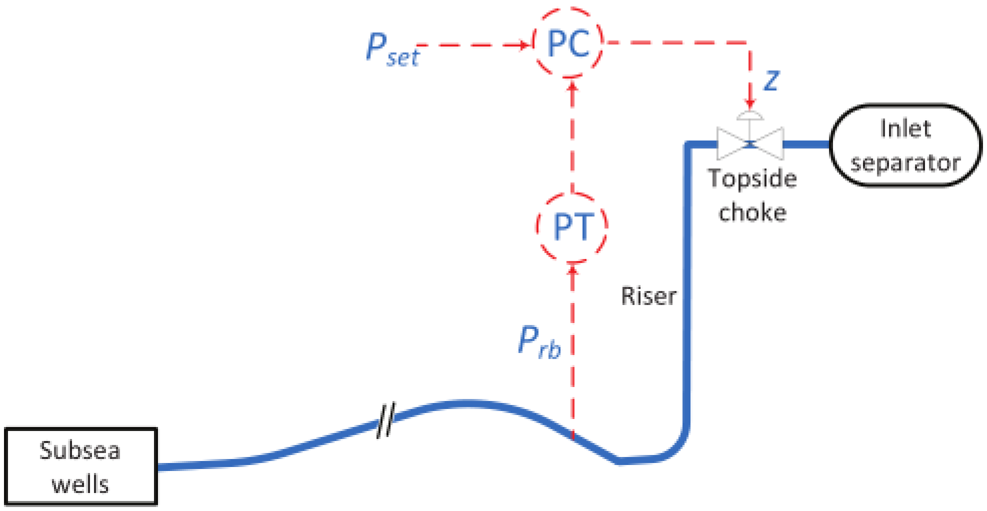
Control of pipeline-riser system

- May cause production shut-down, damage and stress on equipment
- Several solutions exist:
  - Slug catchers: Large and expensive installations
  - Reduce production: Economic losses
  - Automatic control: Cheap and effective
- Reported benefits of anti-slug control:
  - Fewer compressor trips
  - Reduced flaring
  - Increased income

Source: http://www.surfaceequip.com/sites/default/files/photo_gallery/IMG_0281_-_Copy.jpg

Control of pipeline-riser system

- The topside choke valve is often used for anti-slug control
- Opening the valve reduces the gain of the system → No control possible



