Extending and Automating STPA for Requirements Generation and Analysis

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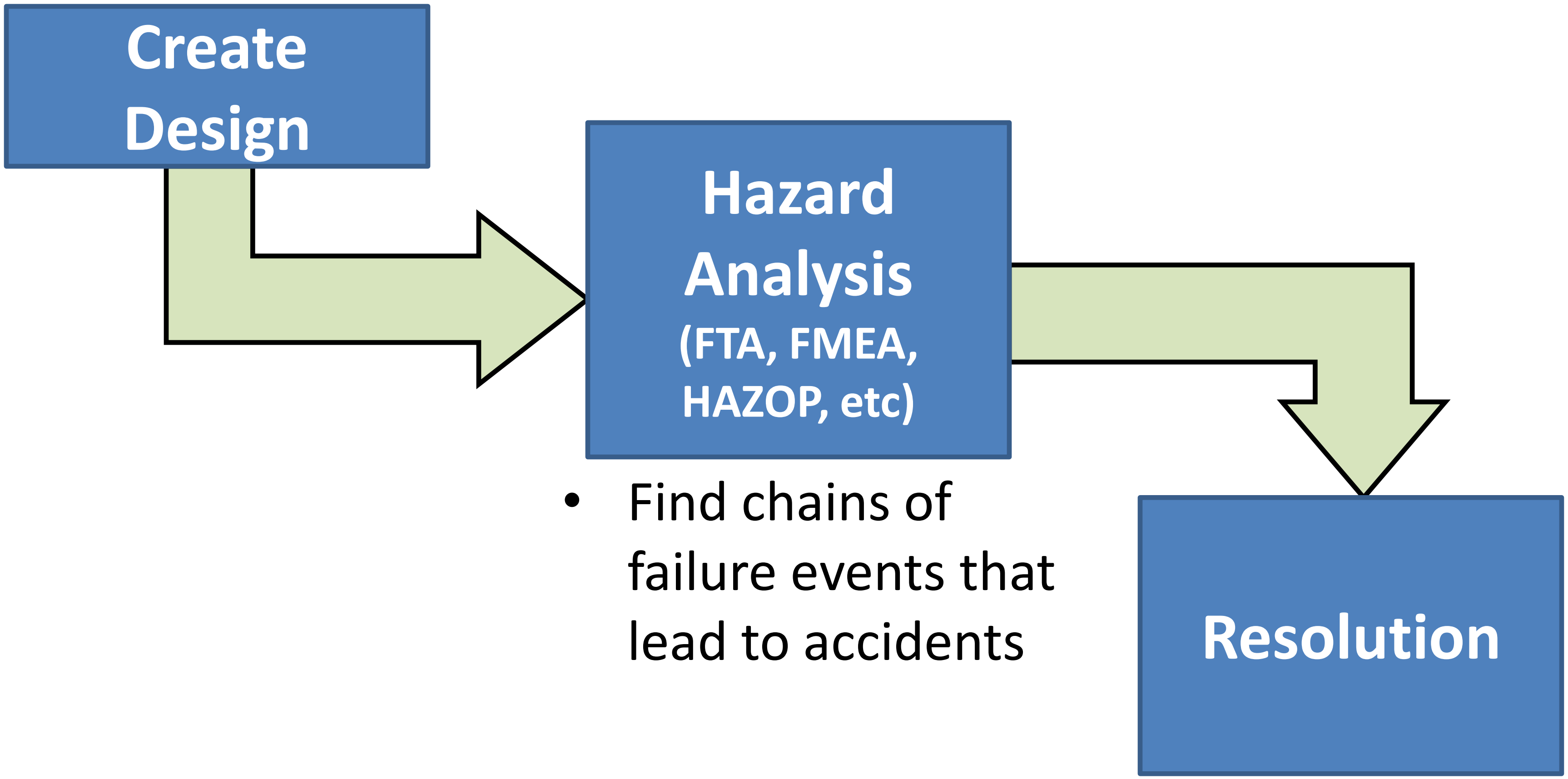
Traditional Safety Engineering

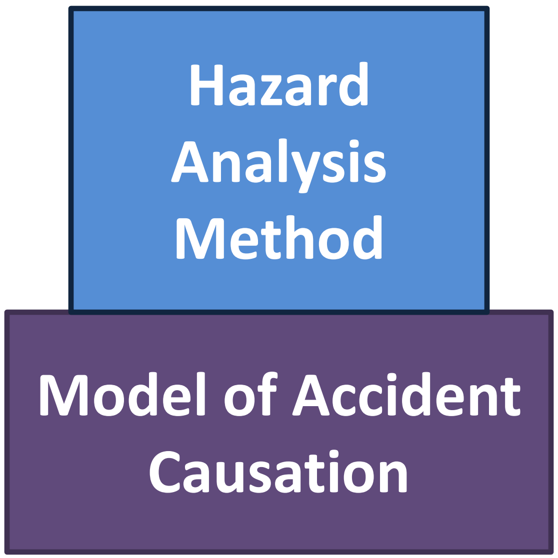


- Find chains of failure events that lead to accidents

- Add redundancy, protective functions, “patches”

