Provable Adversarial Safety in Cyber-Physical Systems

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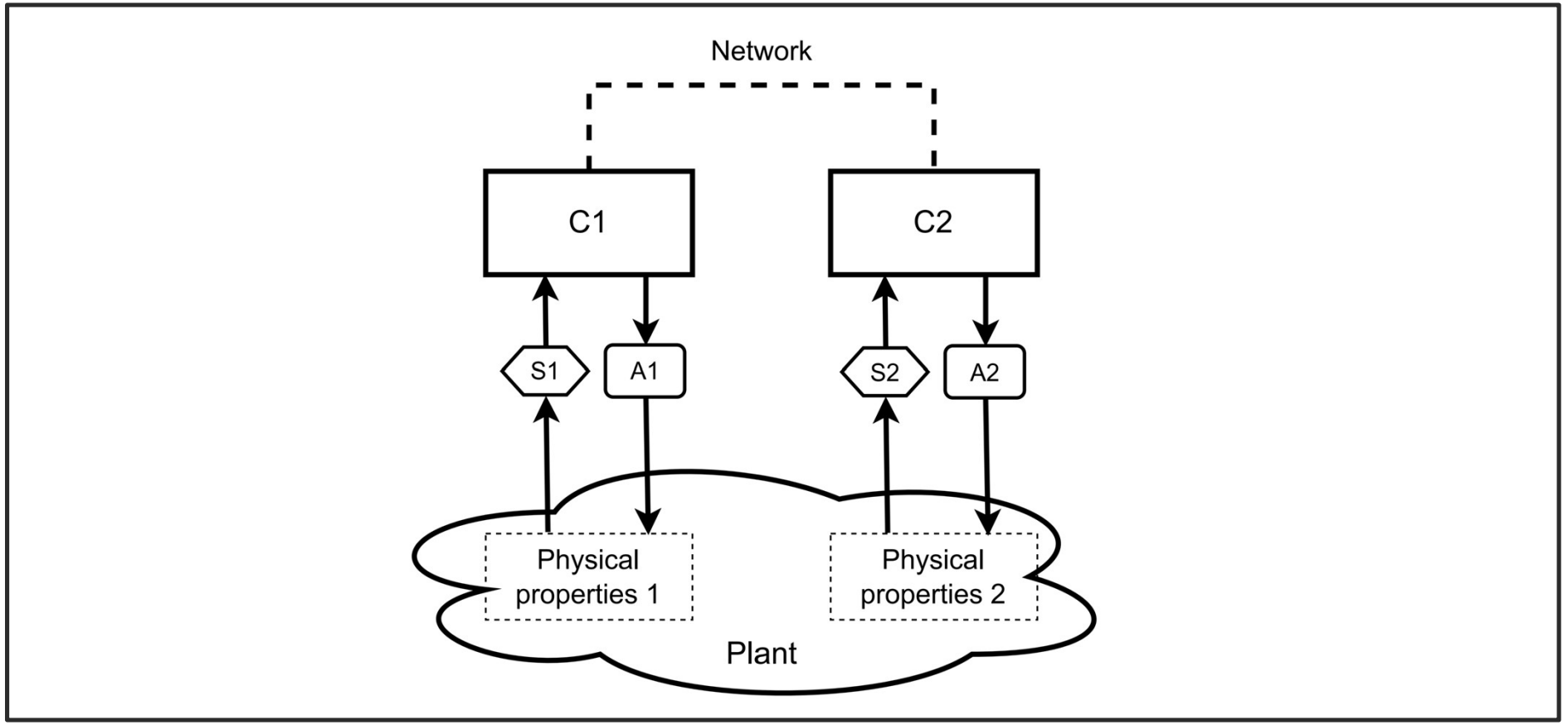
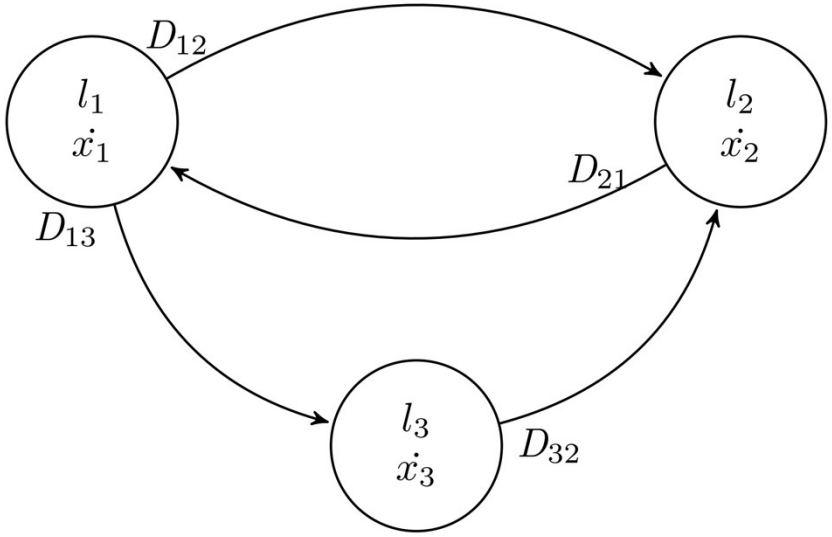
Cyber-physical systems

Cyber-Physical systems



CPS as a hybrid system



$$\mathcal{H} : \begin{cases} \dot{x} = F(x) & x \in C \\ x^+ = G(x) & x \in D, \end{cases}$$

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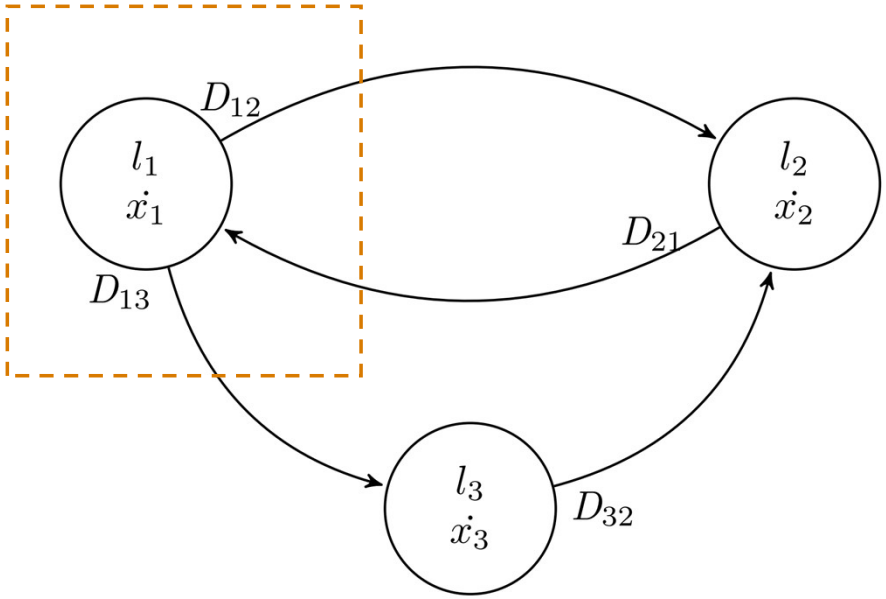

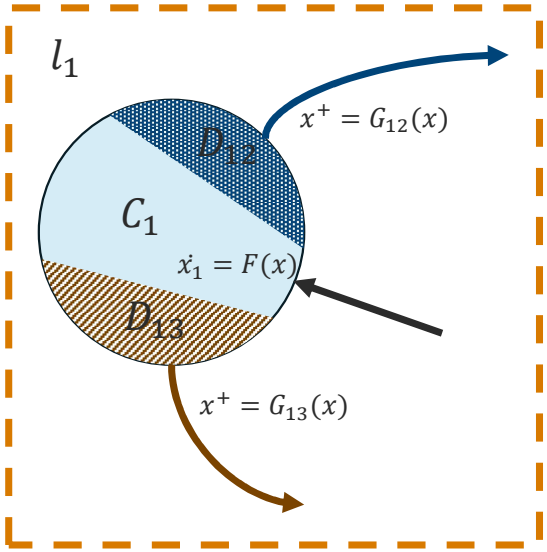

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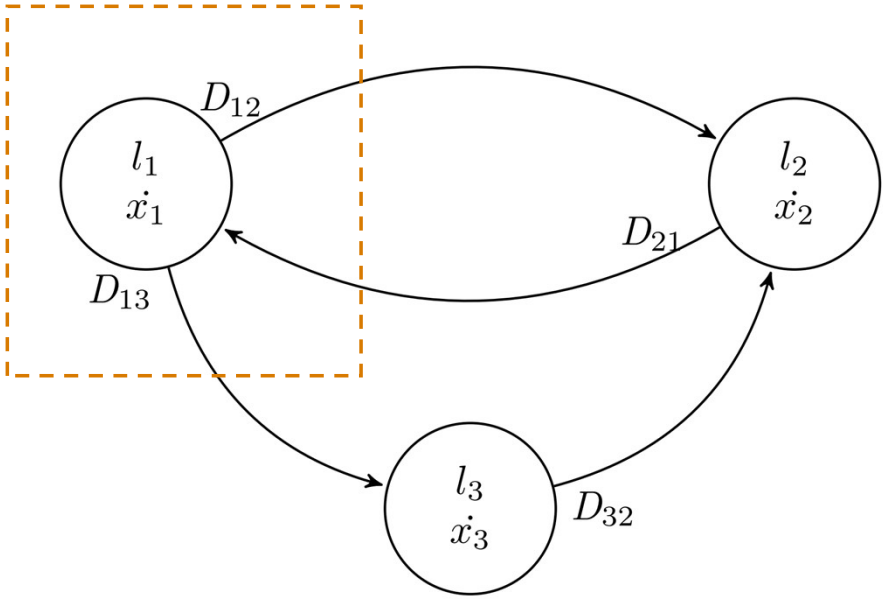
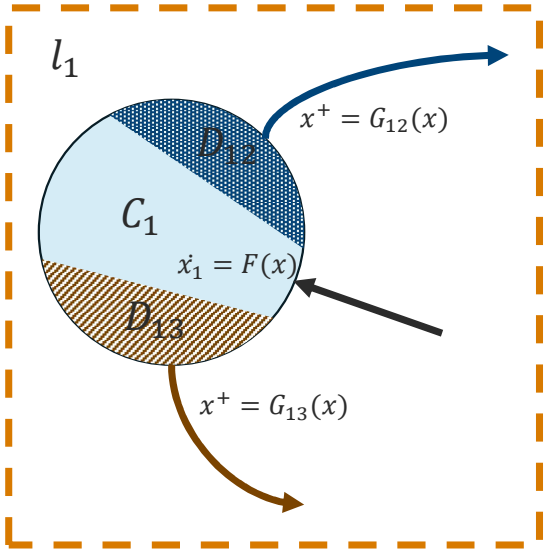
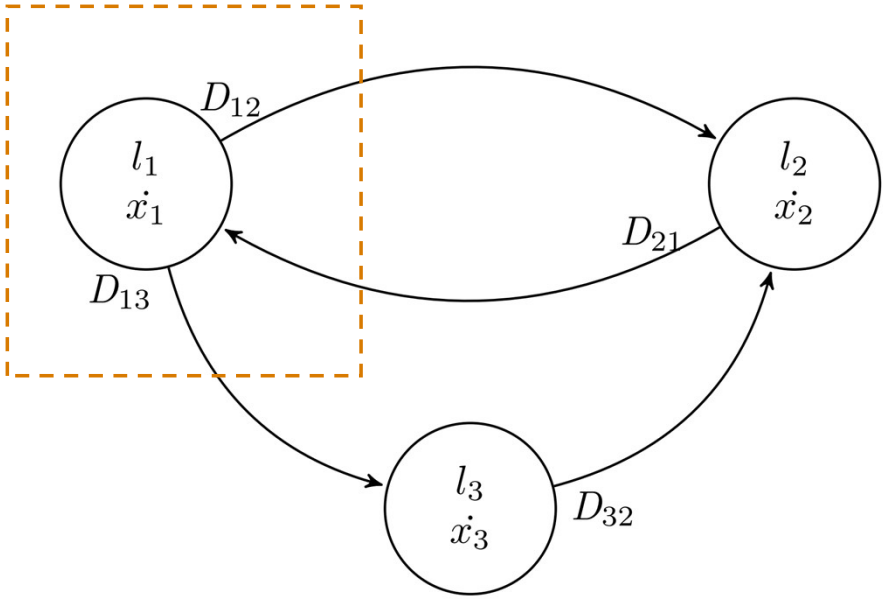