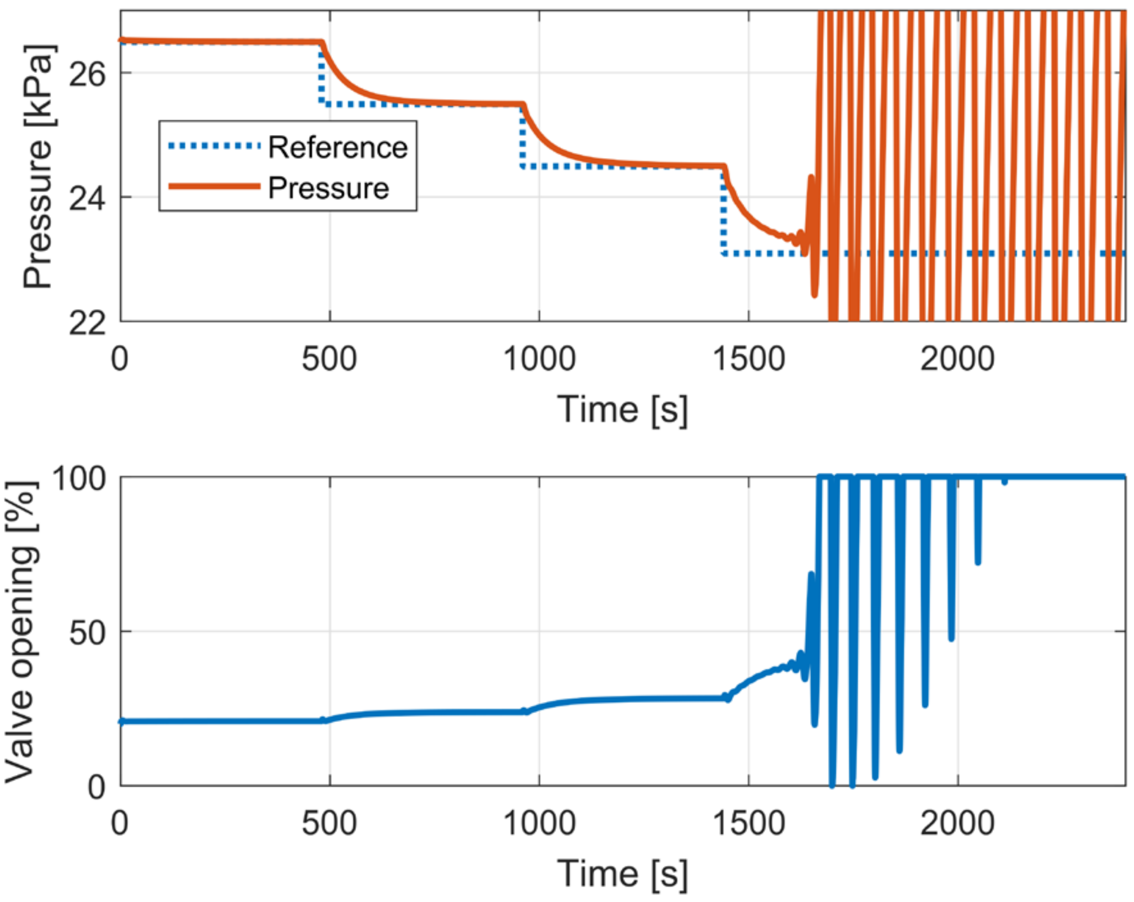
Control of pipeline-riser system

- Anti-slug control is not simple
  - Process parameters changes drastically with operating point
  - Finding PI controller parameters may be difficult and several different PI controllers may be needed (gain scheduling)
  - We propose using an adaptive controller instead

