ORTA DOĞU TEKNİK ÜNİVERSİTESİ
MIDDLE EAST TECHNICAL UNIVERSITY

Cause Mining with STL

Ebru Aydin Gol
Computer Engineering, METU

139th Shonan Meeting

H2020, MSCA – IF No:798482.

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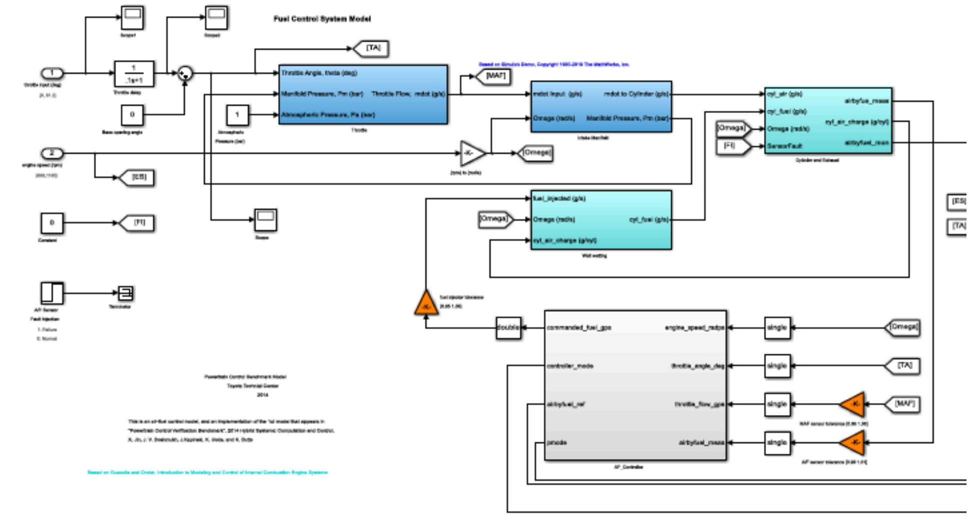
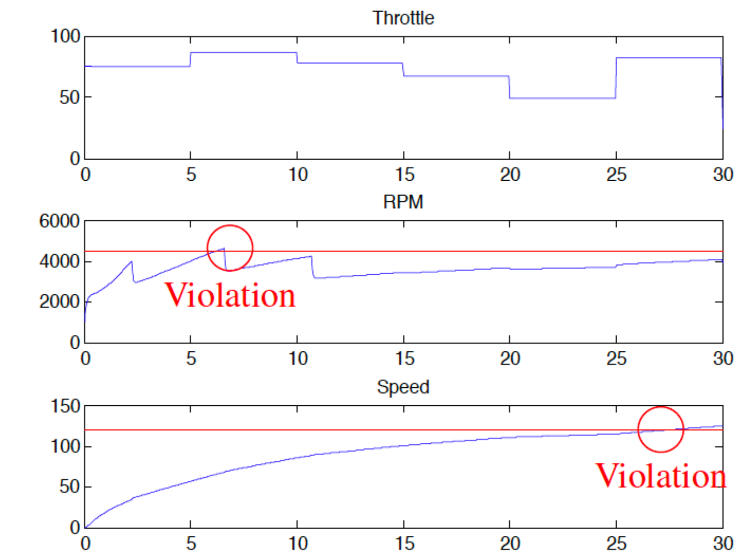
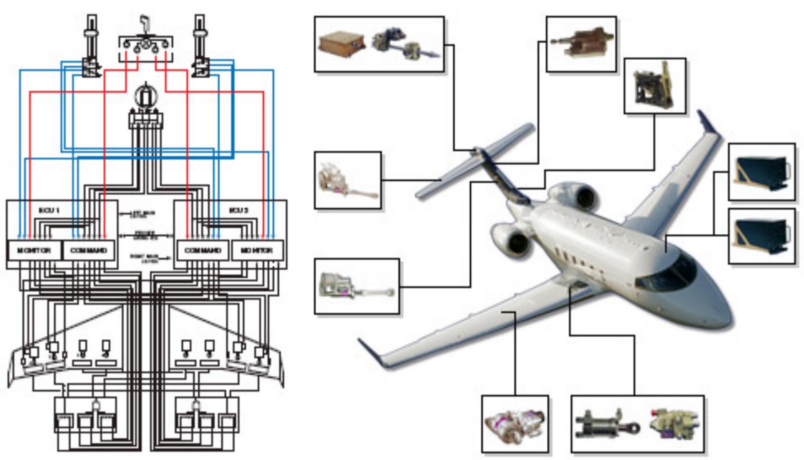


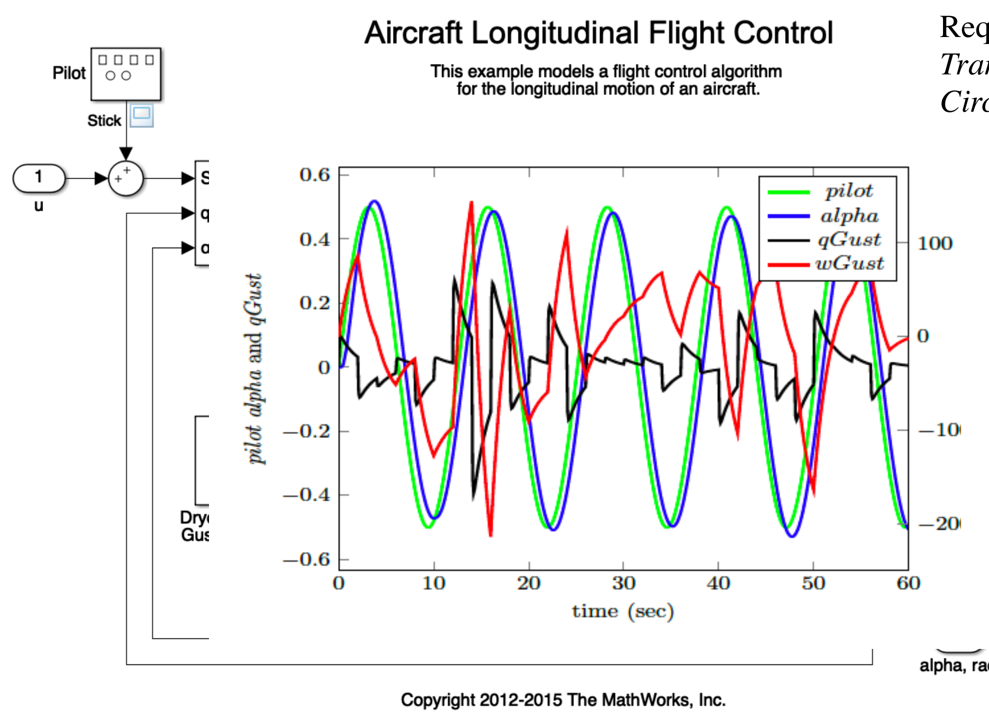
Power train control benchmark model by Toyota