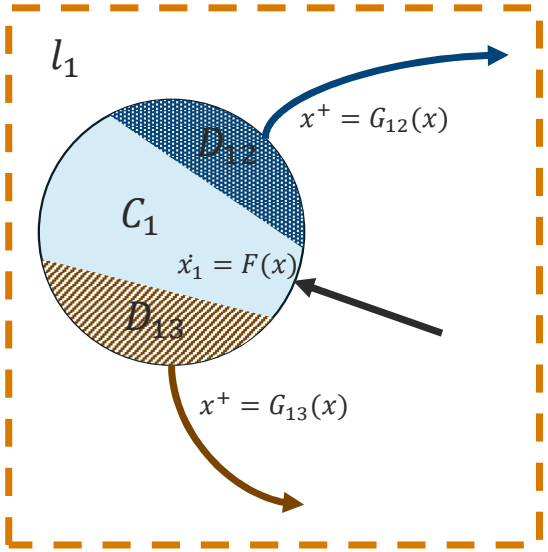


The system flows when $x \in C$ (continuous time)

$$\mathcal{H}: \begin{cases} \dot{x} = F(x) & x \in C \\ x^+ = G(x) & x \in D, \end{cases}$$

CPS as a hybrid system

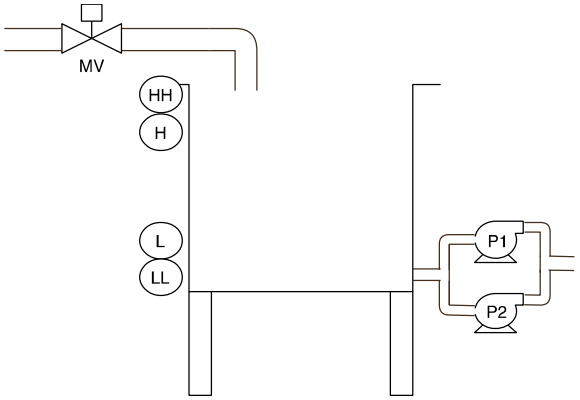


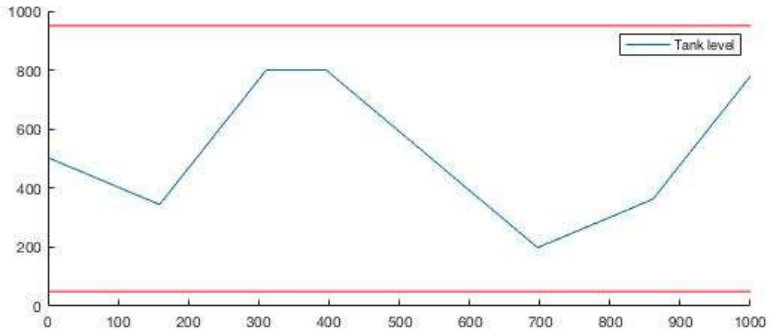


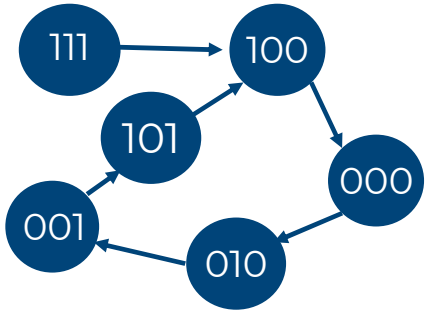
The system jumps when $x \in D$ (discrete time)

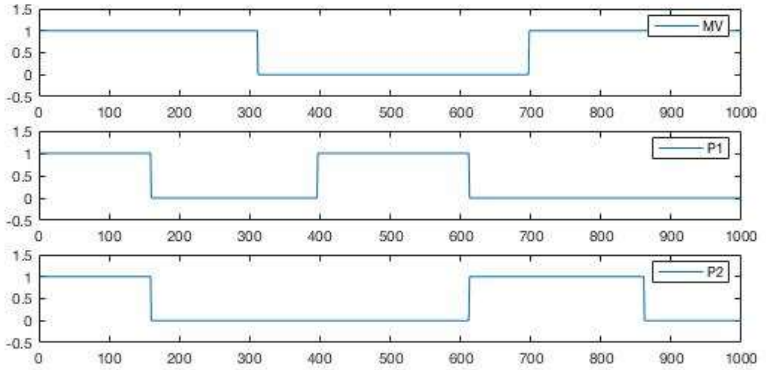
$$\mathcal{H}: \begin{cases} \dot{x} = F(x) & x \in C \\ x^+ = G(x) & x \in D, \end{cases}$$