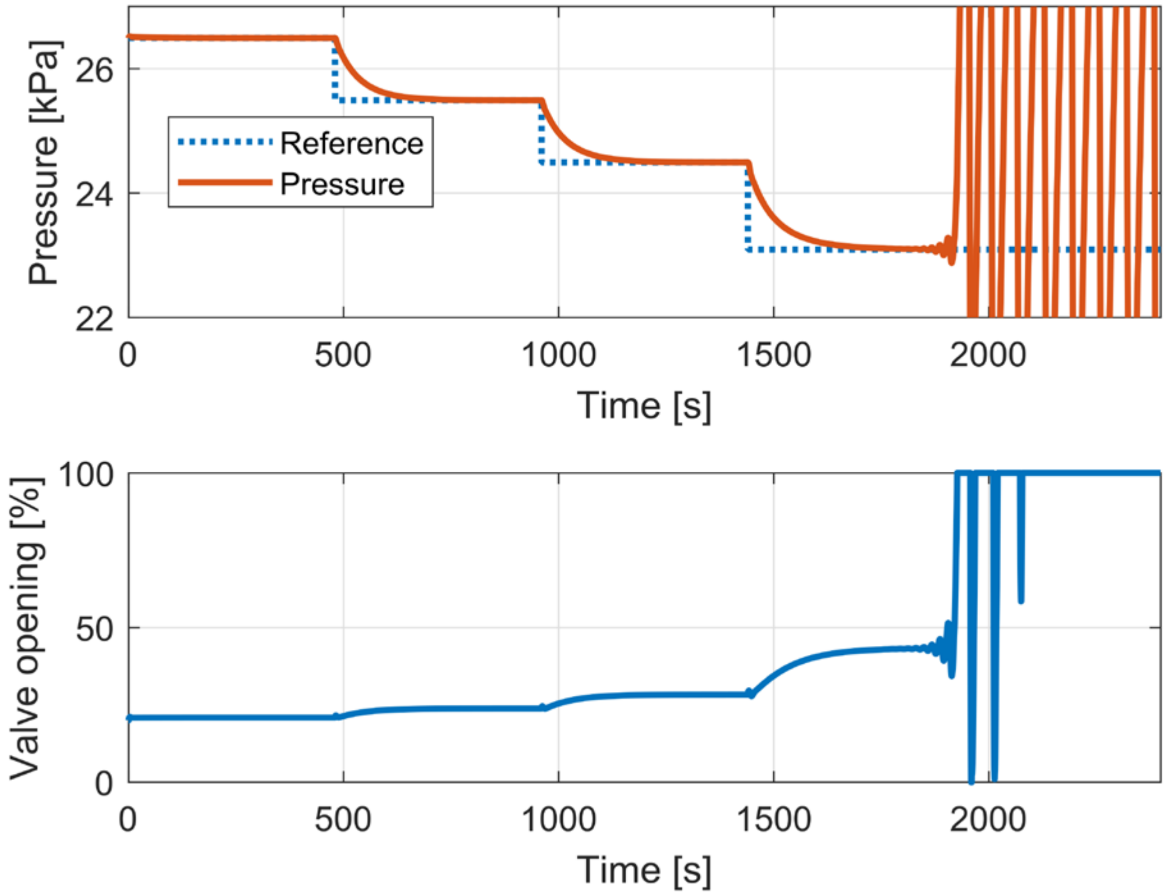
Simulation results

- Implemented on a MATLAB simulation model for anti-slug control
- Pressure setpoint is reduced until system is far into the slugging region