(Vincoli, 1993); (Bahr, 1997); (FAA SSH, 2000); (AF SSH, 2000)

Traditional Hazard Analysis Methods

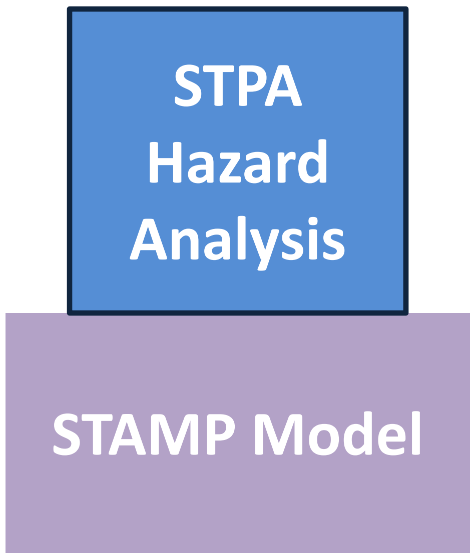


- Failure Modes Effects and Criticality Analysis (1949)
  - Reliability technique; start with component failures, find effects
- Fault Tree Analysis (1961)
  - Top-down approach; start with hazard, find failure combinations
- Hazards and Operability Analysis (1960s)
  - Apply guidewords to components, find consequences
- Event Tree Analysis (1975)
  - Start with initiating event, trace forward in time

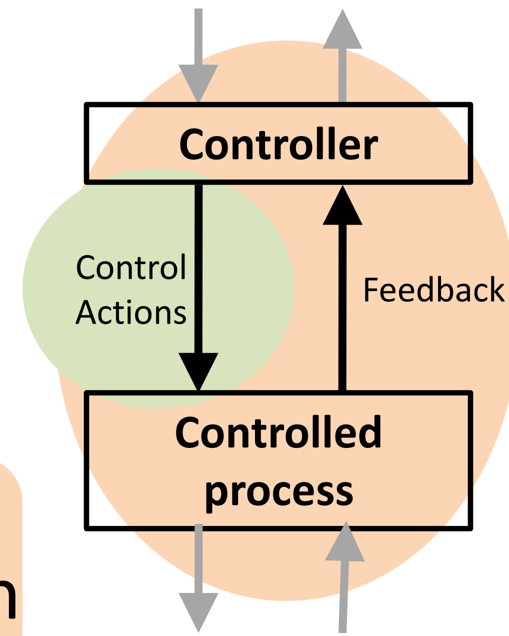
- **Require fairly detailed design**
- **Not much help creating safety requirements from the start**
- **Especially complex software requirements**

(Hammer, 1972); (Lawley , 1974); (Vesely et al, 1981); (Rasmussen, 1975); (Rasmussen, 1990); (Garrett, 2002); (Lisagor, 2006)

STPA (System-Theoretic Process Analysis)