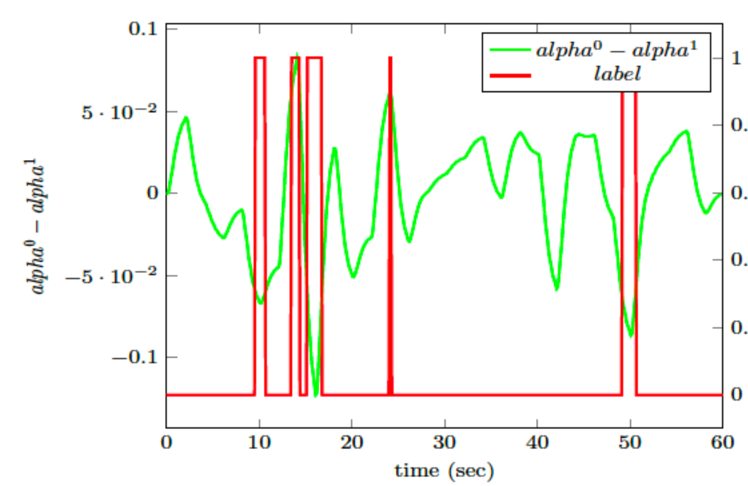


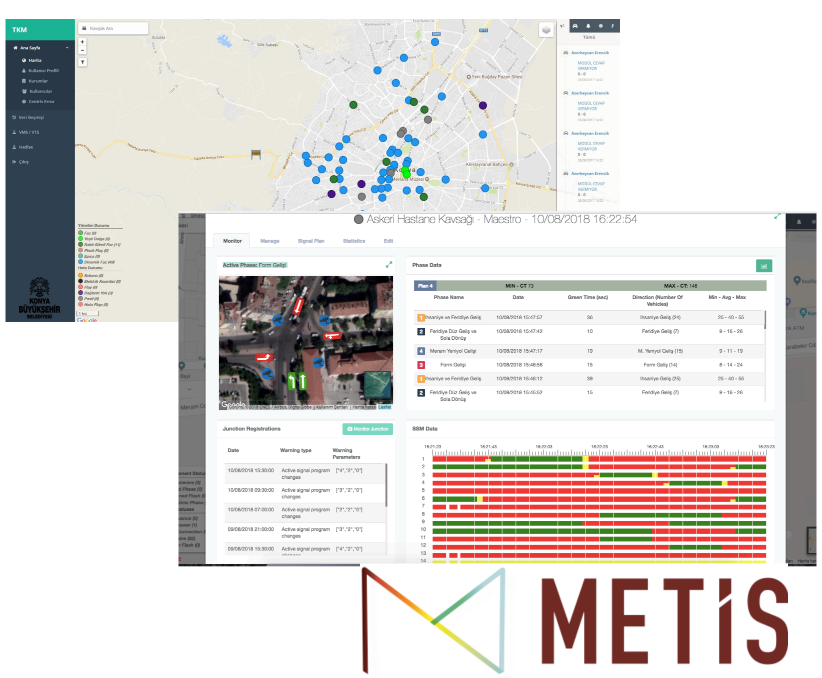
X. Jin, A. Donzé, J. V. Deshmukh and S. A. Seshia, "Mining Requirements From Closed-Loop Control Models," in *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*

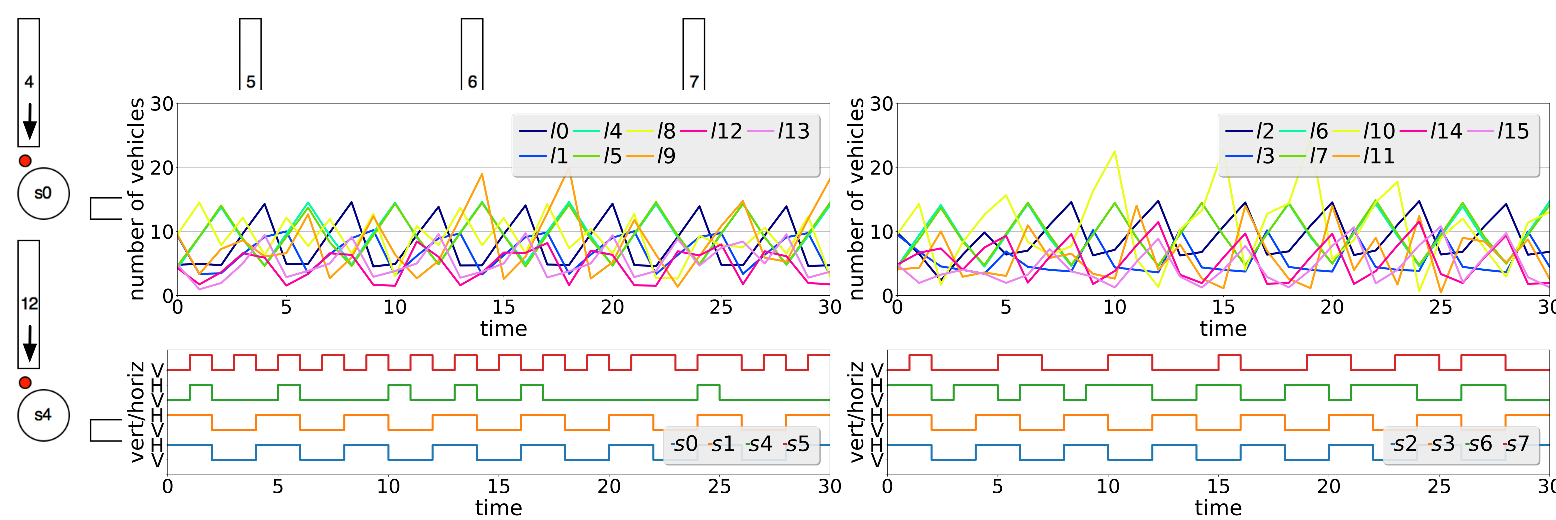


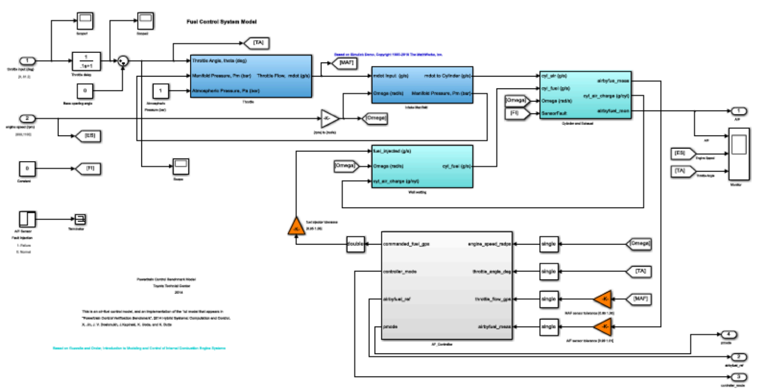
Flight Control System Provider on Challenger 300