Simple tank example

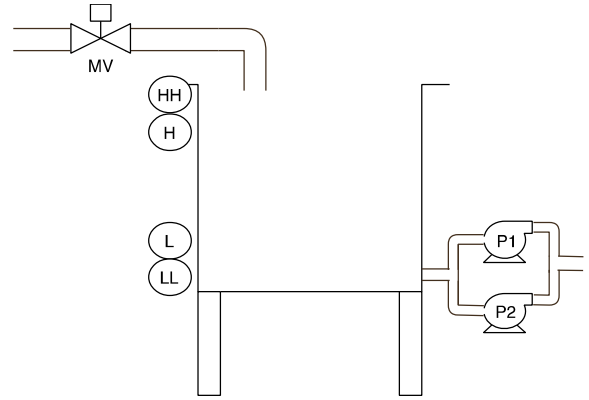


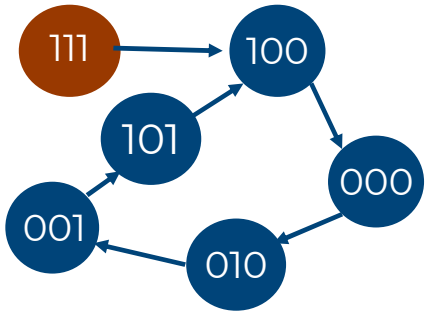


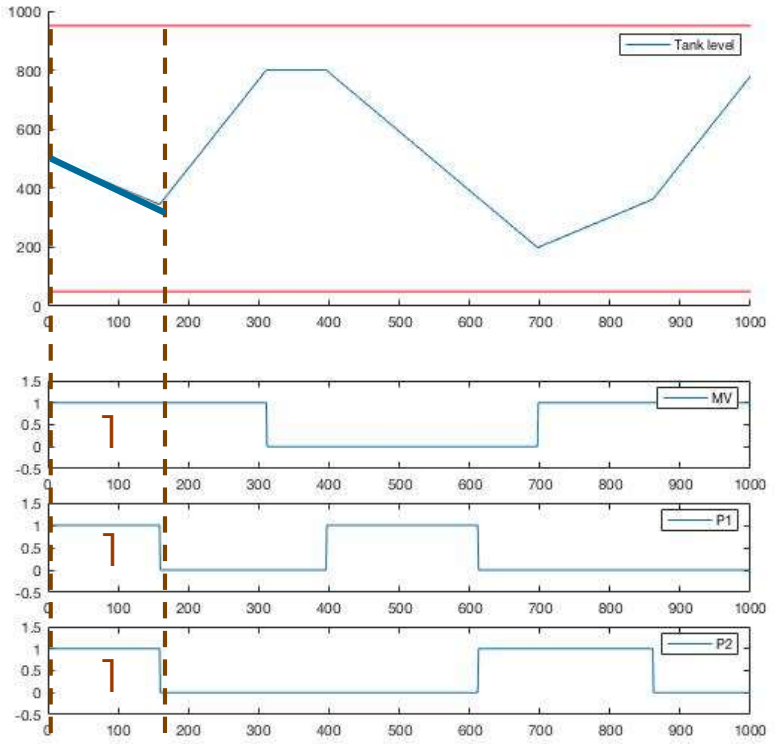




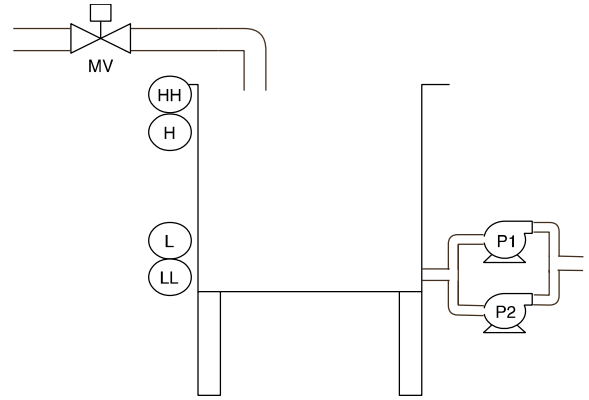
Simple tank example

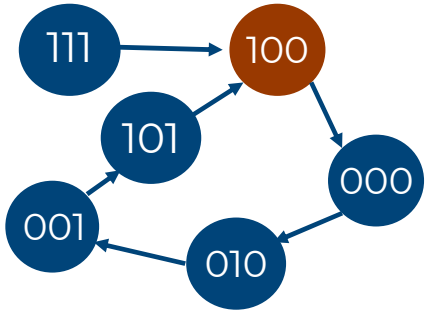


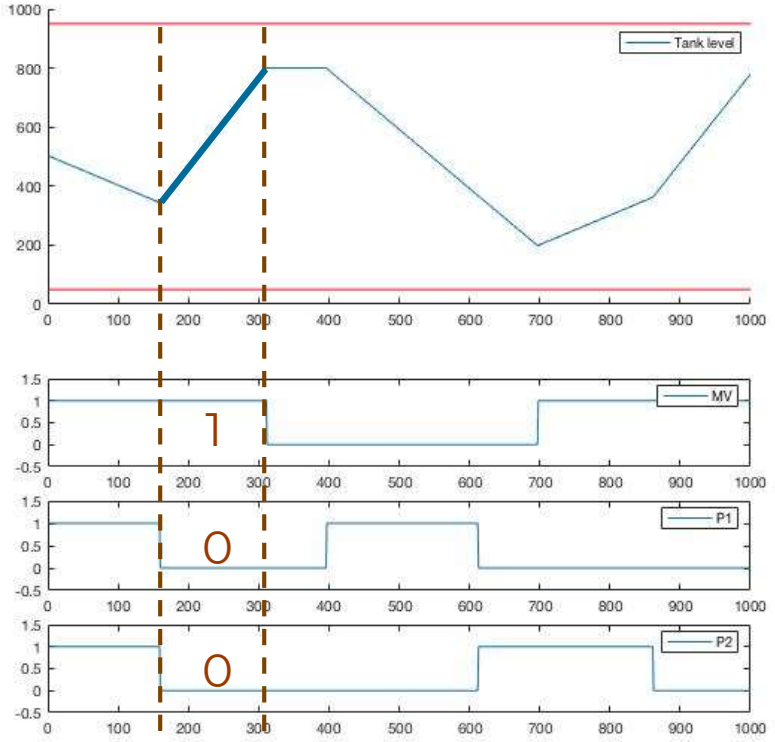




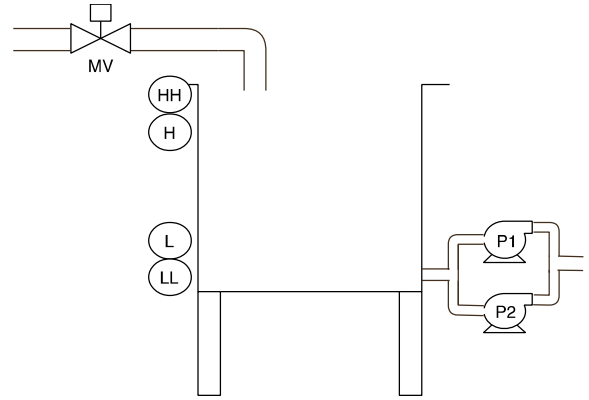
Simple tank example

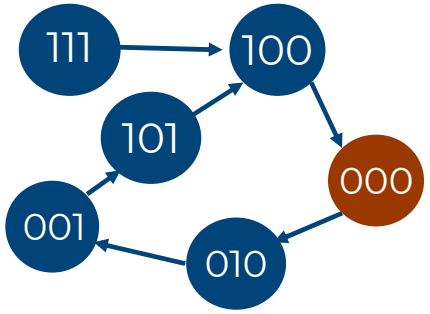


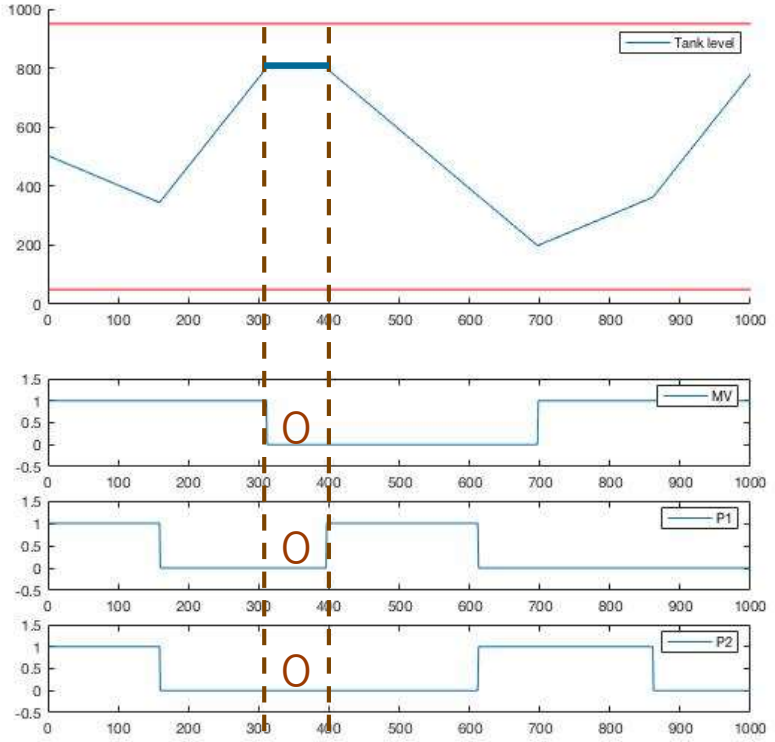




Simple tank example







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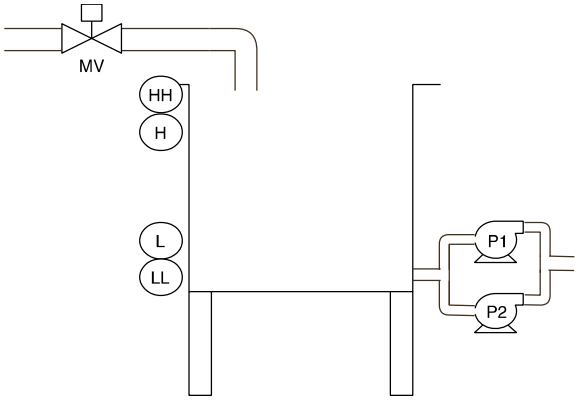

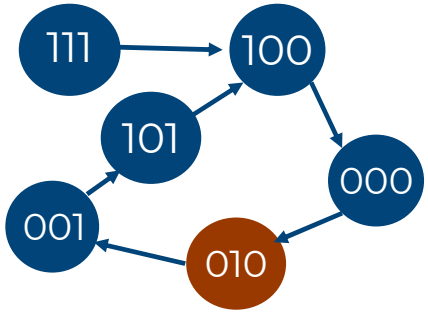

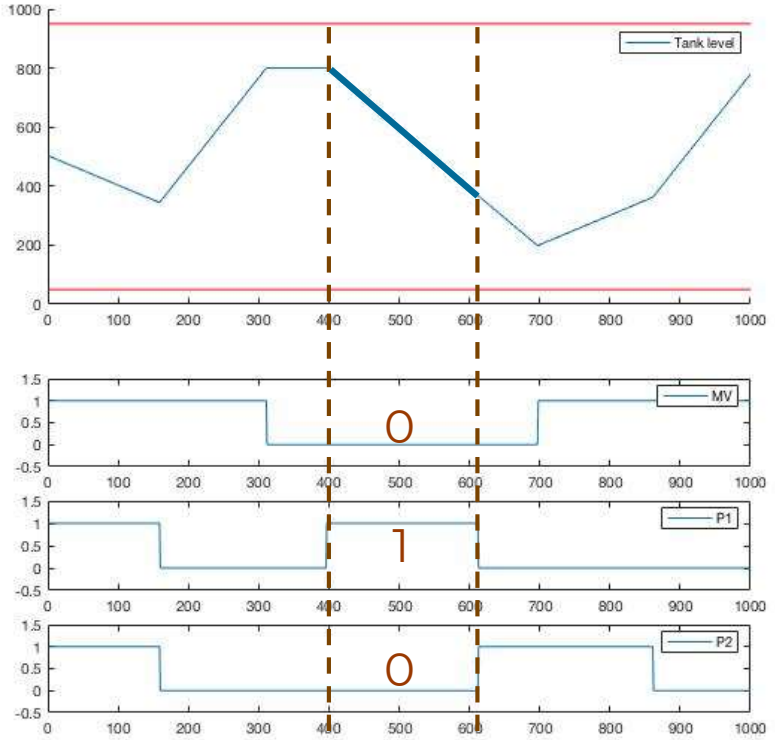

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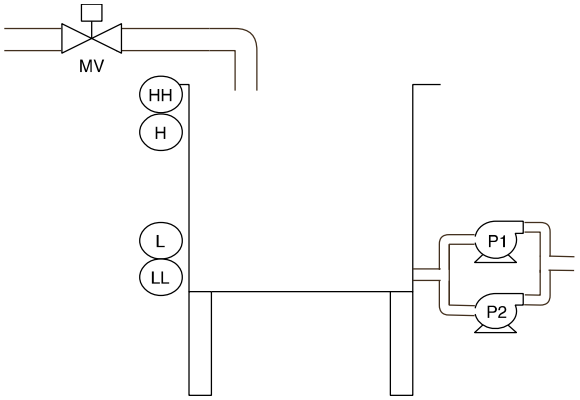

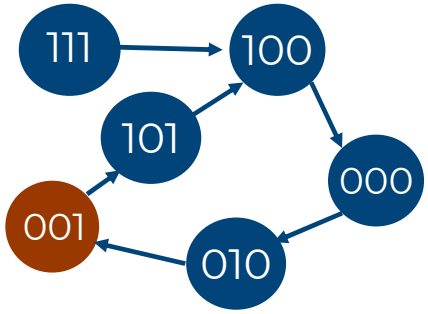

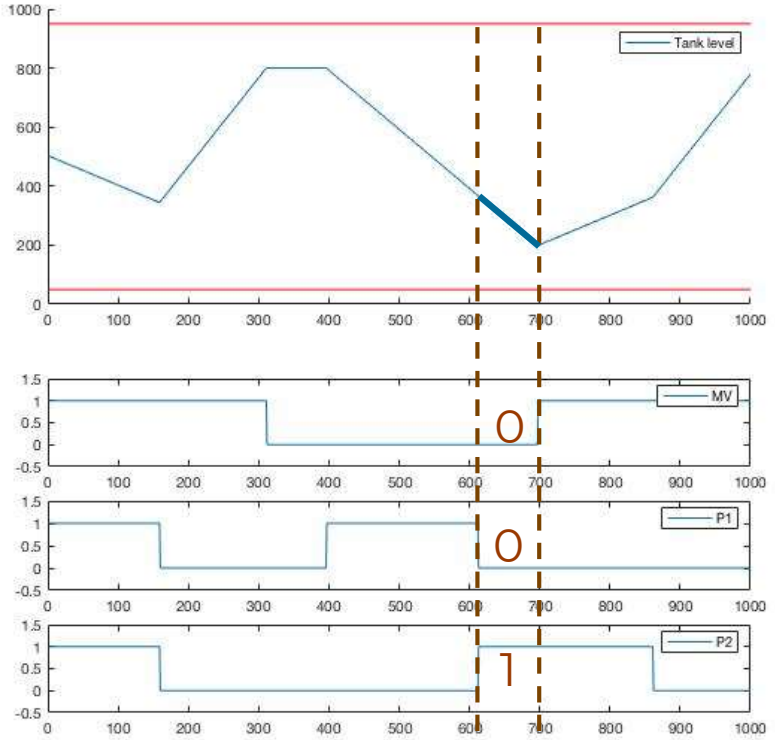

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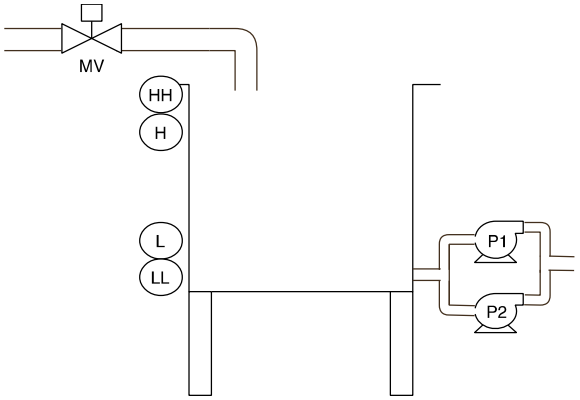