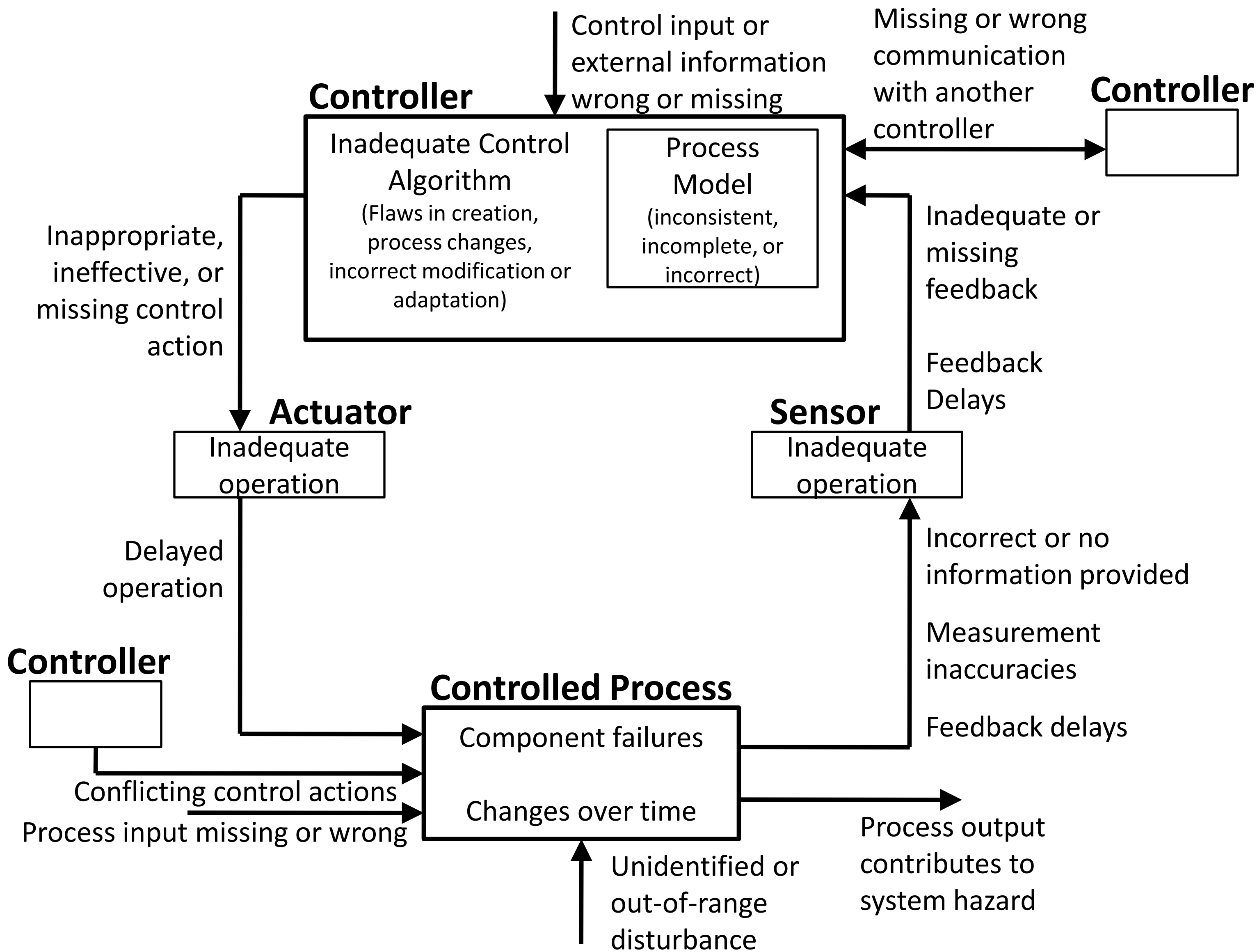
- Built on STAMP model
- Start from hazards
- Identify hazardous control actions and safety constraints
- Identify scenarios that lead to violation of safety constraints



Applied without systematic procedures for these parts

(Leveson, 2011)

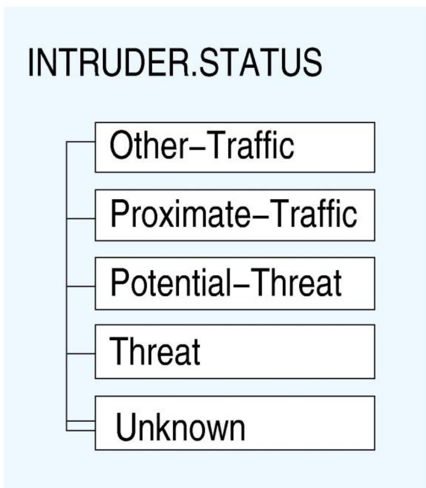
STPA Control Flaws



Need to create requirements specification without control flaws

Formal (model-based) requirements specification language

Example: SpecTRM-RL Model of TCAS II Collision Avoidance Logic



= Other–Traffic

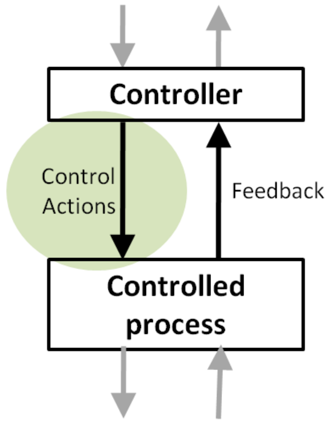
AND	OR			
Alt–Reporting **in–state** Lost	T	T	T	.
Bearing–Valid	F	.	T	.
Range–Valid	.	F	T	.
Proximate–Traffic–Condition	.	.	F	.
Potential–Threat–Condition	.	.	F	.
Other–Aircraft **in–state** On–Ground	.	.	.	T

Formal mathematical representation:

