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 \( \tau_i \) 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

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

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

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

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

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

**Pressure [kPa]**

- Reference
- Pressure

**Valve opening [%]**

**Time [s]**

0 500 1000 1500 2000
Simulation results
Simulation results

- Pressure [kPa] vs. Time [s]
- Valve opening [%] vs. Time [s]
STPA Results

Conventional Control

Adaptive Control
## STPA Results

| 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

Human Operator

Valve opening calculator (PI Controller)

Valve Position Controller

Valve Actuator

Pressure Sensor

Choke Valve

Set desired pressure (increase/decrease/keep)
Tune parameters (aggressive/conservative/optimal)

Deviation between actual pressure and desired pressure

Adaptation mechanism

Adaptation mechanism

Human Operator

Valve opening calculator

Valve Position Controller

Valve Actuator

Pressure Sensor

Choke Valve

Set desired pressure (increase/decrease/keep)

Deviation between actual pressure and desired pressure

Adaptive Choke Valve

Adaptive Choke Valve

Prediction model

Tune parameters (aggressive/conservative/optimal)

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# STPA Results

## Conventional Control

| Controller          | Responsibility | Process Model | Feedback                          |
|---------------------|----------------|---------------|-----------------------------------|
| Human Operator      | Adjust desired pressure to maximize oil/gas production | Production rate  |
|                     |                | - Optimal    | Pipeline-riser pressure           |
|                     |                | - Not optimal|                                   |
| PI Controller       | Update parameters to properly control Choke valve opening | Actual pressure |
|                     |                | - High than desired pressure | On hindsight by pipeline-riser pressure |
|                     |                | - Same with desired pressure |                                   |
|                     |                | - Lower than desired pressure |                                   |

## Adaptive Control

| Controller          | Responsibility | Process Model | Feedback                          |
|---------------------|----------------|---------------|-----------------------------------|
| Human operator      | Adjust desired pressure to maximize oil/gas production | Production rate  |
|                     |                | - Optimal    | Pipeline-riser pressure           |
|                     |                | - Not optimal|                                   |
| Adaptive controller | Update parameters to properly control Choke valve opening | Actual pressure |
|                     |                | - High than desired pressure | In advance by predicted pipeline-riser pressure |
|                     |                | - Same with desired pressure |                                   |
|                     |                | - Lower than desired pressure |                                   |

### Controller Parameters
- Optimal
- Aggressive
- Conservative

### Feedback
- 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 |
|----------------------|------------------|
| **UCA.HO.079**       | **UCA.AM.066**   |
| Human operator does not provide “Tune to optimal parameters” command when parameters are aggressive, pressure is close to slugging, and disturbance occurs [H-1] |
| **LSC.HO.079.07**    |                  |
| 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 **because there is no direct feedback that indicates whether the parameters are aggressive or optimal**. As a result, slugging occurs in the riser [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
Discussion

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

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