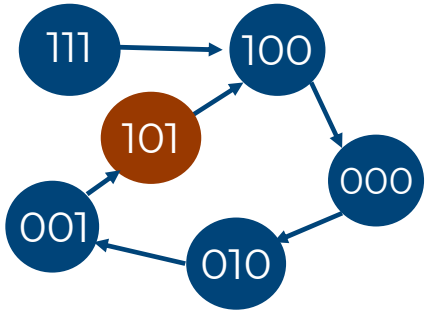

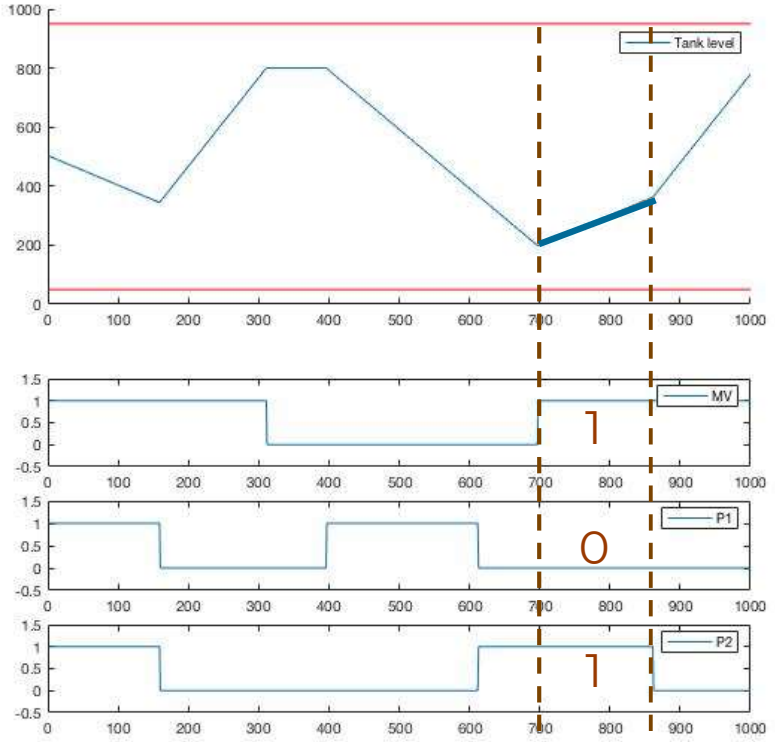

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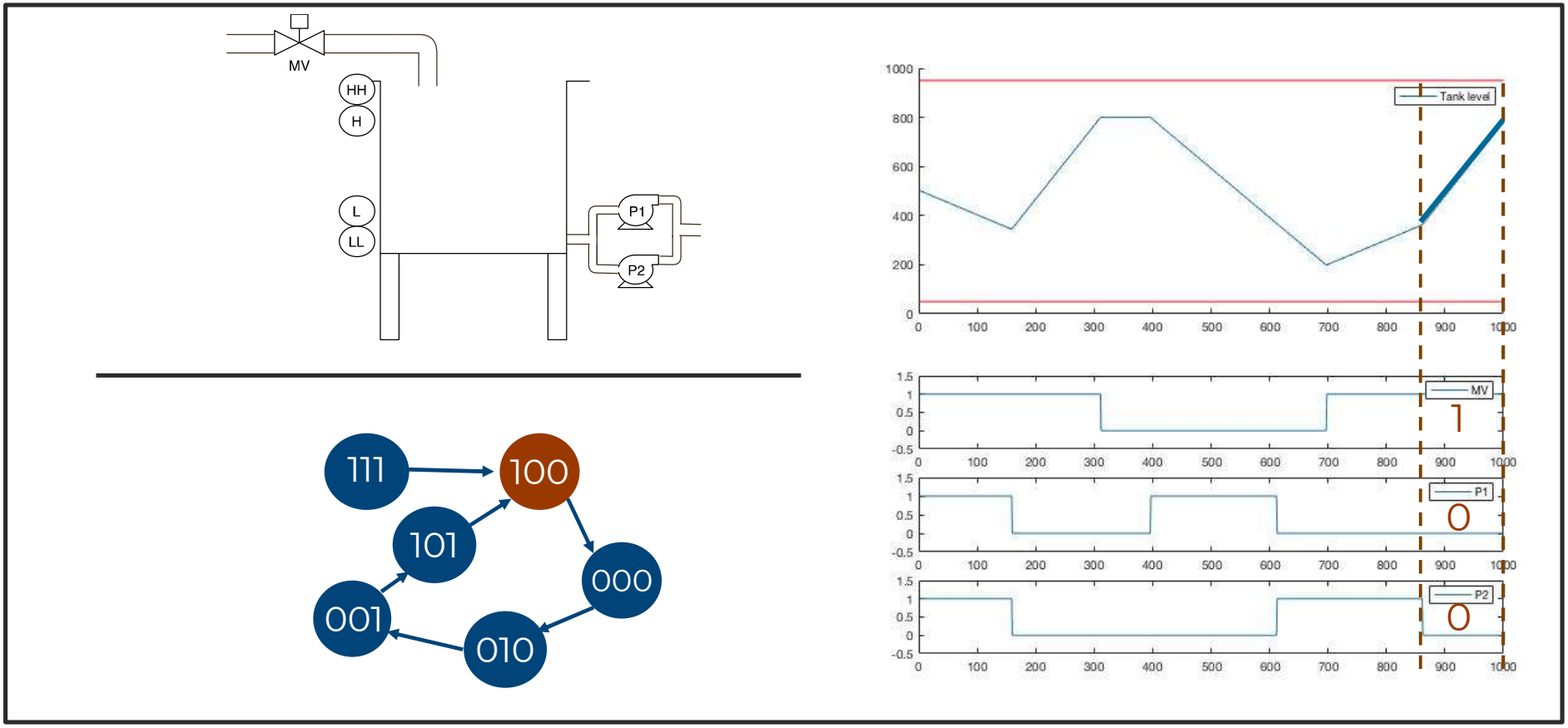
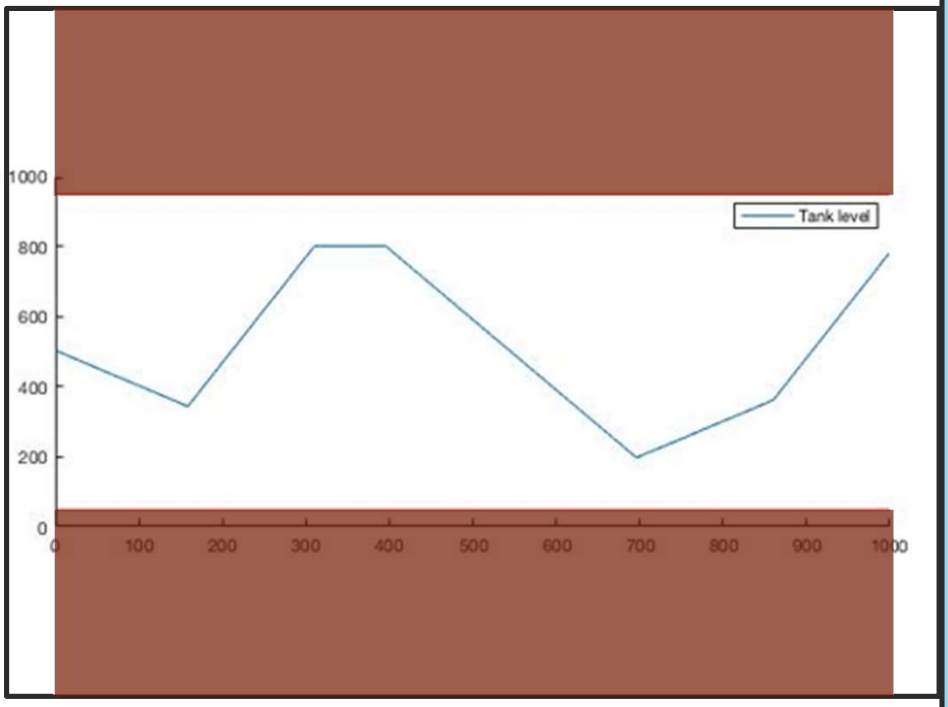


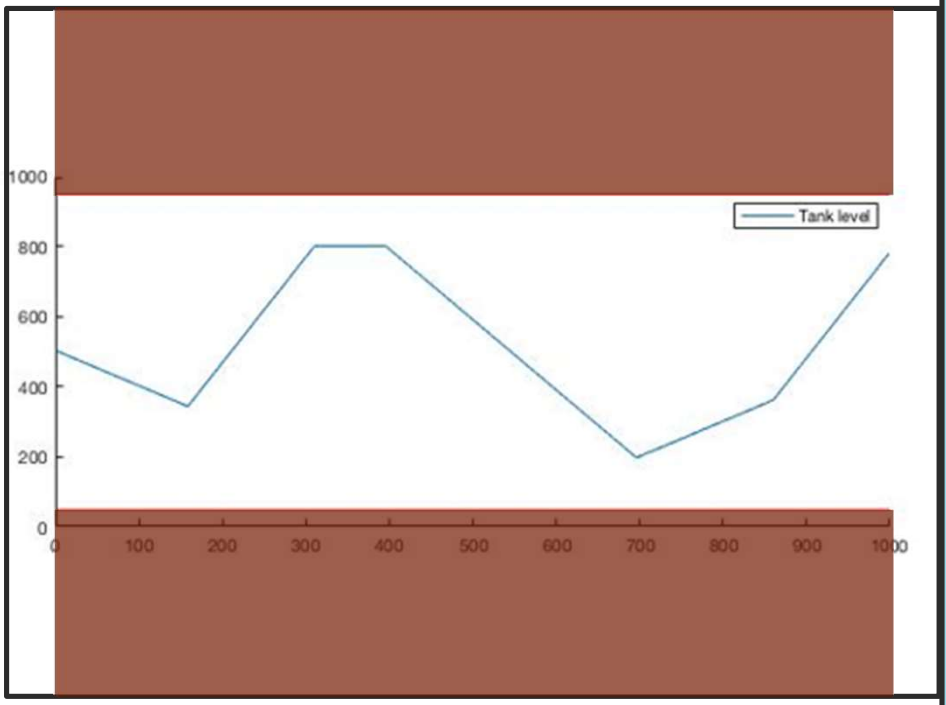
Barrier function candidate



Safe region

Unsafe region

Barrier function candidate

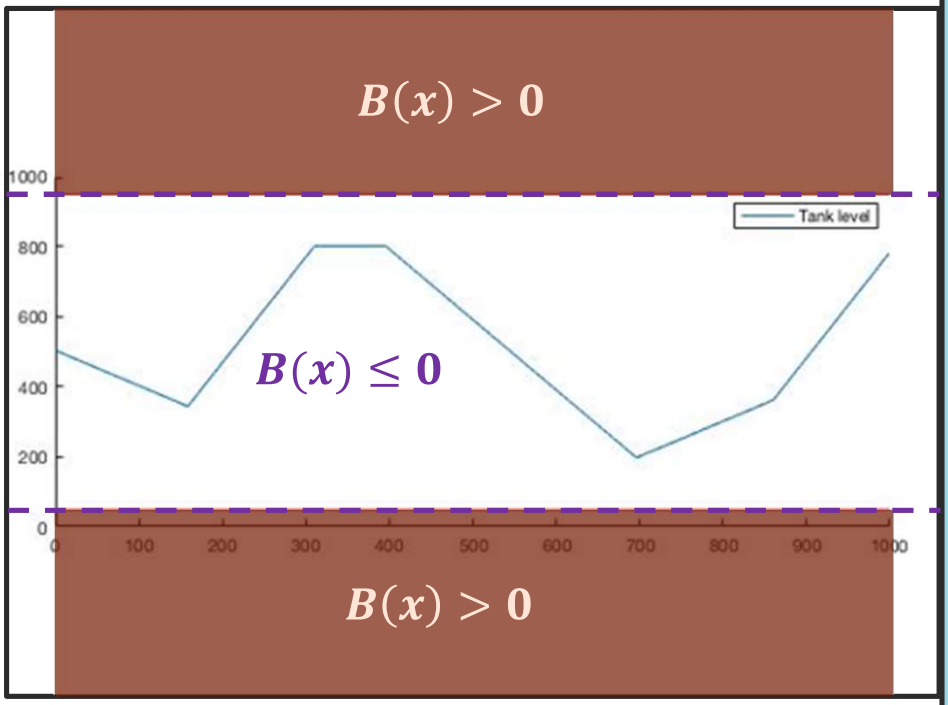


Safe region

Unsafe region

- Barrier function ($B(x)$) takes a positive value when the system is at unsafe region.