Other-Traffic =
(Alt-Reporting == Lost) ∧ ¬Bearing-Valid ∨ (Alt-Reporting == Lost) ∧ ¬Range-Valid ∨
(Alt-Reporting == Lost) ∧ Bearing-Valid ∧ Range-Valid ∧ ¬Proximate-Traffic-Condition ∧
¬Potential-Threat-Condition ∨ (Other-Aircraft == On-Ground)

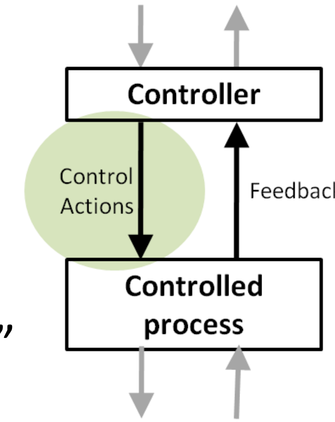
(Leveson, 2000), (Zimmerman, 2002)

Structure of a Hazardous Control Action



Example:
“Operator provides open train door command when train is moving”

Structure of a Hazardous Control Action



Example:
"Operator provides open train door command when train is moving"

Source (S) | Type (T) | Control Action (CA) | Context (C)

Four parts of a hazardous control action
- Source: the controller that can provide the control action
- Type: whether the control action was provided or not provided
- Control Action: the controller's command that was provided / missing
- Context: the system or environmental state in which command is provided

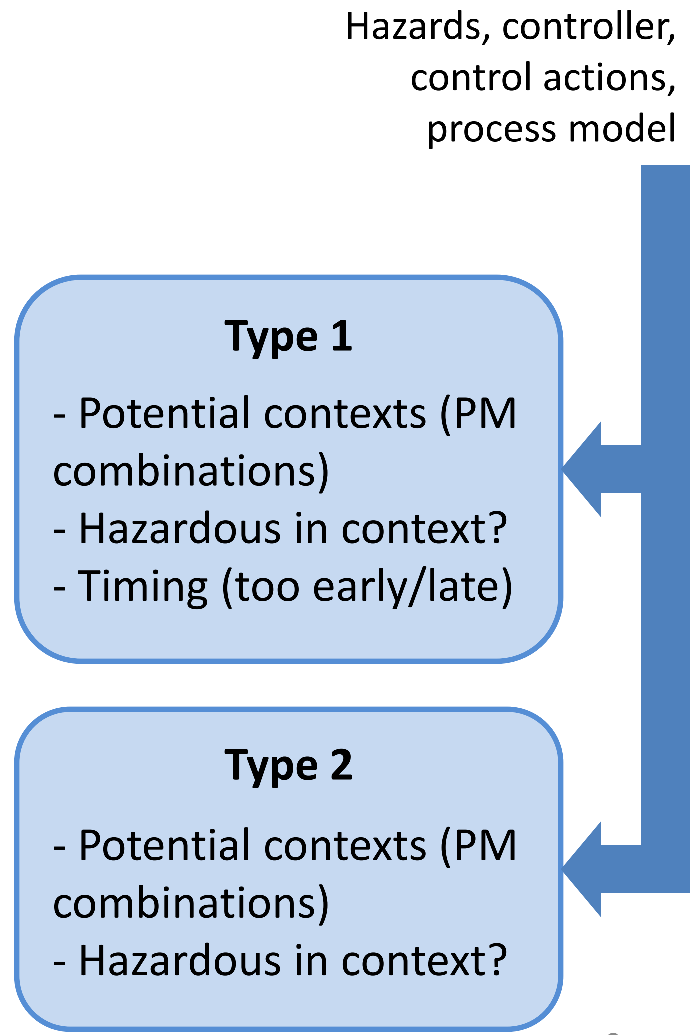
Process Model

Train motion: Stopped / Moving

Train location: At platform / Not Aligned

Identifying Hazardous Control Actions

- Type 1: Providing control action causes hazard
  - 1a) Define potential contexts (combinations of process model values)
  - 1b) Determine whether the control action is hazardous in each context
  - 1c) Determine whether control action can still be hazardous if too early/too late
- Type 2: Not providing control action causes hazard
  - Same as above, but for an absence of the selected control action