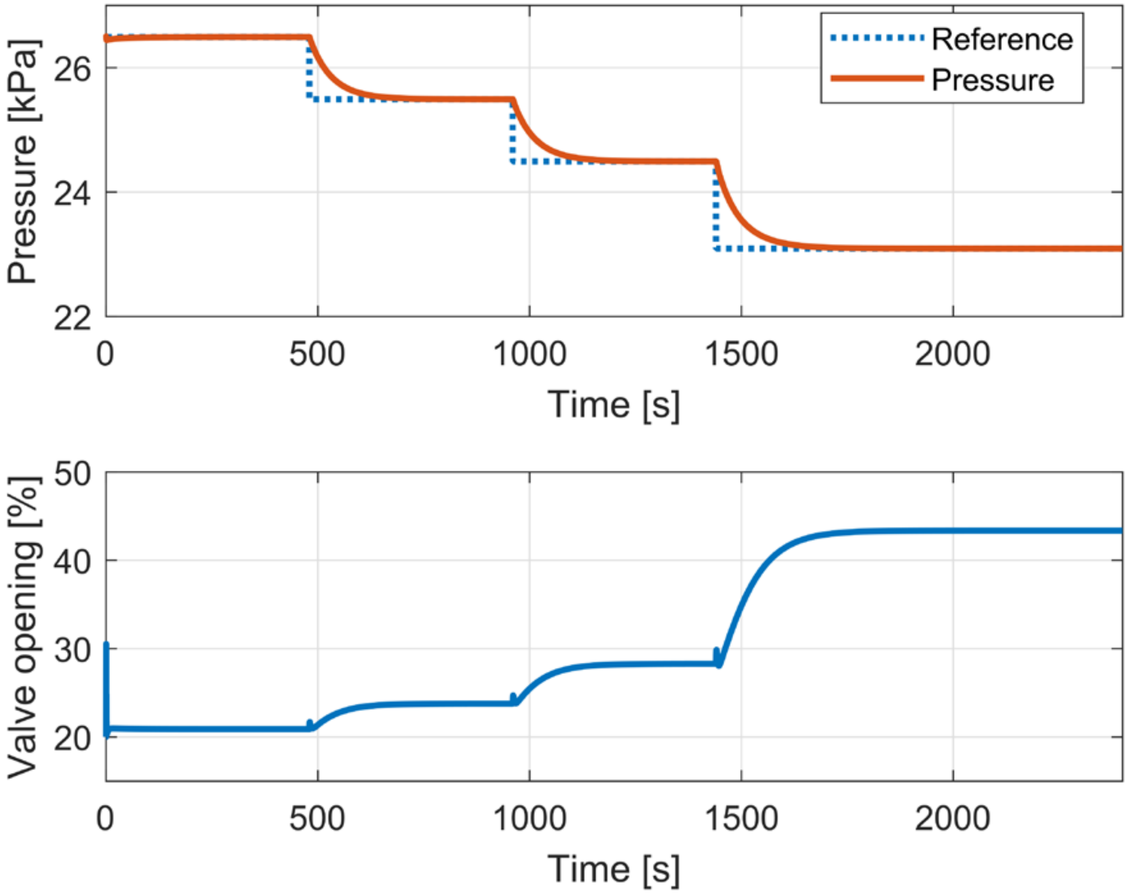
Simulation results



Simulation results

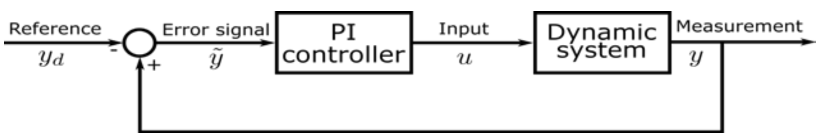


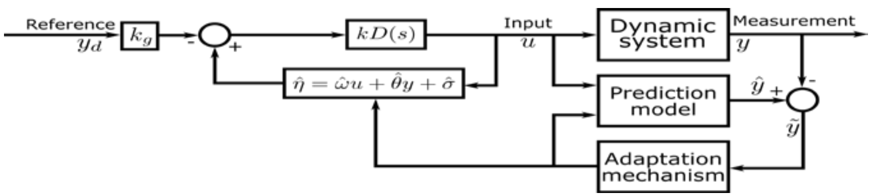
Simulation results



STPA Results

Conventional Control	Adaptive Control





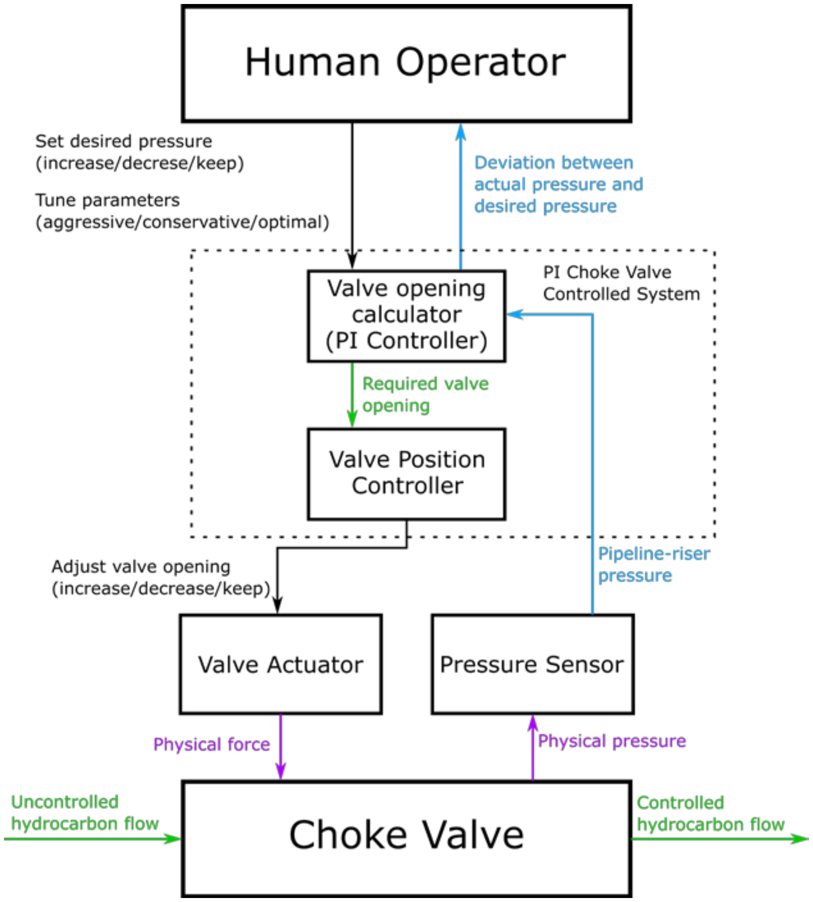
STPA Results

Conventional Control	Adaptive Control

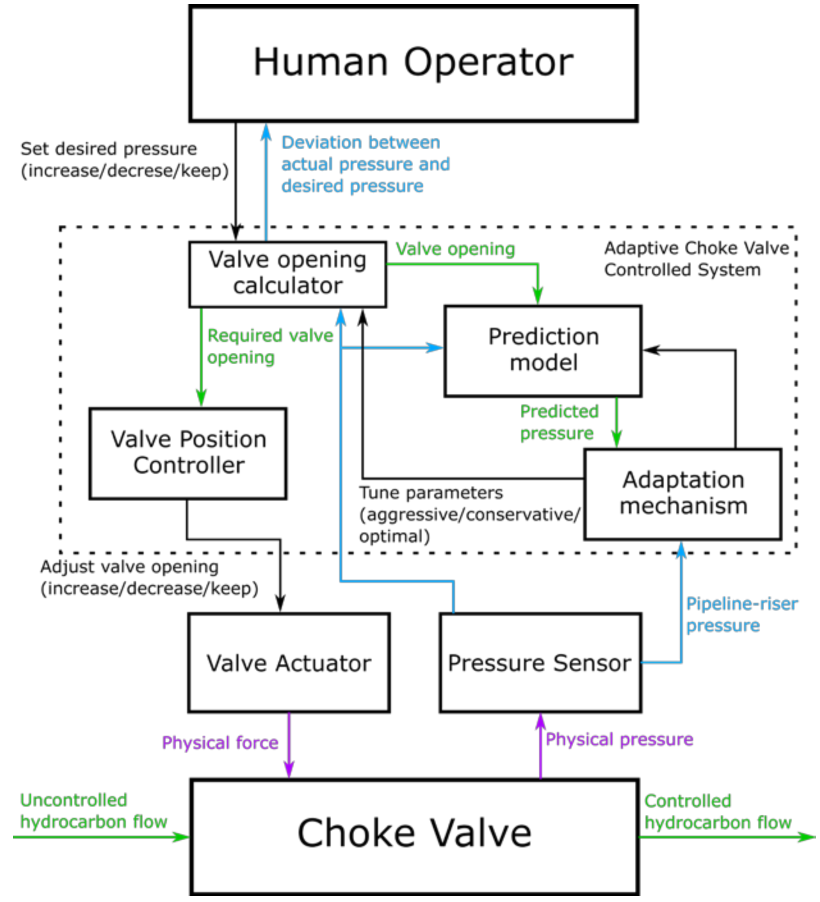
System	Losses	System-Level Hazards	System-Level Constraints
Choke valve controlled system	L-1: Shutdown of oil/gas production	H-1: Slugging occurs in riser	SC-1: Occurrence of slugging should be prevented
	L-2: Damage to subsea production systems	H-2: Pressure exceeds upper or lower limit	SC-2: Pressure should be maintained between upper and lower limit
	L-3: Reduced oil/gas production	H-3: Pipeline-riser pressure is not optimal	SC-3: Pipeline-riser pressure should be optimal