Barrier function candidate



Safe region

Unsafe region

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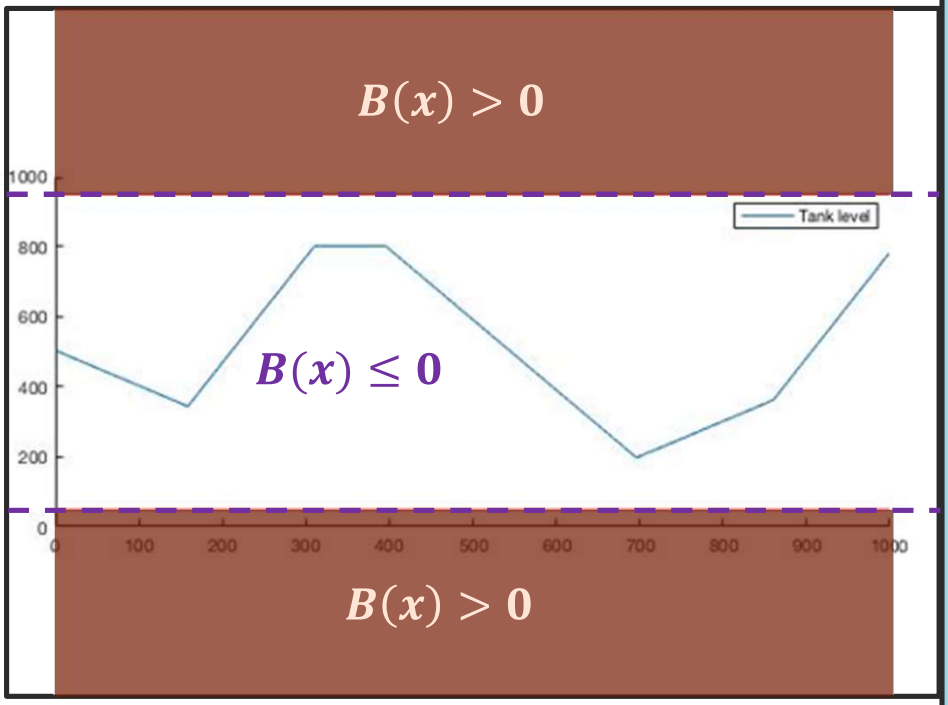
Safety analysis

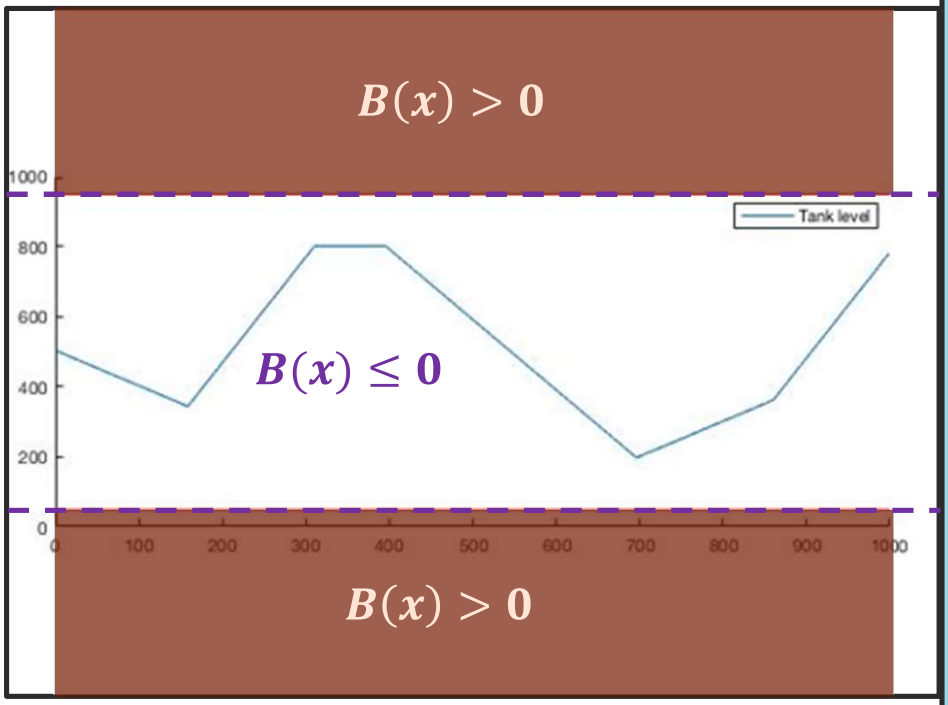


Safe region

Unsafe region

- How to guarantee safety using the barrier certificate $B(x)$?

Safety analysis



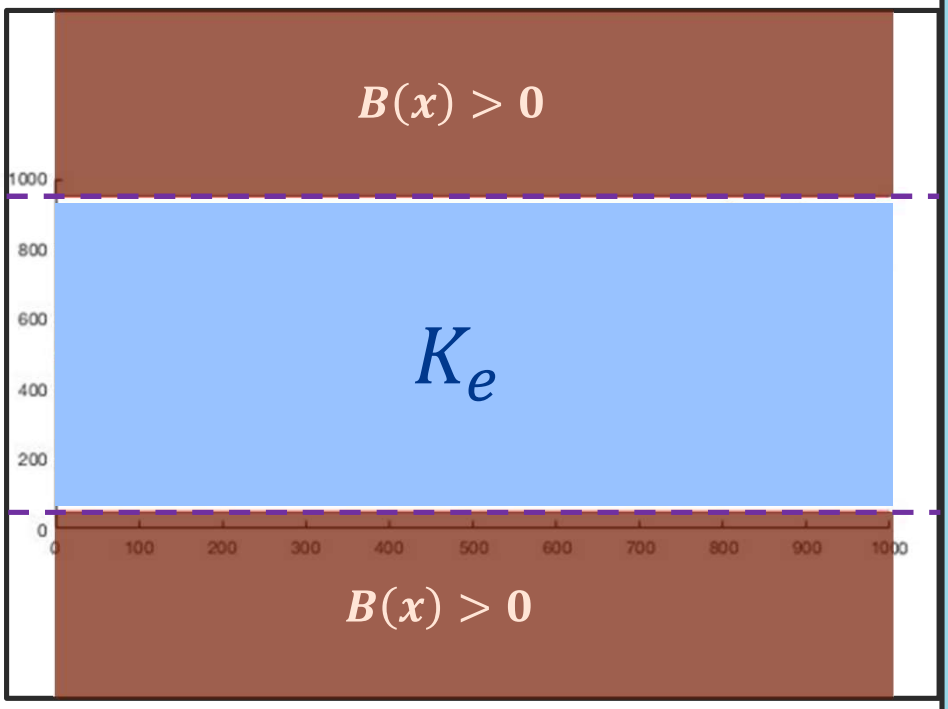
Safe region

Unsafe region

- How to guarantee safety using the barrier certificate $B(x)$?
  - Define the set K_e.

$$K_e := \{x \in X : B(x) \leq 0\}.$$

Safety analysis



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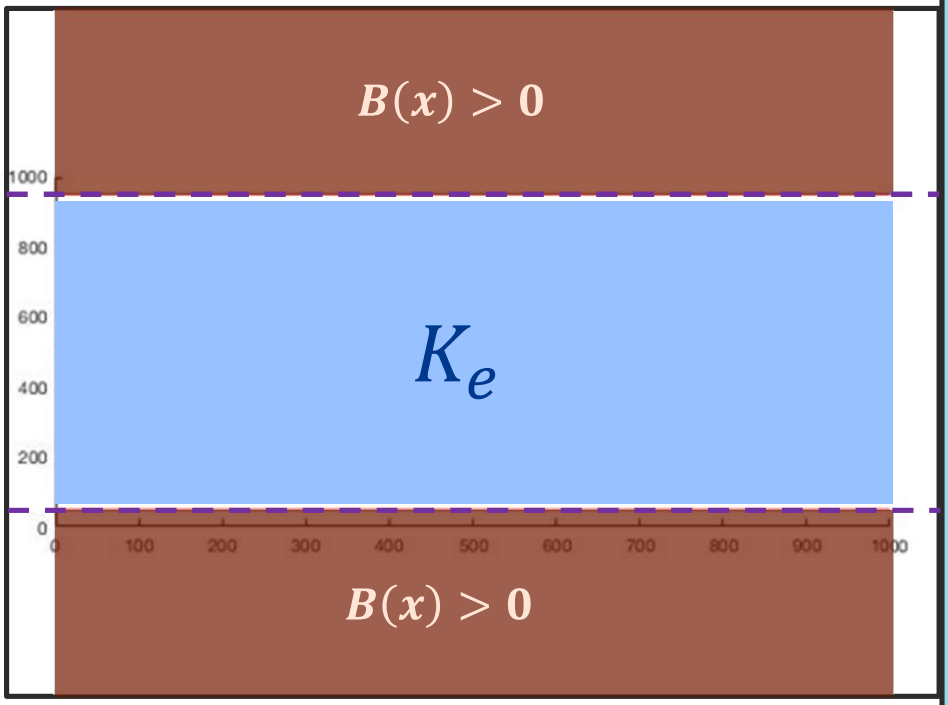

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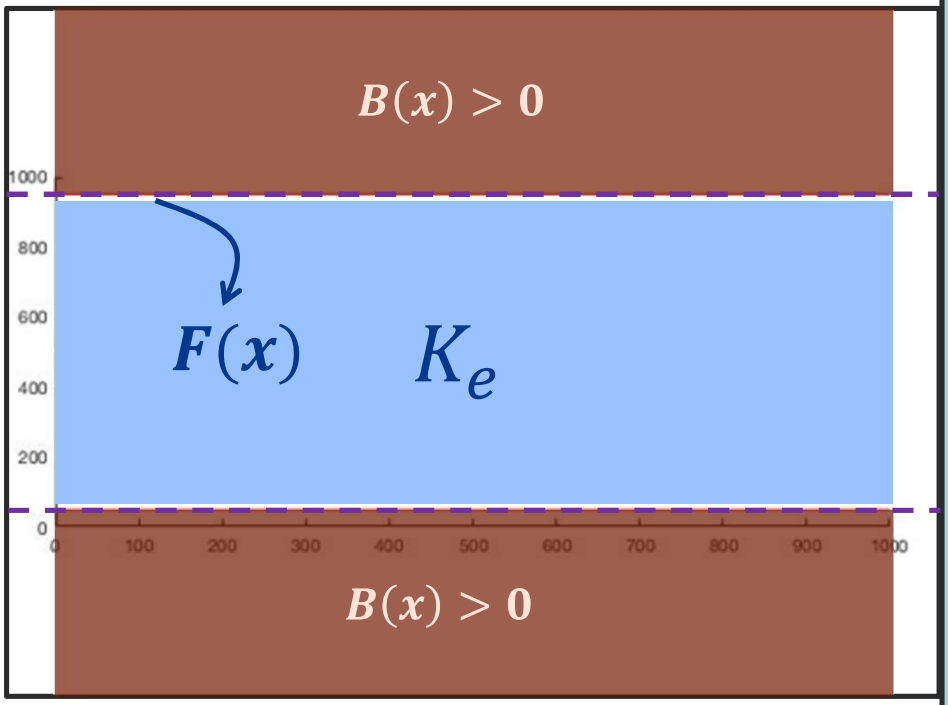
$$K_e := \{x \in X : B(x) \leq 0\}.$$

  - $\dot{x} = F(x)$ always flows to a safe region on the edge of K_e.