Example: Train door controller

System Hazards

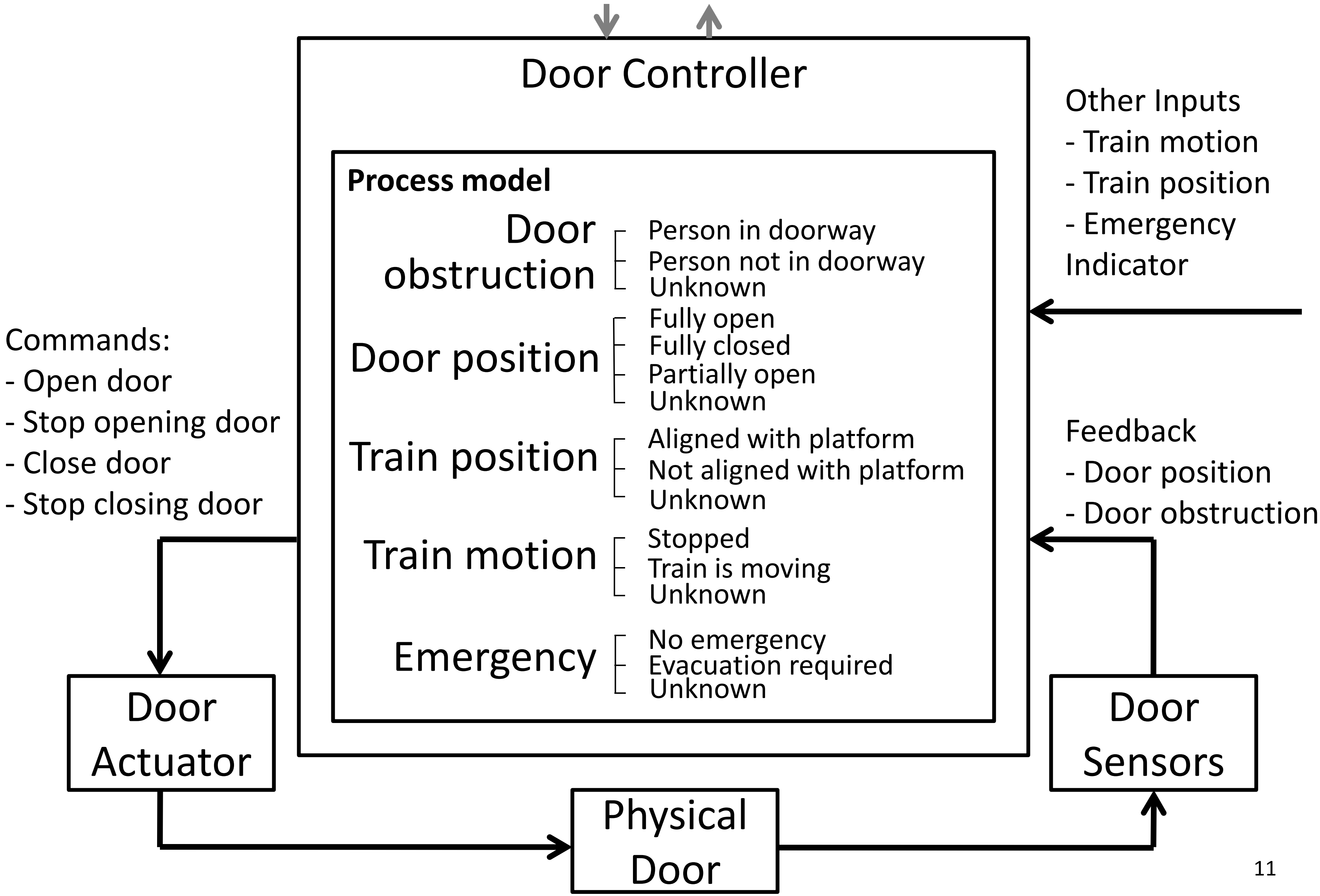
H-1: Doors close on a person in the doorway

H-2: Doors open when the train is moving or not at platform

H-3: Passengers/staff are unable to exit during an emergency

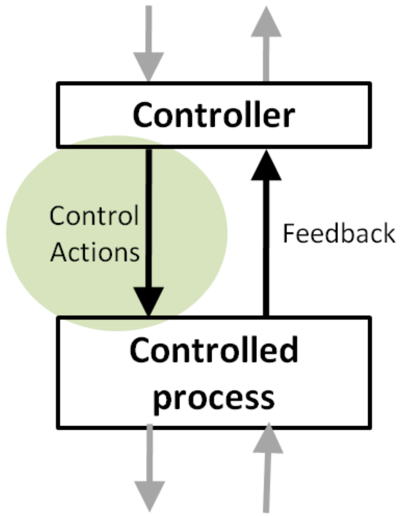
Image: http://upload.wikimedia.org/wikipedia/commons/f/fe/Mbta-redline-bombardier.jpg

Example: Control loop



Process

- ✔ Identify hazards
- ✔ Create control structure
- ✔ Create process model
- ➡ Identify Unsafe Control Actions
  - For each control action, consider:
  - 1) Providing causes hazard
  - 2) Not providing causes hazard
- Identify Causes of Unsafe Control Actions