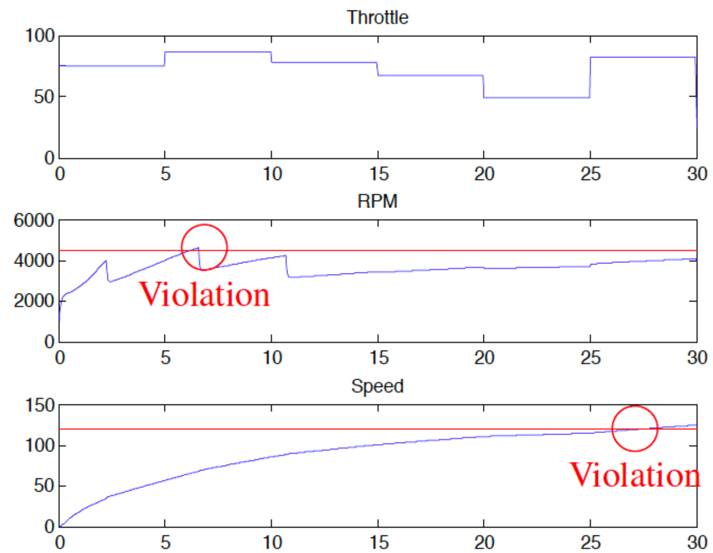








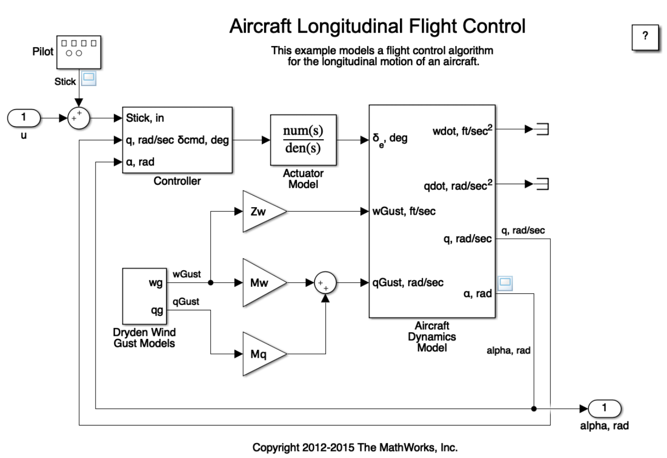
Power train control benchmark model by Toyota