Safety analysis



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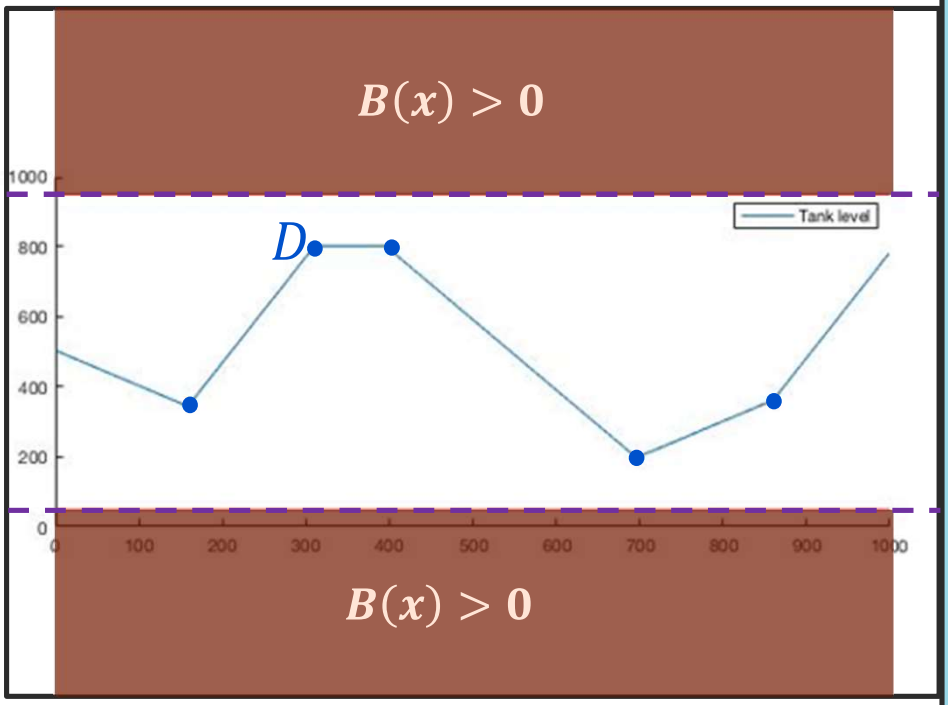
$$\langle \nabla B(x), F(x) \rangle \leq 0 \qquad \forall x \in (U(\partial K_e) \backslash K_e) \cap C,$$

Safety analysis



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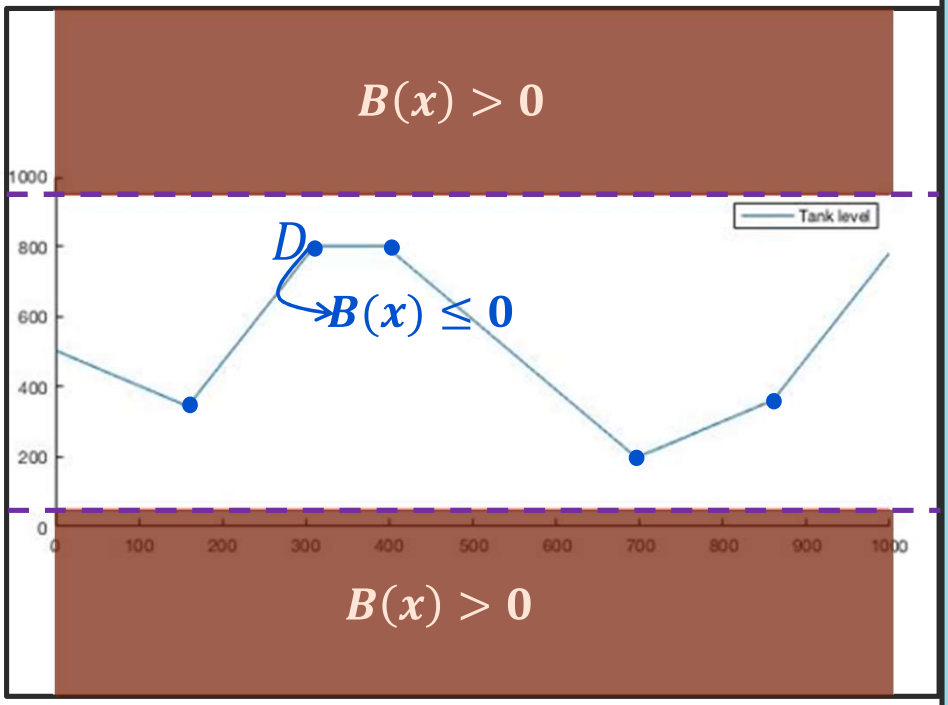
  - $B(x)$ is nonpositive in transition D.

Safety analysis



Safe region

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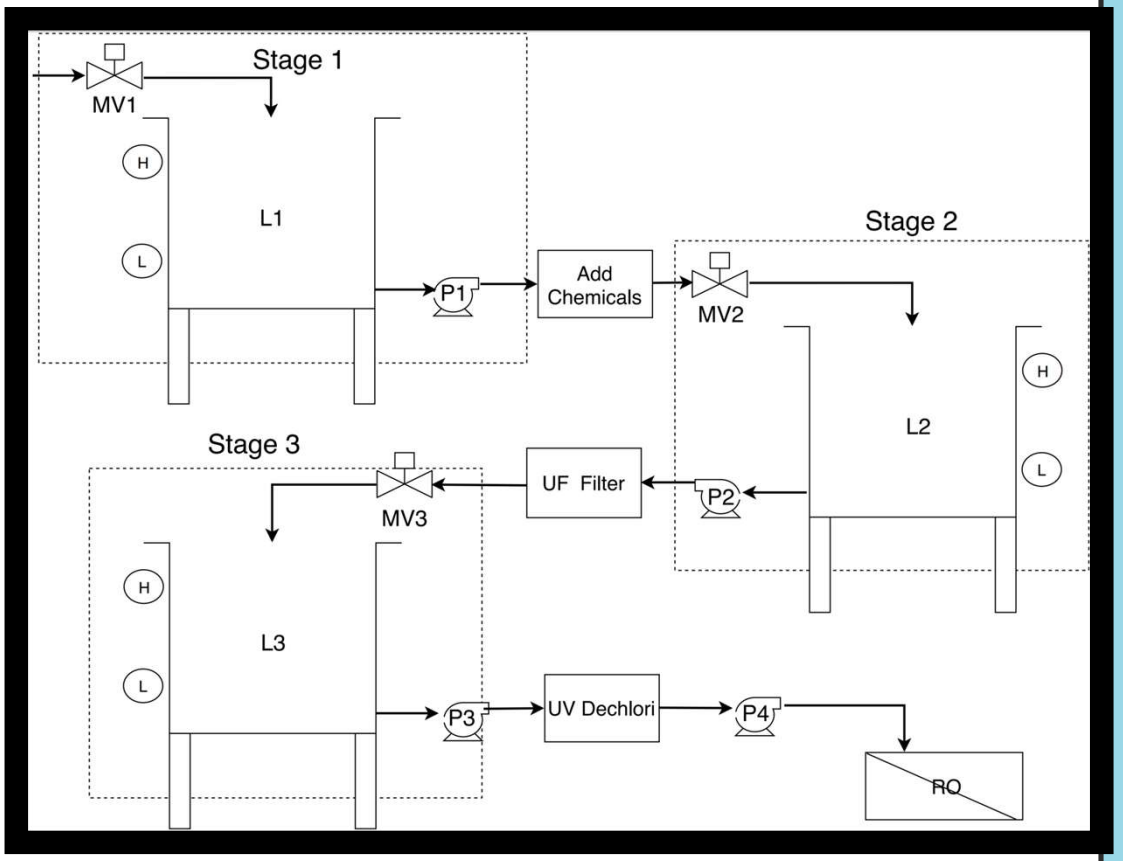
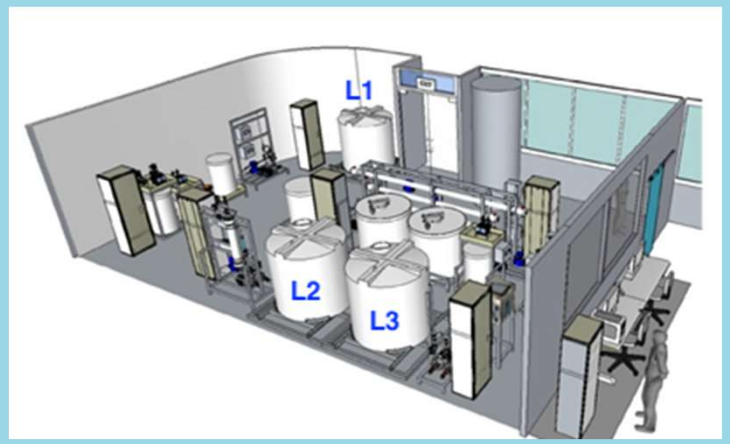
$$\langle \nabla B(x), F(x) \rangle \leq 0 \qquad \forall x \in (U(\partial K_e) \backslash K_e) \cap C,$$

  - $B(x)$ is nonpositive in transition D.

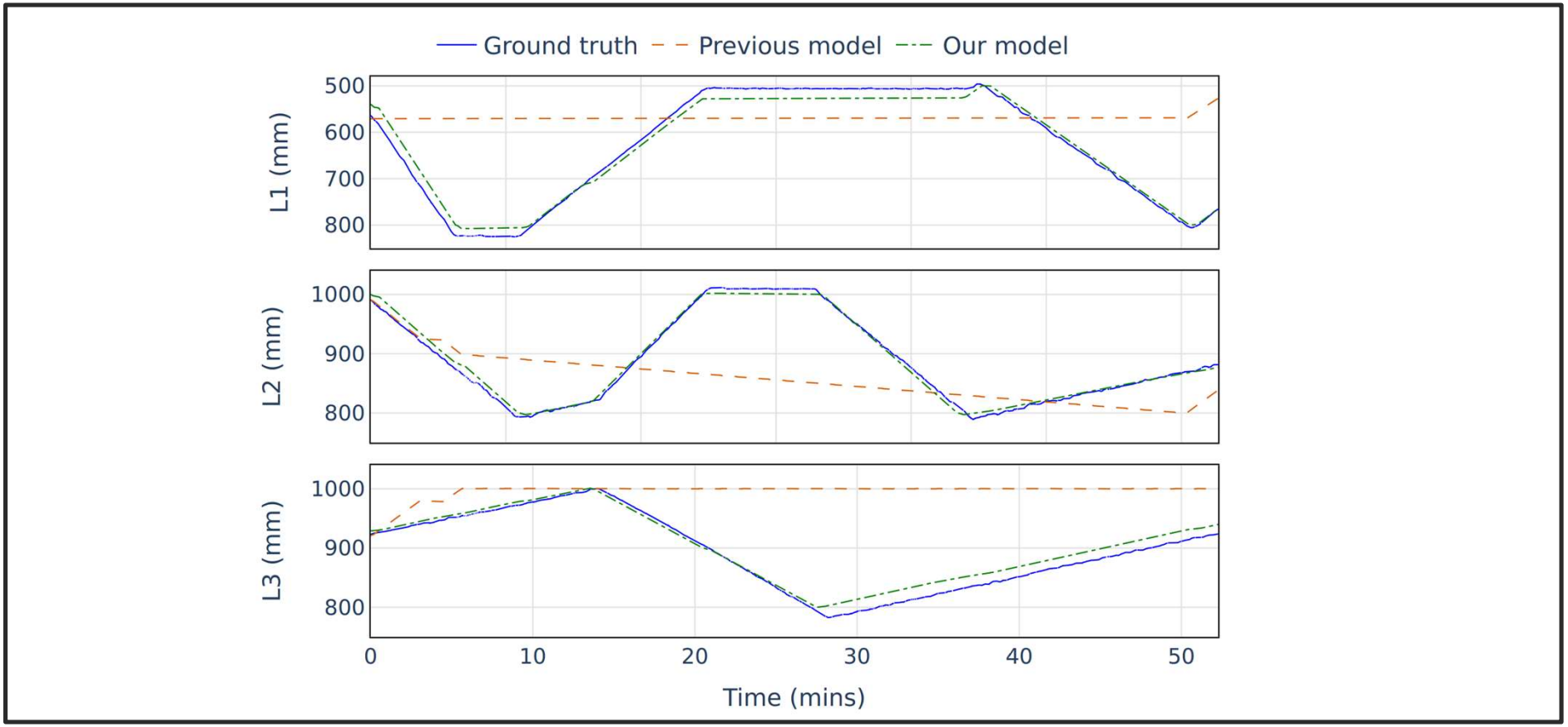
$$B(G(x)) \leq 0 \qquad \forall x \in D \cap K_e,$$