STPA Results

Conventional Control



Adaptive Control



STPA Results

Conventional Control

Controller	Responsibility	Process Model	Feedback
Human Operator	Adjust desired pressure to maximize oil/gas production	Production rate • Optimal • Not optimal	Pipeline-riser pressure
	Update parameters to properly control Choke valve opening	Parameters • Optimal • Aggressive • Conservative	On hindsight by pipeline-riser pressure
PI Controller	Adjust Choke valve opening to meet the desired pressure, using fixed or irregularly updated parameters	Actual pressure • High than desired pressure • Same with desired pressure • Lower than desired pressure	Deviation between actual pressure and desired pressure

Adaptive Control

Controller	Responsibility	Process Model	Feedback
Human operator	Adjust desired pressure to maximize oil/gas production	Production rate • Optimal • Not optimal	Pipeline-riser pressure
Adaptive controller	Update parameters to properly control choke valve opening	Parameters • Optimal • Aggressive • Conservative	In advance by predicted pipeline-riser pressure
	Adjust choke valve opening to meet the desired pressure, with continuous, self-adjusting parameters	Actual pressure • High than desired pressure • Same with desired pressure • Lower than desired pressure	Deviation between actual pressure and desired pressure

STPA Results

	Conventional Controller	Adaptive Controller
Number of UCAs	**120**	**120**
UCAs related with H-1	8	8
UCAs related with H-2	18	18
UCAs related with H-3	94	94
Number of scenarios related with H-1	**42**	**30**
Scenarios caused by human error	15	2
Scenarios caused by technical failure	19	20
Scenarios caused by design requirement	6	0
Scenarios caused by software flaw	1	7
Scenarios caused by other reasons	1	1