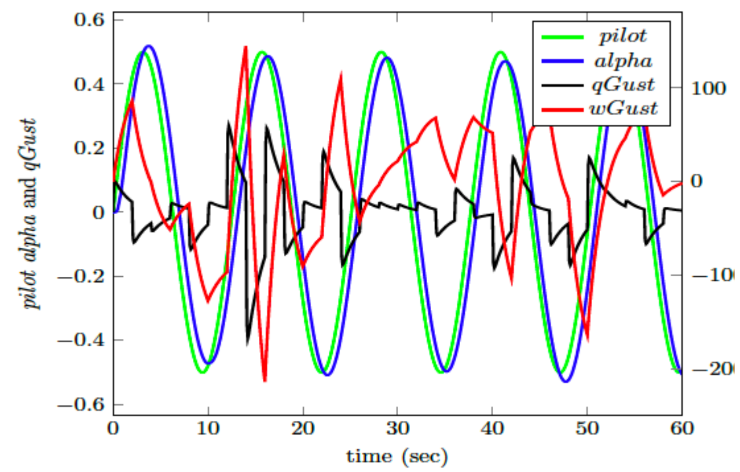


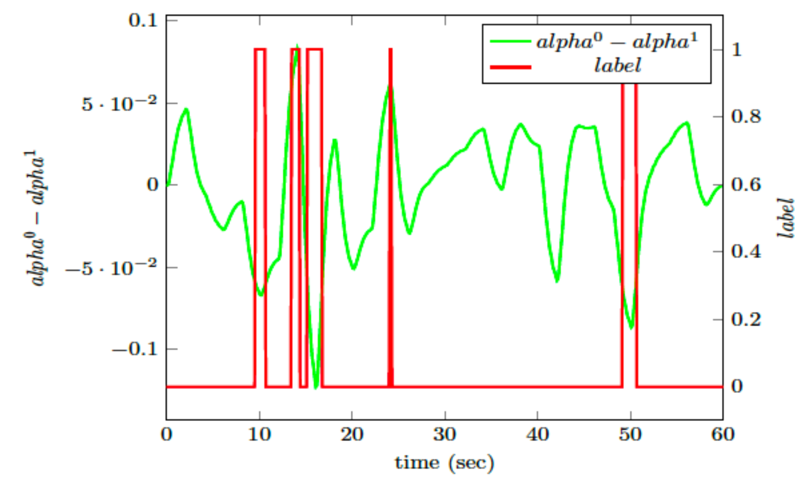
Human readable

System independent

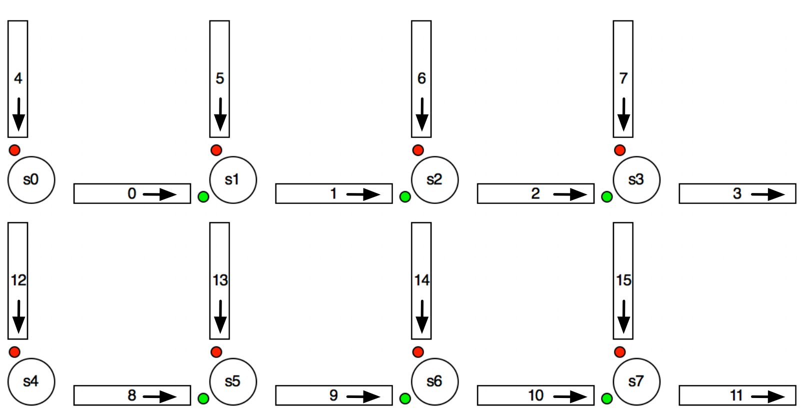
Accurate representation

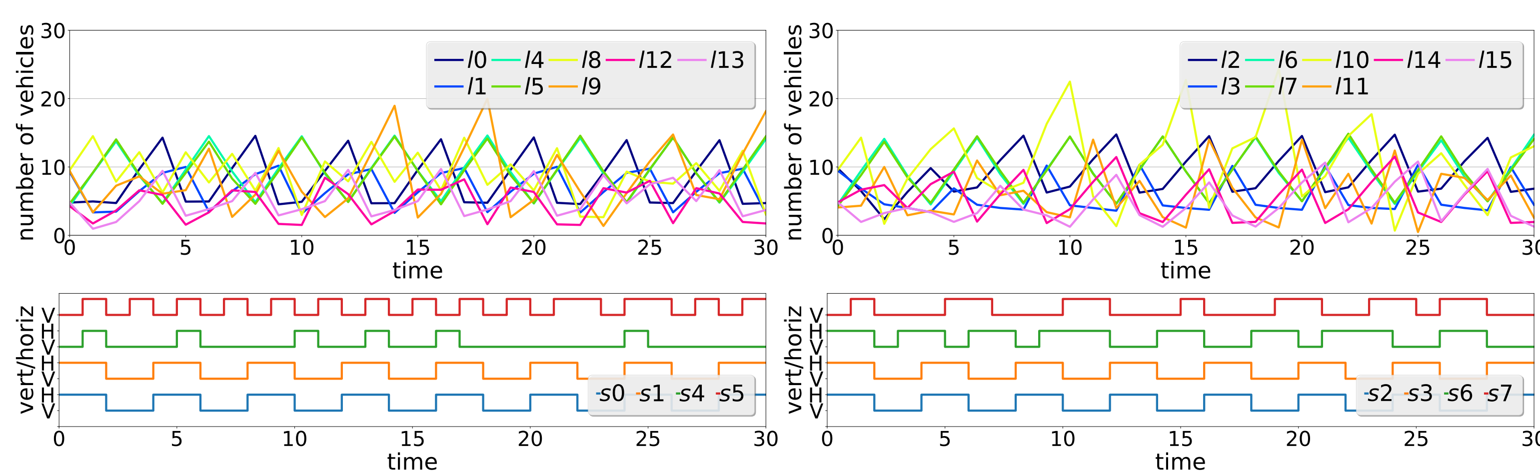




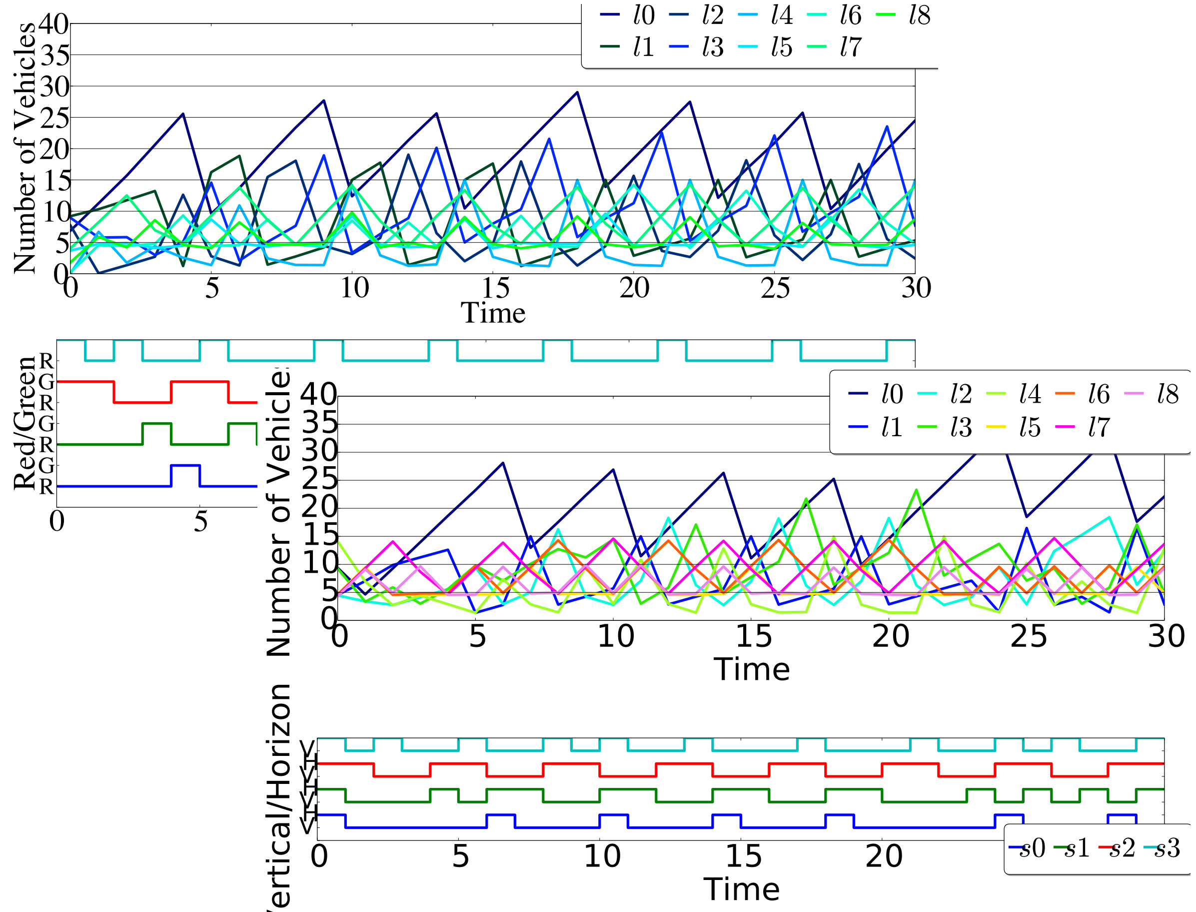


Can we describe the cause of the undesired event?





Our Approach in a Nutshell

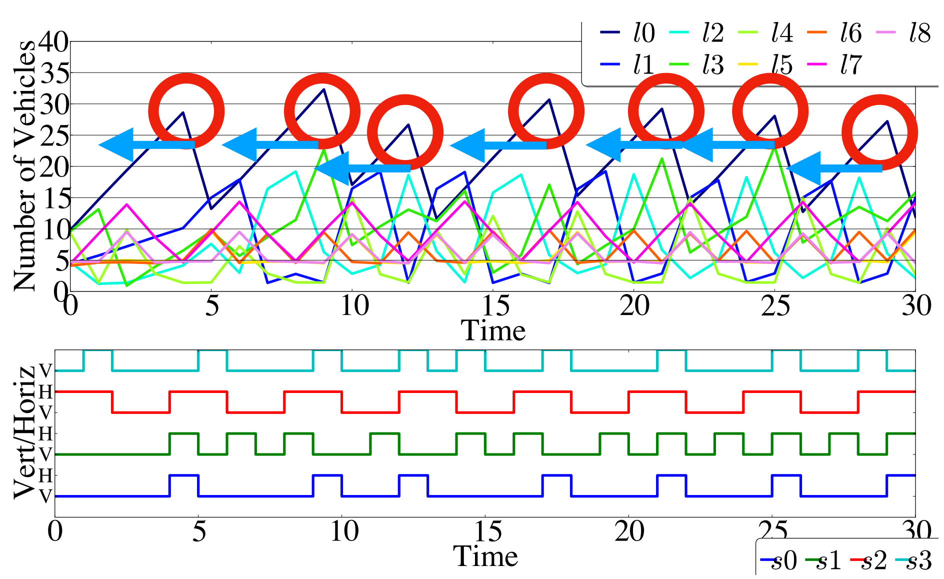


$$\phi = \phi_1 \vee \phi_2 \vee \phi_3$$

$$\phi_1 = \mathbf{P}_{[1,1]}((x^1 > 15) \wedge (s^1 = 1) \wedge (s^0 = 0))$$

$$\phi_2 = \mathbf{P}_{[1,1]}((x^1 > 25) \wedge (s^1 = 1))$$

$$\phi_3 = \mathbf{P}_{[1,1]}((x^4 < 10) \wedge (s^1 = 1) \wedge (s^0 = 0))$$

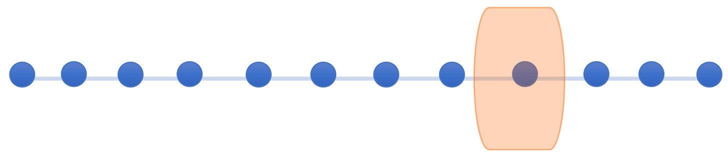


Outline

- Temporal logics
- Problem Definition
- Greedy Search for Formula Synthesis
- Iterative Search for Formula Synthesis
- Search for Controllable Formula
- Discussion

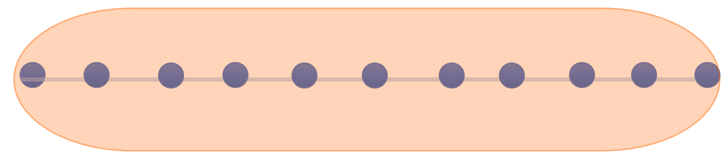
Linear Temporal Logic

Eventually ***a***



F a

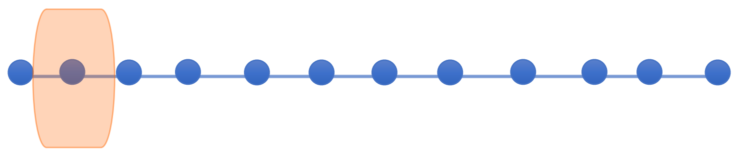
Globally ***a***



G a

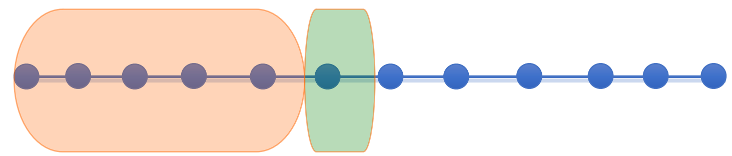
G (request → F response)