1) Control action is provided

- Control action: *Door Open* command
- 1a) Define potential contexts (combinations of process model variables)

Control Action	Train Motion	Emergency	Train Position	Door Obstruction	Door Position
Door open command	Stopped	No	Aligned with platform	Not obstructed	Closed
Door open command	Stopped	No	Aligned with platform	Not obstructed	Open
Door open command	Stopped	Yes	Aligned with platform	Obstructed	Closed
…	…	…	…	…	…

1) Control action is provided

Control action: *Door Open* command

- 1a) Define potential contexts (combinations of process model variables)
- 1b) Determine whether the control action is hazardous in each context

Control Action	Train Motion	Emergency	Train Position	Door Obst. / Position	Hazardous?
Door open command	Moving	No	(doesn't matter)	(doesn't matter)	**Yes**
Door open command	Moving	Yes	(doesn't matter)	(doesn't matter)	**Yes***
Door open command	Stopped	Yes	(doesn't matter)	(doesn't matter)	**No**
Door open command	Stopped	No	Not at platform	(doesn't matter)	**Yes**
Door open command	Stopped	No	At platform	(doesn't matter)	**No**

***Design decision: In this situation, evacuate passengers to other cars. Meanwhile, stop the train and then open doors.**

1) Control action is provided

Control action: *Door Open* command

- 1a) Define potential contexts (combinations of process model variables)
- 1b) Determine whether the control action is hazardous in each context
- 1c) Determine whether control action can still be hazardous if too early/too late

Control Action	Train Motion	Emergency	Train Position	Door Obst. / Position	Hazardous ?	Hazardous if provided too early?	Hazadous if provided too late?
Door open command	Moving	No	(doesn't matter)	(doesn't matter)	Yes	Yes	Yes
Door open command	Moving	Yes	(doesn't matter)	(doesn't matter)	Yes*	Yes*	Yes*
Door open command	Stopped	Yes	(doesn't matter)	(doesn't matter)	No	No	Yes
Door open command	Stopped	No	Not at platform	(doesn't matter)	Yes	Yes	Yes
Door open command	Stopped	No	At platform	(doesn't matter)	No	No	No

2) Control action is <u>not</u> provided

Control action: *Door Open* command

- 2a) Identify process model variables
- 2b) Determine whether the absence of control action is hazardous in each context

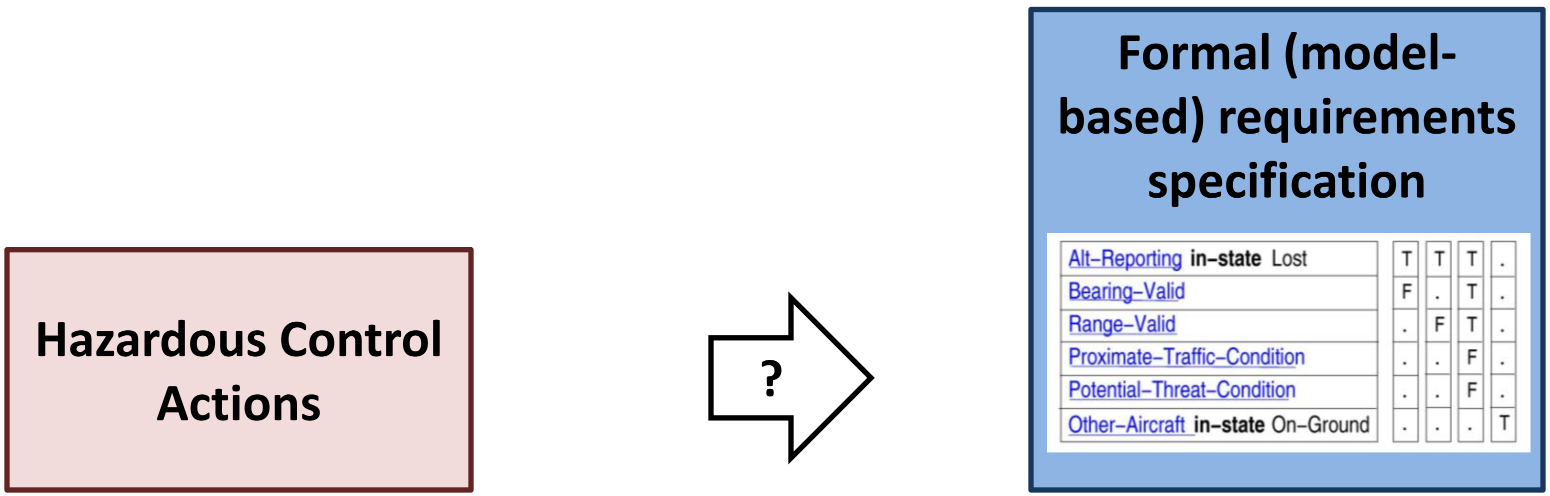
Control Action	Train Motion	Emergency	Train Position	Door Obst. / Pos.	Hazardous?
Door open command not provided	Stopped	Yes	(doesn't matter)	(doesn't matter)	**Yes**
Door open command not provided	Stopped	(doesn't matter)	(doesn't matter)	Closing on obstruction	**Yes**
Door open command not provided	(all others)				**No**