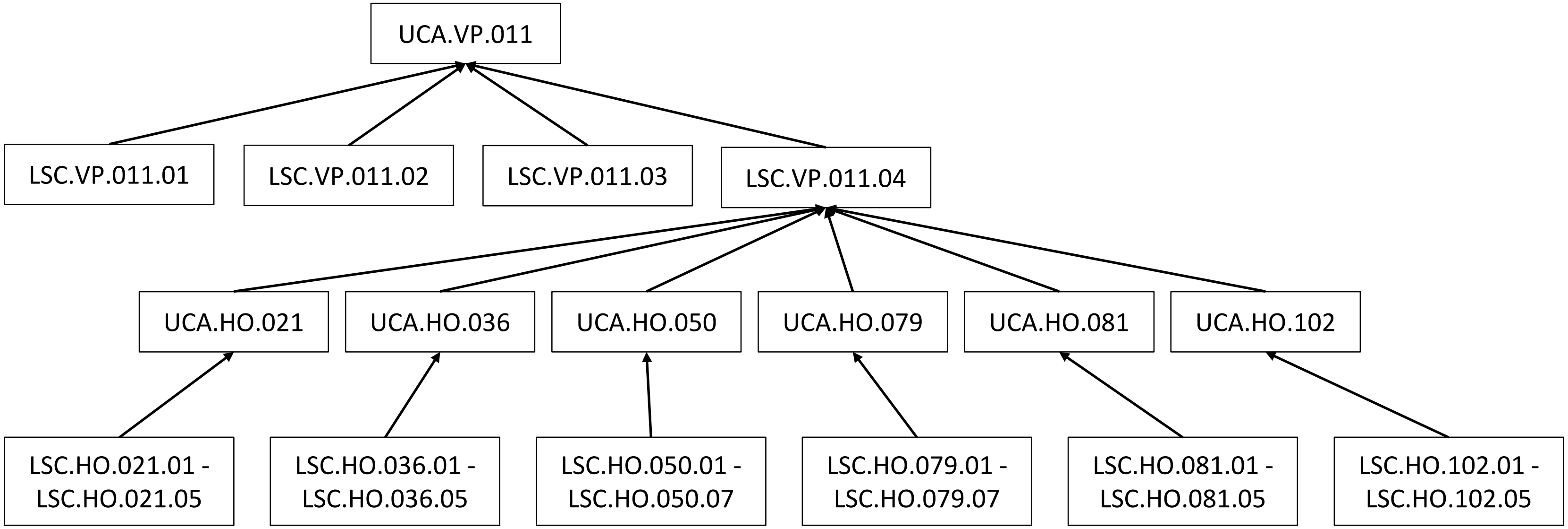
STPA Results

Conventional Control	Adaptive Control
<u>UCA.HO.079</u> Human operator does not provide “Tune to optimal parameters” command when parameters are aggressive, pressure is close to slugging, and disturbance occurs [H-1] **<u>LSC.HO.079.07</u>** The parameters are aggressive, riser pressure is close to slugging and a disturbance occurs, but the human operator does not provide “Tune to optimal parameters” command [UCA.HO.079], because the human operator is not aware of this situation. This flawed process model occurs ***<u>because there is no direct feedback that indicates whether the parameters are aggressive or optimal</u>***. As a result, slugging occurs in the riser [H-1].	**<u>UCA.AM.066</u>** Adaptive mechanism does not provide “Tune to optimal parameters” command when parameters are aggressive, pressure is close to slugging, and disturbance occurs [H-1]

STPA Results

	Conventional Controller	Adaptive Controller
Parameters	Fixed or irregularly updated by human operator	Continuously self-adjusted by adaptive mechanism and prediction model
UCAs related with parameter tuning	Provided by human operator	Provided by adaptive mechanism
Main cause of loss scenarios related with parameter tuning	Human error (15 scenarios) and technical failure (19 scenarios)	Technical failure (20 scenarios) and software flaw (7 scenarios)
Direct feedback of parameters	Non-existent	By prediction model
Loss scenarios caused by absence of parameter feedback	Six scenarios	None

Discussion


UCA.VP.011
LSC.VP.011.01
LSC.VP.011.02
LSC.VP.011.03
LSC.VP.011.04
UCA.HO.021
UCA.HO.036
UCA.HO.050
UCA.HO.079
UCA.HO.081
UCA.HO.102
LSC.HO.021.01 - LSC.HO.021.05
LSC.HO.036.01 - LSC.HO.036.05
LSC.HO.050.01 - LSC.HO.050.07
LSC.HO.079.01 - LSC.HO.079.07
LSC.HO.081.01 - LSC.HO.081.05
LSC.HO.102.01 - LSC.HO.102.05

Discussion

- UCA 1
- UCA 2
- UCA 3
- UCA 4
- UCA 5
- UCA 6
- UCA 7

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- UCA n

- Loss Scenario 1
- Loss Scenario 2
- Loss Scenario 3
- Loss Scenario 4
- Loss Scenario 5
- Loss Scenario 6
- Loss Scenario 7

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- Loss Scenario n

Concluding Remarks

- We have compared a PI and an adaptive controller from a control and safety perspective.
- The control perspective tells us whether the controllers are able to perform the required task, i.e., bring the dynamic system to the desired value.
- It does not evaluate the complexity of the control system or the amount of hazards the controller introduces to our system.
- To evaluate the hazards we applied STPA and by doing so introduced a new tool for evaluation of control systems.
- The STPA showed that, amongst other things, that the adaptive controller is less sensitive to human errors and more sensitive to technical errors such as software flaws.

Concluding Remarks

- Furthermore, we identified a key difference between PI control and adaptive control, i.e., the feedback of control parameters.
- An adaptive controller continuously monitors and automatically updates its controller parameters whereas a PI controller is dependent on a human operator to do the same.
- It can be difficult for a human operator to perform this evaluation of control parameters.
- The STPA provided different results for the different controllers.
- This indicates that it is important to consider the type of controller when performing a hazard analysis and not consider the controller as a generic device.

Thank you