Next ***a***



X a

a Until ***b***



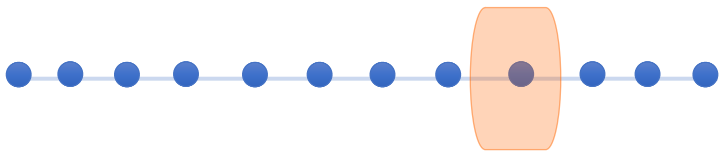
a U b

$$\phi = T \mid F\ \phi \mid G\ \phi \mid \phi U\ \phi \mid X\ \phi \mid \phi \wedge \phi \mid \phi \vee \phi \mid \neg \phi$$

Boolean operators: $\wedge$, $\vee$, $\neg$
Temporal operators: F, G, U, X

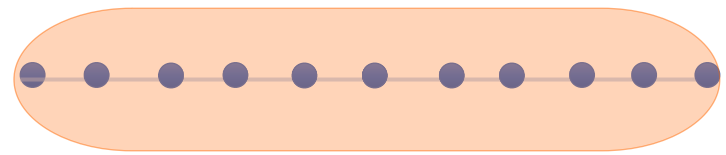
Linear Temporal Logic

Eventually ***a***



F a

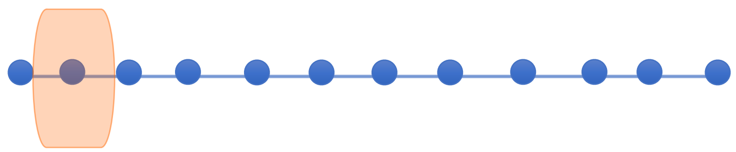
Globally ***a***



G a

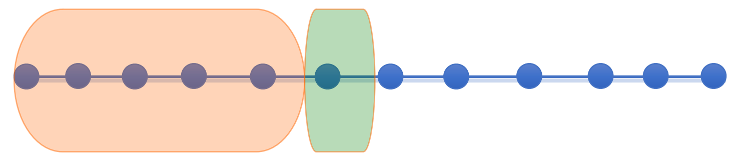
G (request → F grant)

Next ***a***



X a

a Until ***b***



a U b

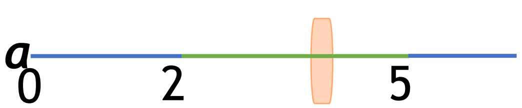
$$\phi = T \mid F\ \phi \mid G\ \phi \mid \phi U\ \phi \mid X\ \phi \mid \phi \wedge \phi \mid \phi \vee \phi \mid \neg \phi$$

Boolean operators: $\wedge$, $\vee$, $\neg$

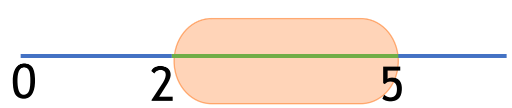
Temporal operators: F, G, U, X

Metric Temporal Logic

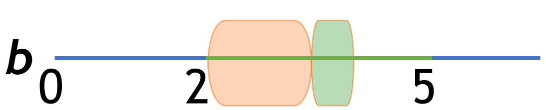
$F_{[2,5]}\ a$



$G_{[2,5]}\ a$



$a\ U_{[2,5]}\ b$

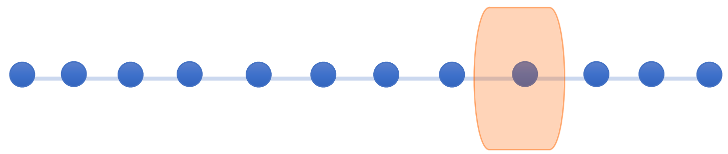


Real time, boolean predicates

$G_{[0,t]}$ (r → $F_{[0,\,c]}$ g)

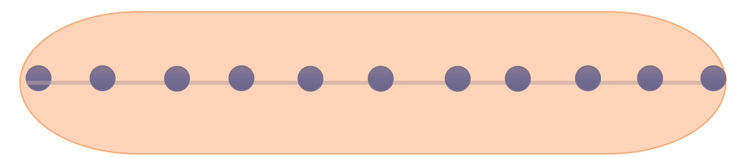
Linear Temporal Logic

Eventually ***a***



F a

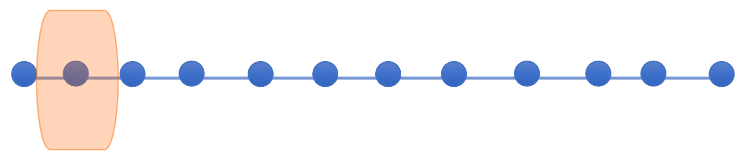
Globally ***a***



G a

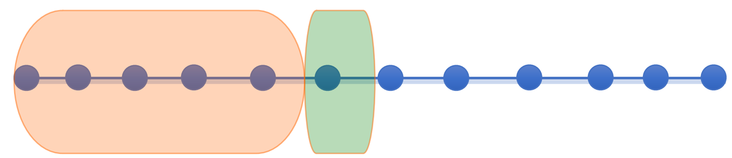
G (request → F grant)

Next ***a***



X a

a Until ***b***



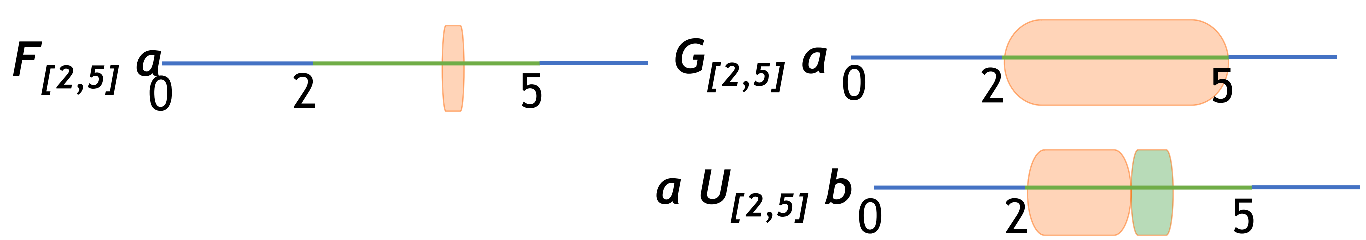
a U b

$$\phi = T \mid F\ \phi \mid G\ \phi \mid \phi U\ \phi \mid X\ \phi \mid \phi \wedge \phi \mid \phi \vee \phi \mid \neg \phi$$

Boolean operators: $\wedge\ ,\ \vee\ ,\ \neg$

Temporal operators: F, G, U, X

Metric Temporal Logic



Real time, boolean predicates

$G_{[0,t]}$ (r → $F_{[0,\ c]}$ g)

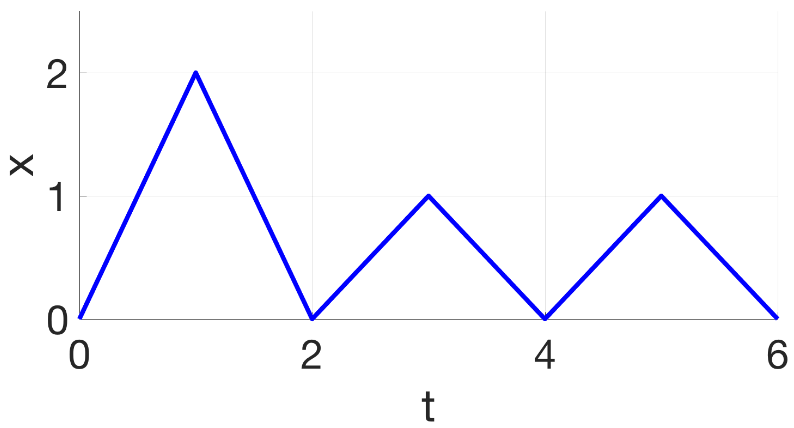
Signal Temporal Logic

Real time, real valued predicates

$G_{[0,T]}$ (r[t] > 0 → $F_{[0,\ D]}$ g[t] > 0)