Resulting List of Hazardous Control Actions

Hazardous Control Actions
Door open command provided while train is moving and there is no emergency
Door open command provided too late while train is stopped and emergency exists
Door open command provided while train is stopped, no emergency, and not at platform
Door open command provided while train is moving and emergency exists
Door open command not provided while train is stopped and emergency exists
Door open command not provided while doors are closing on someone

Much of this can be automated to assist the safety engineer!

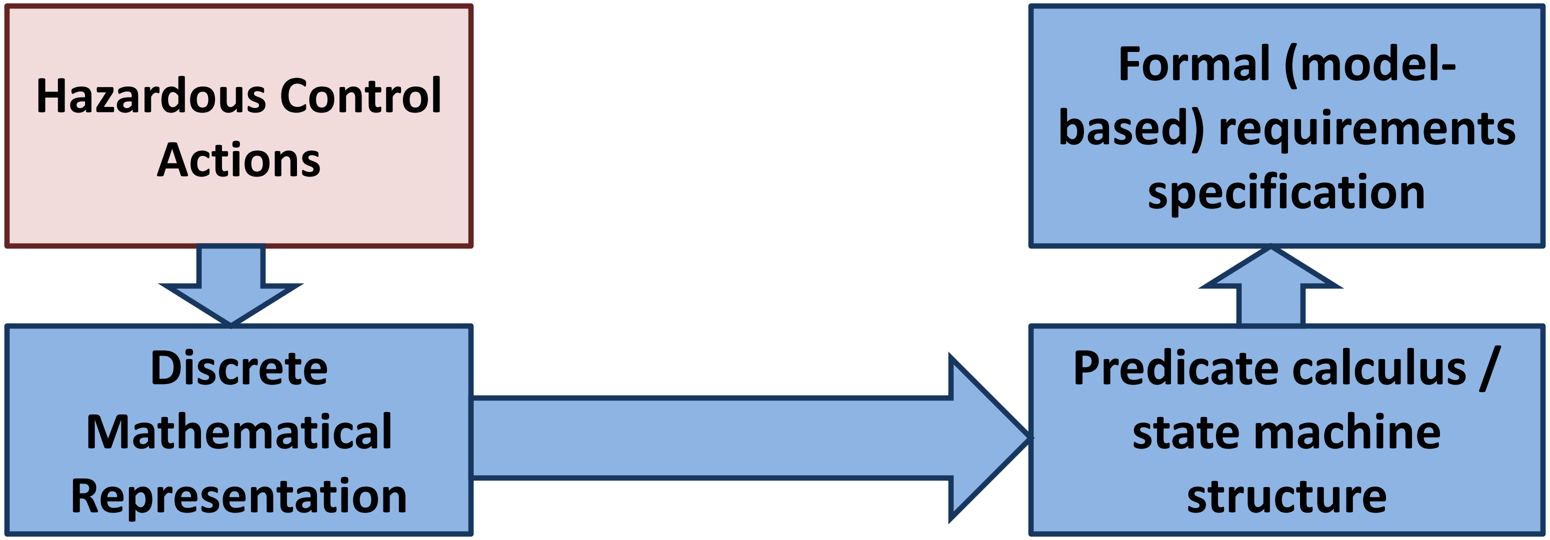
Generating safety requirements



Alt–Reporting **in–state** Lost	T	T	T	.
Bearing–Valid	F	.	T	.
Range–Valid	.	F	T	.
Proximate–Traffic–Condition	.	.	F	.
Potential–Threat–Condition	.	.	F	.
Other–Aircraft **in–state** On–Ground	.	.	.	T

Generating safety requirements

- Formal requirements can be derived using
  - Discrete mathematical structure for hazardous control actions
  - Predicate calculus underlying formal requirements
- Automatically generate formal requirements given these relationships!