Use case: SWaT

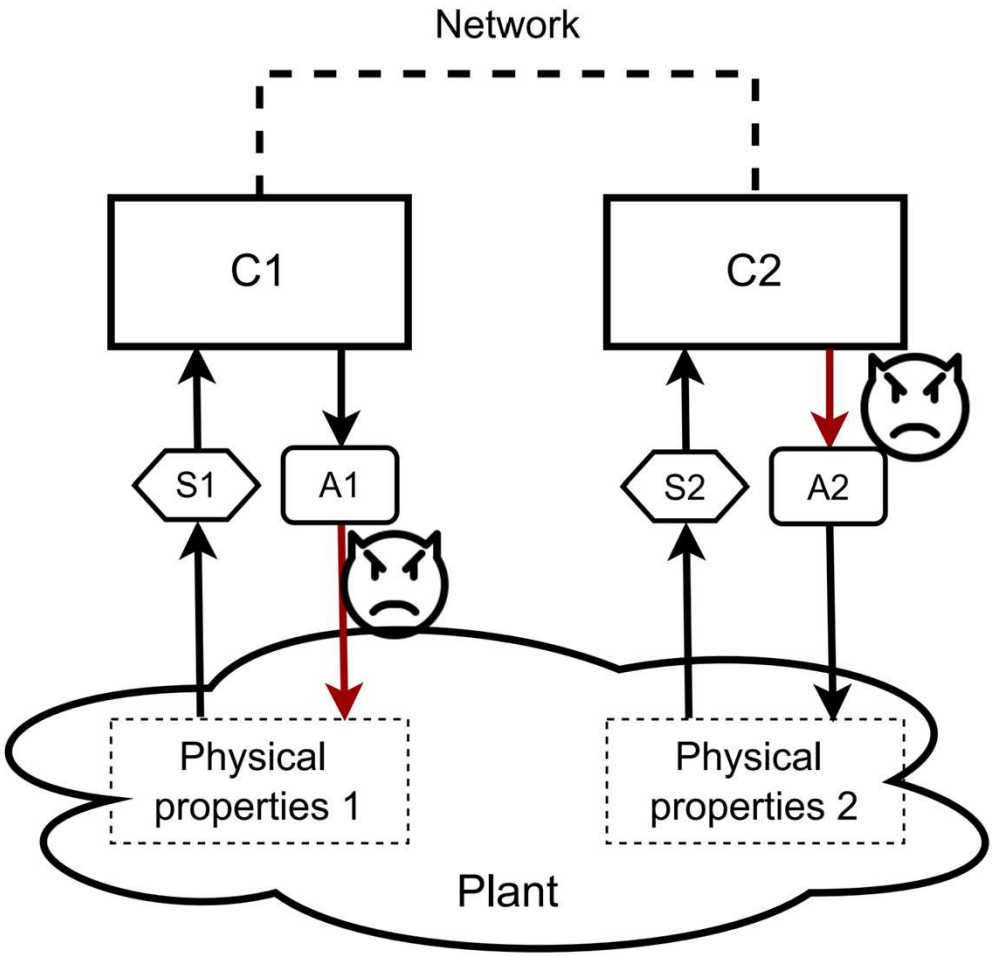




Modeling SWaT

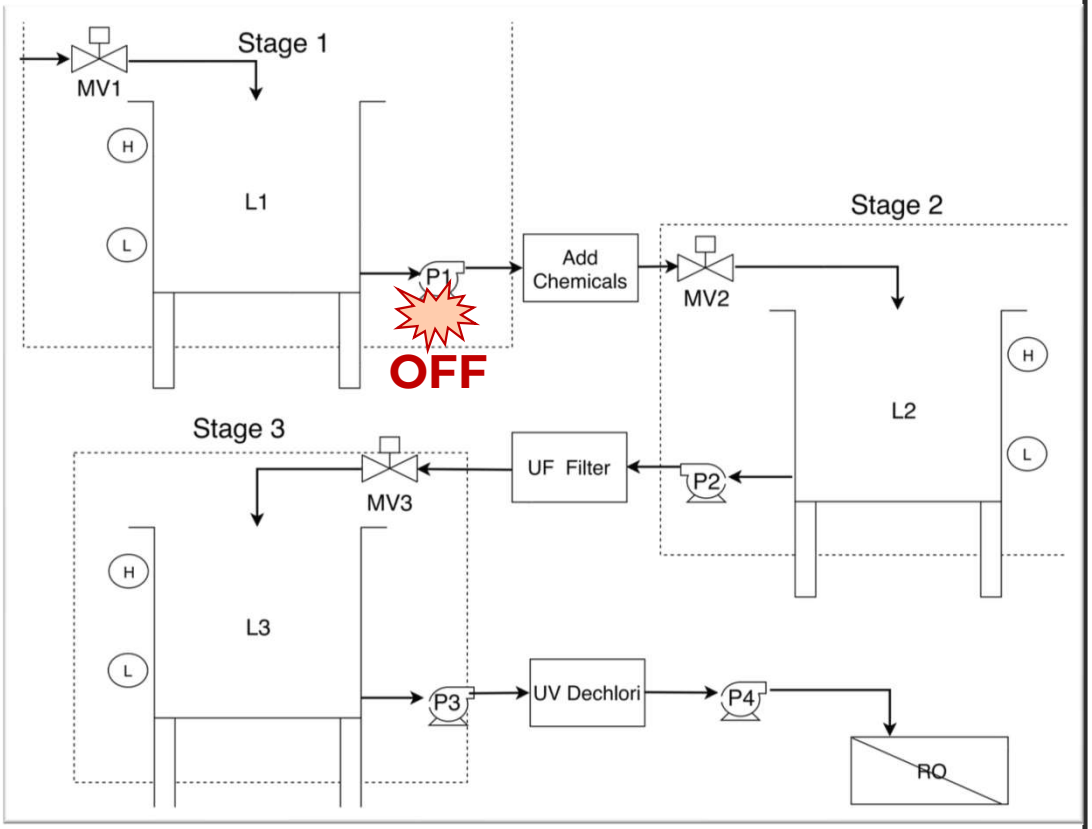


Threat model

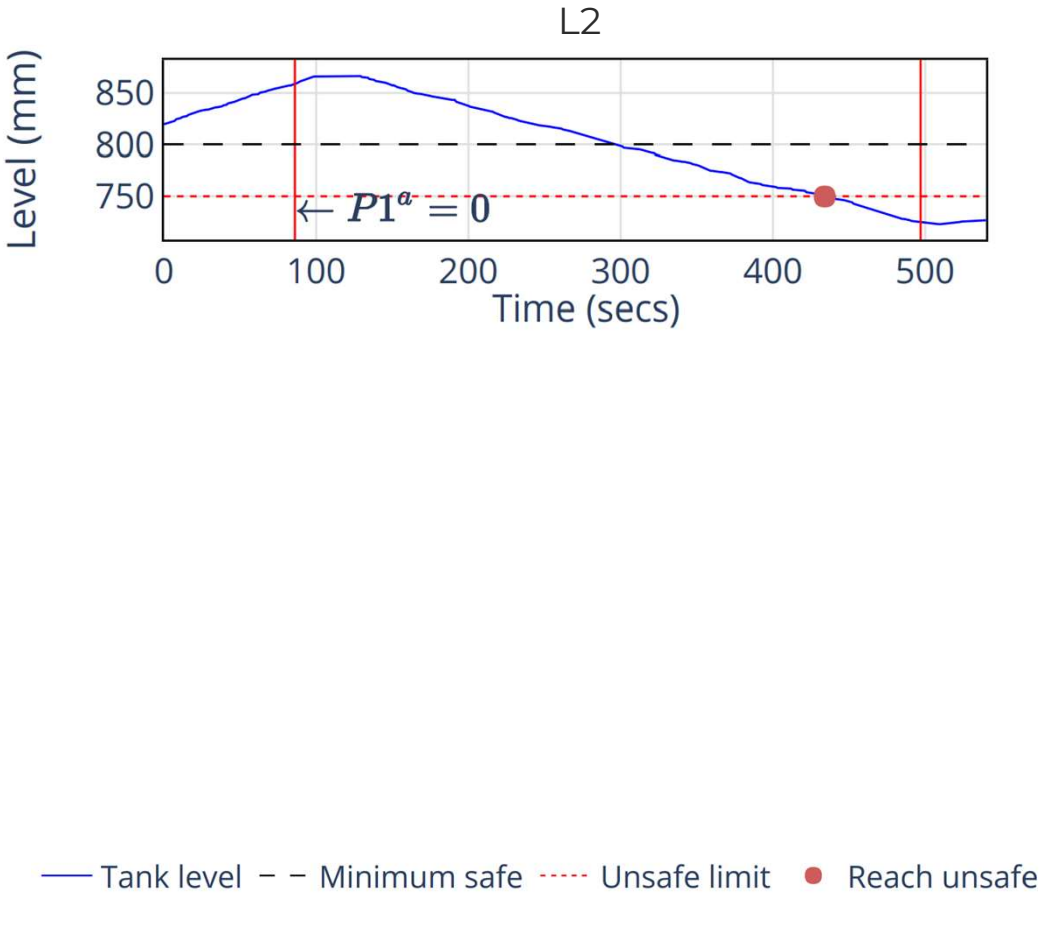


- Attackers affect only actuators.
- Attackers compromise one actuator at a time.