Signal Temporal Logic

- Predicates are over real values (signals), real time
- Allows for quantitative semantics



$$\phi = T \mid \phi_1 U_{[a,b]}\, \phi_2 \mid \phi_1 \wedge \phi_2 \mid \neg\phi \mid x < c$$

$$F_{[a,b]}\phi = T U_{[a,b]}\phi$$

$$G_{[a,b]}\phi = \neg(F_{[a,b]}\neg\phi)$$

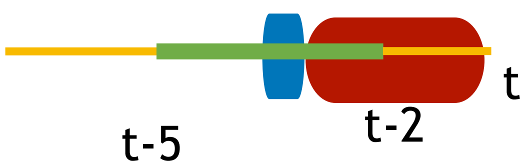
Past Time Signal Temporal Logic

$$\phi = T \mid \phi_1 S_{[a,b]}\ \phi_2 \mid \phi_1 \wedge \phi_2 \mid \neg\phi \mid x < c$$

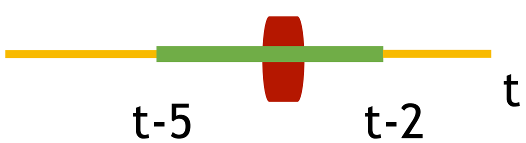
$$P_{[a,b]}\phi = T\ S_{[a,b]}\phi$$

$$A_{[a,b]}\phi = \neg(P_{[a,b]}\neg\phi)$$

$a\ S_{[2,5]}\ b$



$P_{[2,5]}\ a$



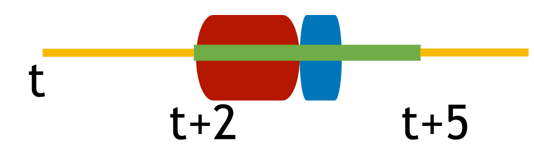
$A_{[2,5]}\ a$

$$\phi = T \mid \phi_1 U_{[a,b]}\ \phi_2 \mid \phi_1 \wedge \phi_2 \mid \neg\phi \mid x < c$$

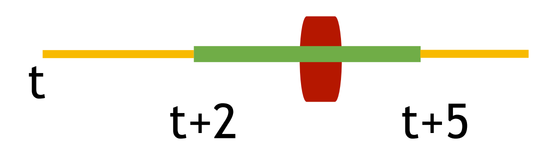
$$F_{[a,b]}\phi = T\ U_{[a,b]}\phi$$

$$G_{[a,b]}\phi = \neg(F_{[a,b]}\neg\phi)$$

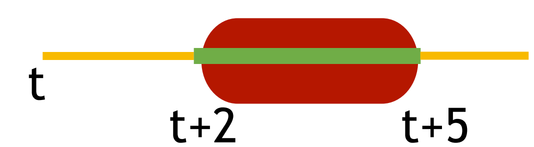
$a\ U_{[2,5]}\ b$



$F_{[2,5]}\ a$



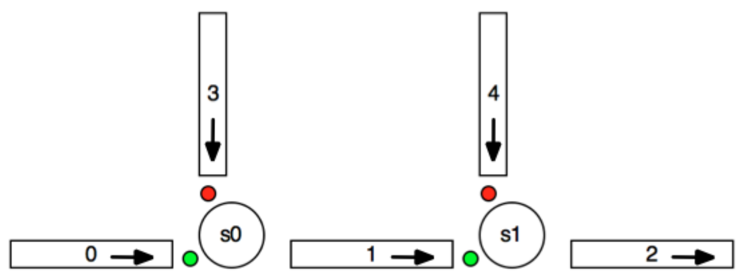
$G_{[2,5]}\ a$

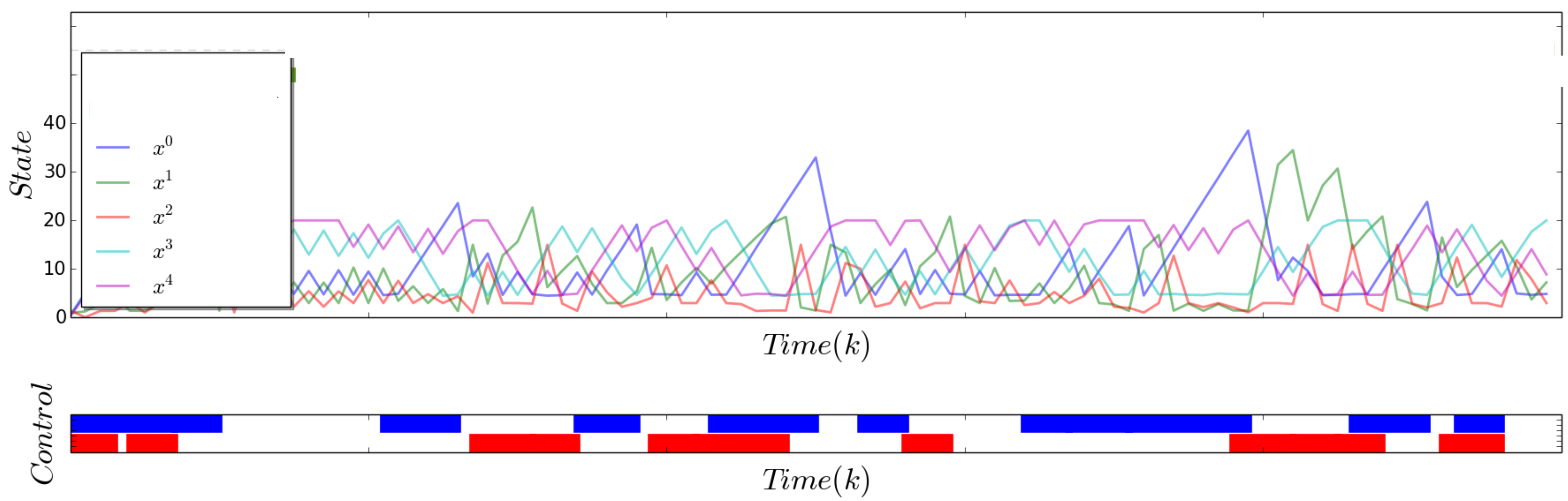


Problem Formulation

$$x_l[t+1] = x_l[t] + d_l[t] - f_l^{out}(x_l[t]) + \sum_{k \in \mathcal{L}_v^{out}} \beta_{kl} f_k^{out}(x_k[t])$$

Given a system and a function over the signals for labeling unwanted events, find the cause of these events.