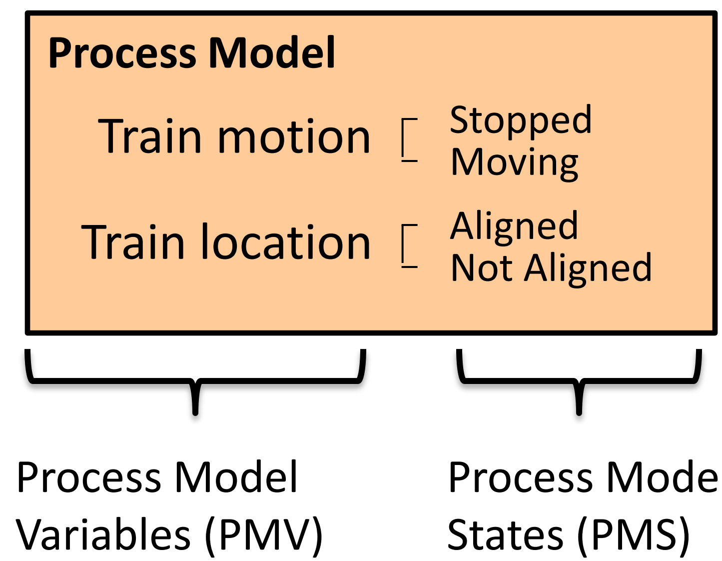
Hazardous control actions: mathematical representation

Example: "Operator provides open train door command when train is moving"

Source (S) — Type (T) — Control Action (CA) — Context (C)

Hazardous control action as 4-tuple (S, T, CA, C) where:

- $S \in$ Controllers [from control structure]
- $T \in$ {Provided, Not Provided}
- $CA \in$ ControlActions(S)
- $C = \{V, S\} \mid (V \in PMV) \land (S \in PMS) \land$ S child V



Hazardous control actions -> formal requirements specifications

1. Describing hazardous, functional, and required behavior

- $HP(h \in H, ca \in CA, c \in C)$
  - True iff providing command ca in context c will cause hazard h
- $HNP(h \in H, ca \in CA, c \in C)$
  - True iff not providing command ca in context c will cause hazard h
- $FP(f \in F, ca \in CA, c \in C)$
  - True iff providing command ca in context c is necessary to achieve function f
- $R(ca \in CA, c \in C)$
  - True iff command CA is required to be provided in context c

2. Consistency checks

- $\forall h1 \in H, h2 \in H \ \neg \exists \ ca \in CA, c \in C : HP(h1, ca, c) \wedge HNP(h2, ca, c)$
  - For every potential context, it must be possible to avoid hazardous control actions/inactions. In other words, if it is hazardous to provide CA then it should be non-hazardous to not provide CA
- $\forall \ h \in H, f \in F \ \neg \exists \ ca \in CA, c \in C : HP(h, ca, c) \wedge F(f, ca, c)$
  - For every potential context, if it is necessary to provide a command to fulfill a function then it must not be hazardous to provide the command in that context

3. Requirements generation (SpecTRM-RL tables)

- Compute $R(ca \in CA, c \in C)$ to satisfy the following:
- $\forall h,ca,c: h \in H \wedge ca \in CA \wedge c \in C \rightarrow [HP(h, ca, c) \rightarrow \neg R(ca, c)]$
- $\forall h,ca,c: h \in H \wedge ca \in CA \wedge c \in C \rightarrow [R(ca, c) \rightarrow HNP(h, ca, c)]$
- $\forall f,ca,c: f \in F \wedge ca \in CA \wedge c \in C \rightarrow [FP(f, ca, c) \rightarrow R(ca, c)]$

Generating safety requirements

- Example: Generated black-box model for door controller

Behavior required for function

Behavior required for safety

Provide 'Open Doors' command

		Behavior required for function	Behavior required for safety	Behavior required for safety
Door State =	Doors not closing on person			
	Doors closing on person			T
Train Position =	Aligned with platform	T		
	Not aligned with platform			
Train Motion =	Stopped	T	T	T
	Train is moving			
Emergency =	No emergency			
	Emergency exists		T	

Open Doors =
(Train Position in-state Aligned) ∧ (Train Motion in-state Stopped) ∨ (Train Motion in-state Stopped) ∧ (Emergency in-state exists) ∨ (Door State in-state closing on person) ∧ (Train Motion in-state Stopped)

Detecting conflicts

- Can automatically check consistency using info in context tables

Control Action	Train Motion	Emergency	Hazardous?
Door open command	Moving	Yes	**Yes***

Control Action	Train Motion	Emergency	Hazardous?
Door open command not provided	Moving	Yes	**Yes***

- Example: Conflict between opening the door vs. not opening the door

Summary

- Systematic process for performing STPA
- Method to help automate STPA
- Drives the creation of requirements and definition of control algorithms from the STPA analysis
- Automatically generating formal safety requirements
- Analyze not only safety aspects, but also functional goals
- Consistency checks to detect safety vs. functional conflicts

Thank you!

Questions?