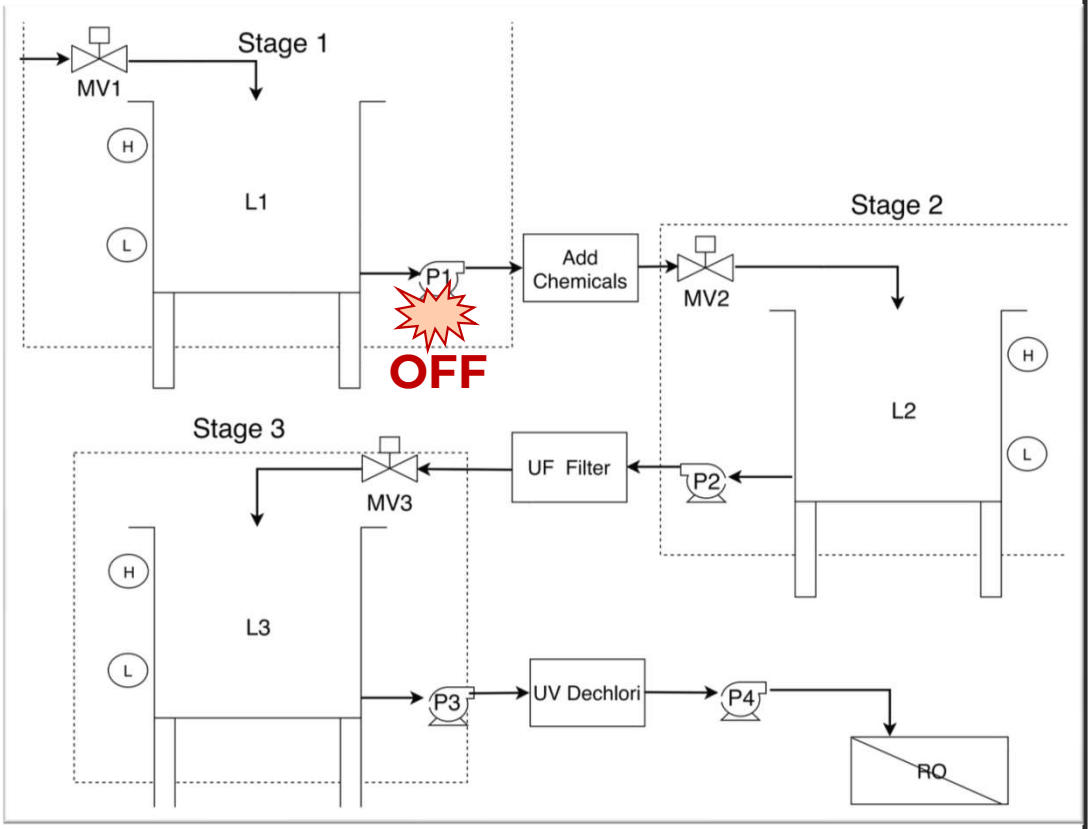
Attacking P1



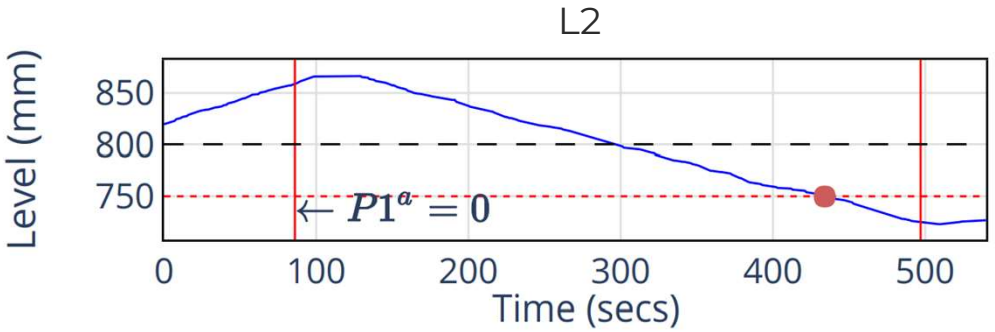
Unsafe controller



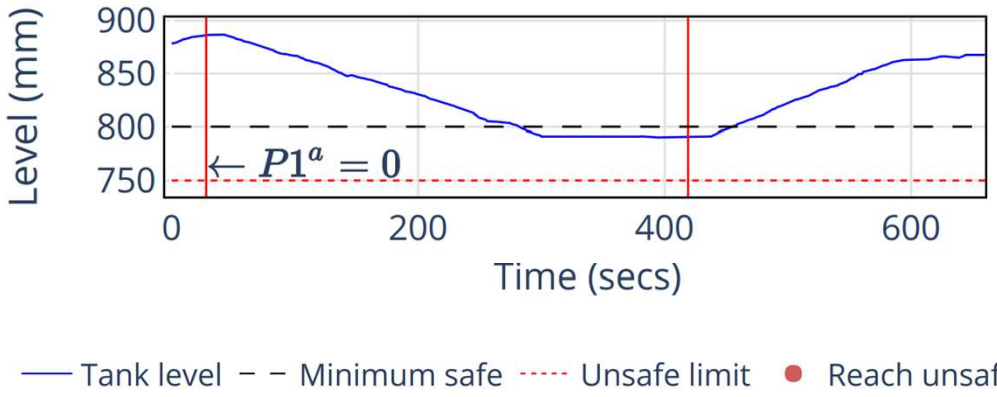
Attacking P1



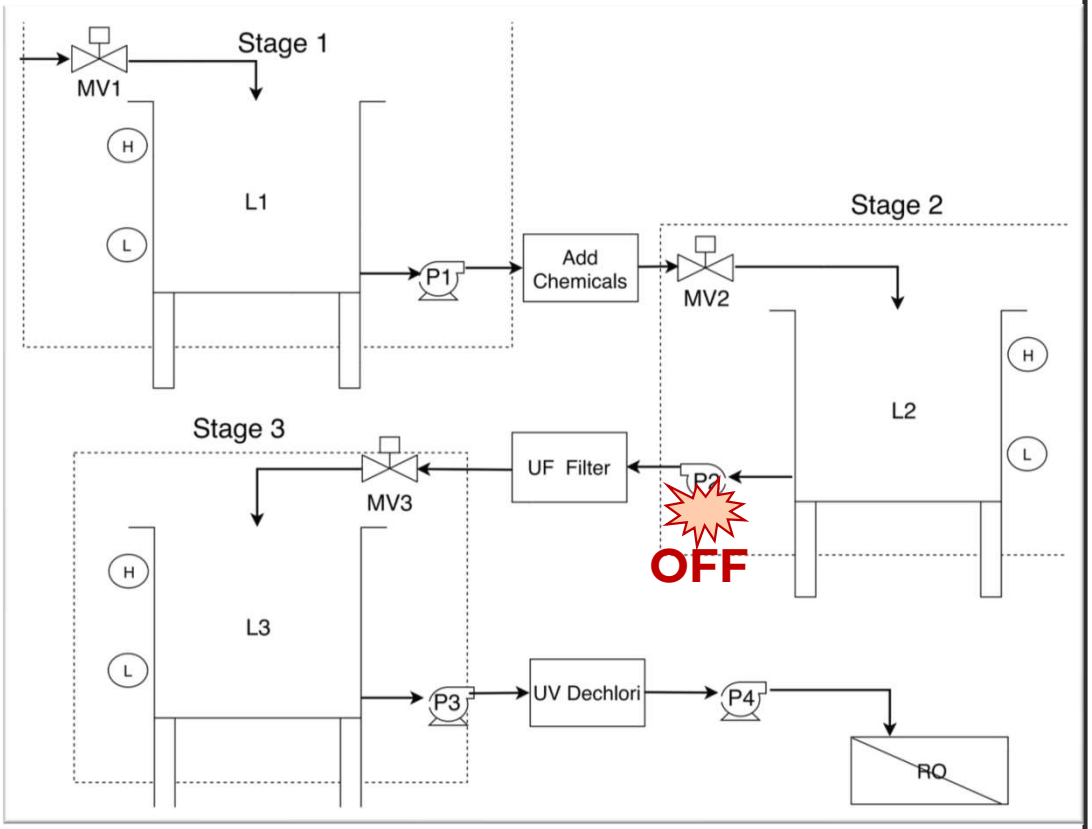
Unsafe controller



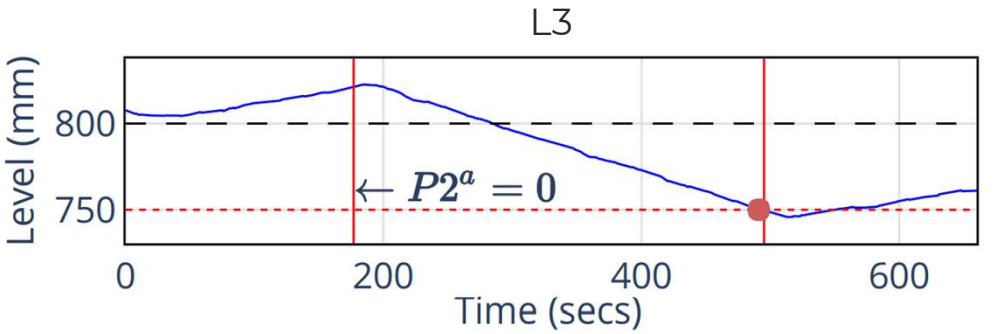
Harden controller



Attacking P2

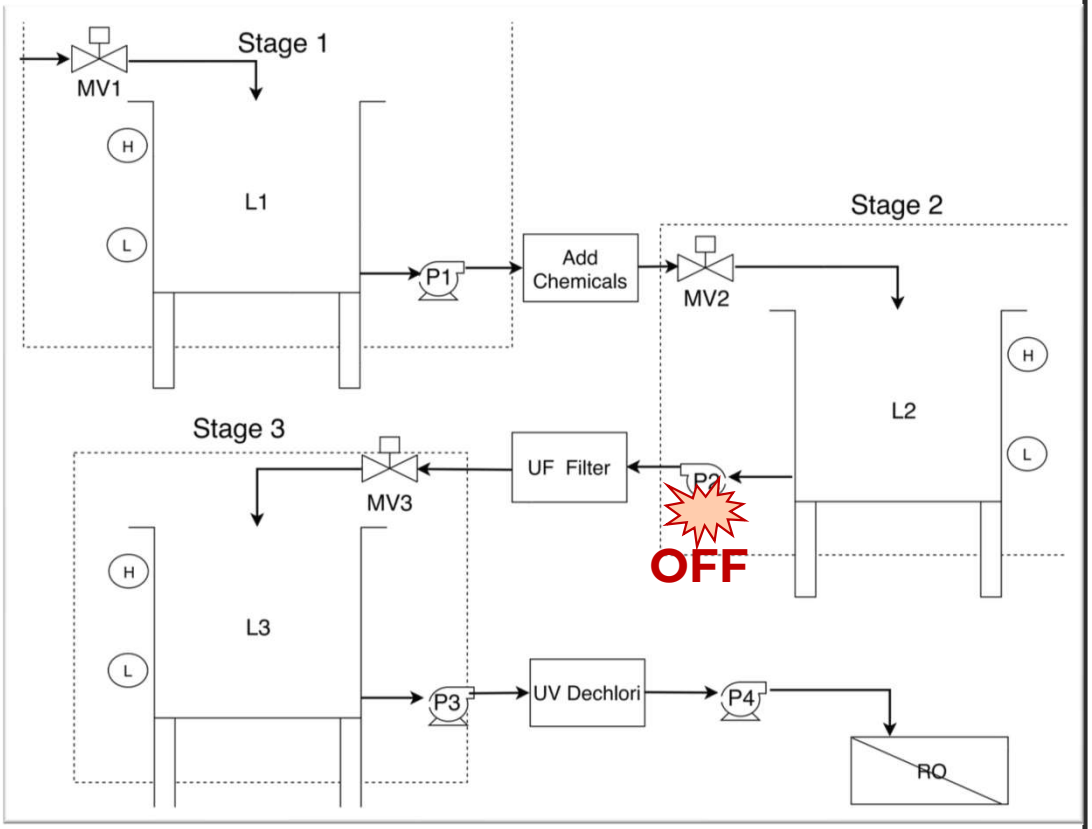


Unsafe controller

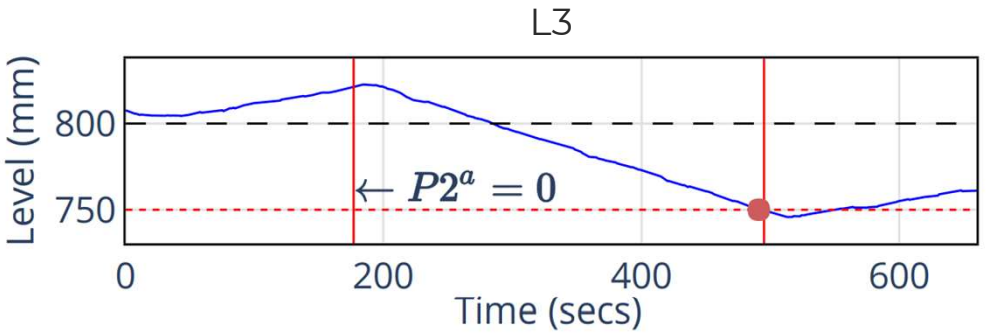


Tank level Minimum safe Unsafe limit Reach unsafe

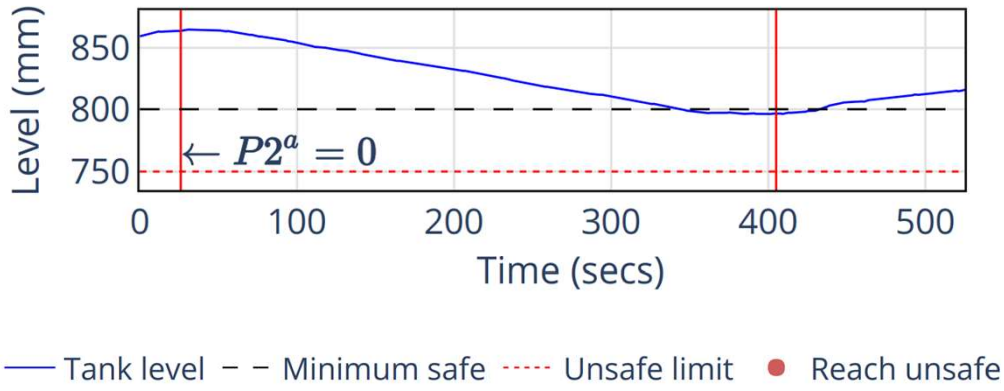
Attacking P2



Unsafe controller



Harden controller



Conclusion