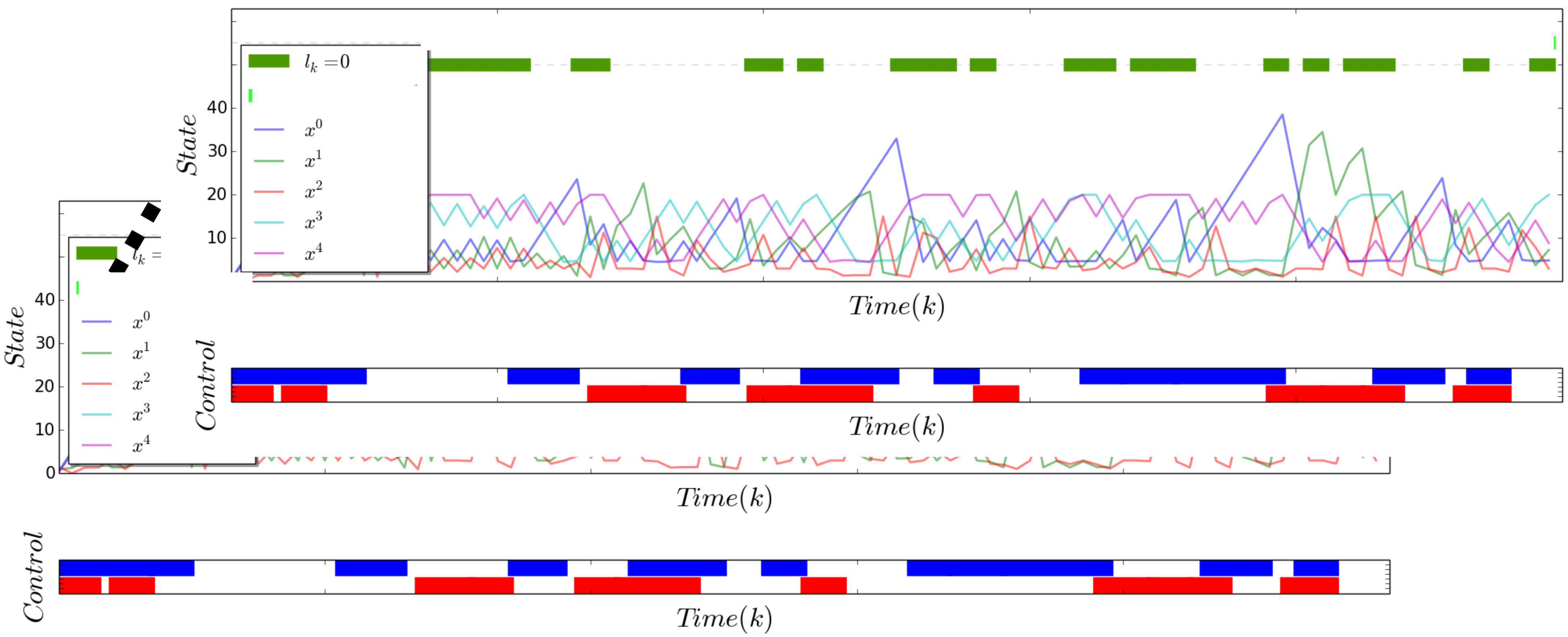


1 - Simulate
2 - Label the traces
3 - Find the reason

Given a set of labeled signals, find a ptSTL formula describing the labeled events

Problem Formulation

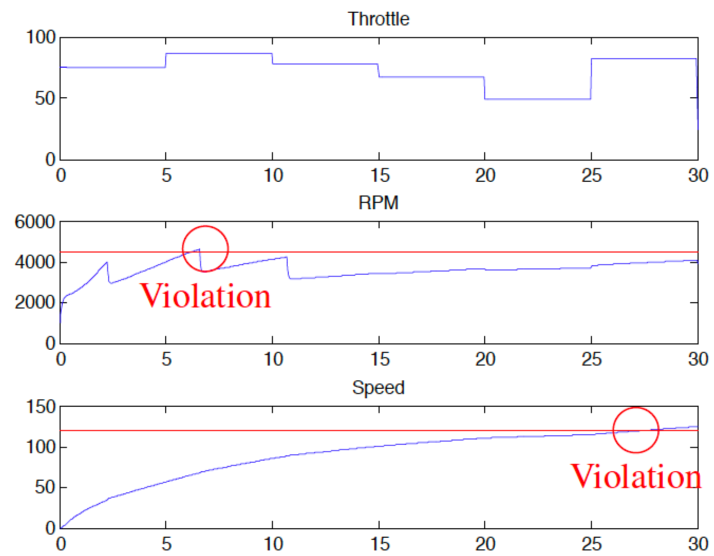
Given a set of labeled signals, find a ptSTL formula describing the labeled events



$$D = \{(T, L) \mid T = (t_0, x_0), \ldots, (t_n, x_n), L = (t_0, l_0), \ldots, (t_n, l_n)\}$$

$$(L, t) = 1 \qquad (T, t) \models \phi$$

Literature on Formula Synthesis



X. Jin, A. Donzé, J. V. Deshmukh and S. A. Seshia, "Mining Requirements From Closed-Loop Control Models," in *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*

"…find formulas defining signals as tight as possible…"

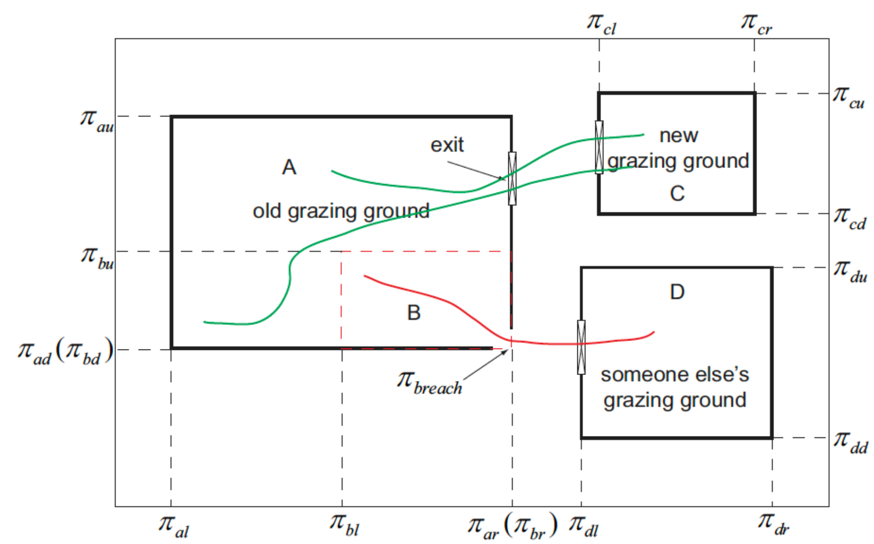


Figure 1: A herding example. The desired behaviors are shown in green, while the undesired ones are shown in red.

"…formula that can discriminate between the desirable behaviors and the undesirable ones is constructed…"

Zhaodan Kong, Austin Jones, Ana Medina Ayala, Ebru Aydin Gol and Calin Belta ,**Temporal Logic Inference for Classification and Prediction from Data**, Hybrid Systems: Computation and Control (HSCC), Berlin, Germany, 2014

Decision Tree Based approaches:

Giuseppe Bombara, Cristian Vasile, Francisco Penedo, Hirotoshi Yasuoka, Calin Belta, **A Decision Tree Approach to Data Classification using Signal Temporal Logic**, Hybrid Systems: Computation and Control (HSCC), Vienna, Austria, 2016

Ahmet Ketenci, Ebru Aydin Gol. **Synthesis of Monitoring Rules via Data Mining**. American Control Conference (ACC), Philadelphia, PA. 2019.

Susmit JhaAshish TiwariSanjit A. SeshiaTuhin SahaiNatarajan Shankar, **TeLEx: learning signal temporal logic from positive examples using tightness metric.** Formal Methods in System Design, 2019

"…to infer signal temporal logic (STL) formulas that characterize the behavior of a dynamical system using only observed signal traces of the system …"

E. Bartocci, L. Bortolussi, and G. Sanguinetti. **Data-driven statistical learning of temporal logic properties.** In Formal Modeling and Analysis of Timed Systems, pages 23{37. Springer, 2014.

Problem Formulation

Given a set of labeled signals, find a ptSTL formula describing the labeled events

$$D = \{(T, L) \mid T = (t_0, x_0), \ldots, (t_n, x_n), L = (t_0, l_0), \ldots, (t_n, l_n)\}$$

$(L, t) = 1$

$(T, t) \vDash \phi$

$$TP(D, \phi) = \sum_{(T,L)\in D} \sum_{t=0}^{n} \begin{cases} 1 \textbf{ if } l_i = 1 \textbf{ and } (T, t) \vDash \phi \\ 0 \textbf{ otherwise} \end{cases}$$

$(L, t) = 1$

$(T, t) \vDash \neg\phi$

$$FN(D, \phi) = \sum_{(T,L)\in D} \sum_{t=0}^{n} \begin{cases} 1 \textbf{ if } l_i = 1 \textbf{ and } (T, t) \vDash \neg\phi \\ 0 \textbf{ otherwise} \end{cases}$$

$(L, t) = 0$

$(T, t) \vDash \neg\phi$

$$TN(D, \phi) = \sum_{(T,L)\in D} \sum_{t=0}^{n} \begin{cases} 1 \textbf{ if } l_i = 0 \textbf{ and } (T, t) \neg \vDash \phi \\ 0 \textbf{ otherwise} \end{cases}$$

$(L, t) = 0$

$(T, t) \vDash \neg\phi$

$$FP(D, \phi) = \sum_{(T,L)\in D} \sum_{t=0}^{n} \begin{cases} 1 \textbf{ if } l_i = 0 \textbf{ and } (T, t) \vDash \phi \\ 0 \textbf{ otherwise} \end{cases}$$

Evaluation

Label		1	0
	1	TP	FN
	0	FP	TN

Problem Formulation

Given a set of labeled signals, find a ptSTL formula describing the labeled events

$$D = \{(T, L) \mid T = (t_0, x_0), \ldots, (t_n, x_n), L = (t_0, l_0), \ldots, (t_n, l_n)\}$$

Evaluation

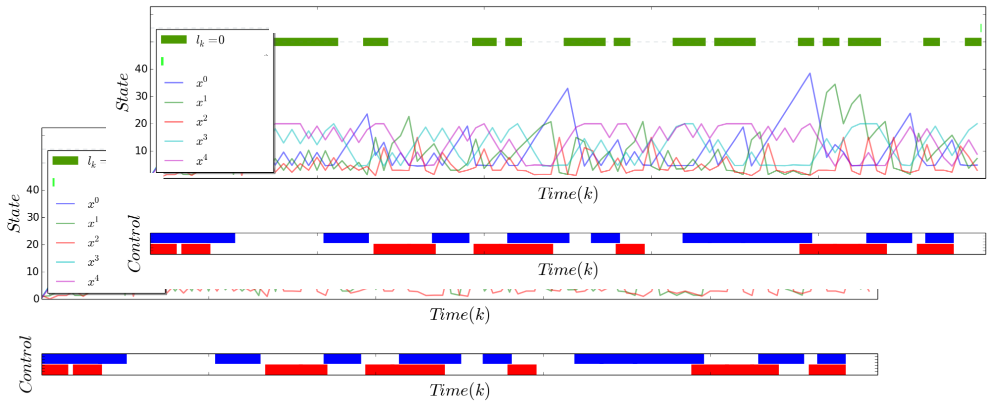
Label		1	0
	1	TP	FN
	0	FP	TN

FN + FP —> 0

$$\phi$$

Name	Abbreviation	Equation
Mismatch	M	FP + FN
Precision	P	TP/(TP+FP)
Recall	R	TP/(TP+FN)
F beta	Fb	$(1+b^2)$ P R / (b^2 P + R)

Greedy Search for Formula Synthesis



Find ϕ minimizing cost

$$\phi = T \mid \phi_1 S_{[a,b]} \phi_2 \mid \phi_1 \wedge \phi_2 \mid \neg \phi \mid P_{[a,b]} \phi \mid A_{[a,b]} \phi \mid x_i \leq c \mid x_i \geq c$$

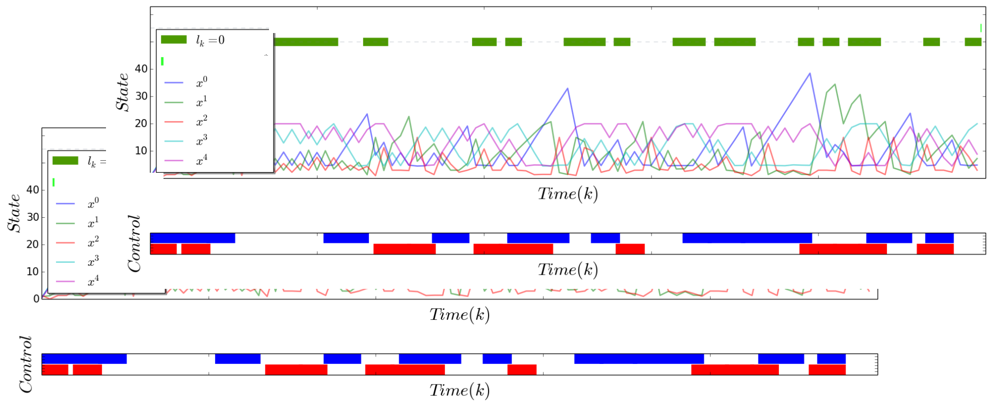
$$A_{[a,b]} x_i \geq c \qquad A_{[0,50]} x_1 \geq 20$$

$$P_{[a,b]} x_i \leq c \qquad P_{[0,20]} x_2 \leq 0$$

Parameter synthesis

Who will write the template formula?

Greedy Search for Formula Synthesis



Find ϕ minimizing cost

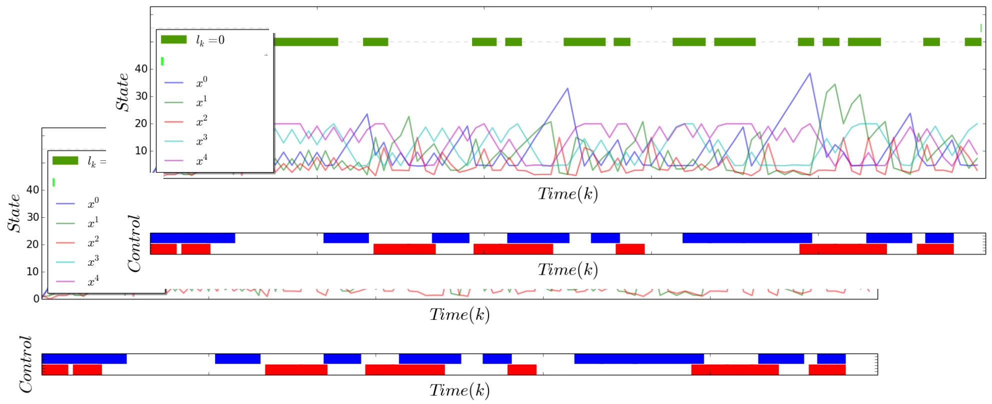
$$\phi = T \mid \phi_1 S_{[a,b]}\ \phi_2 \mid \phi_1 \wedge \phi_2 \mid \neg\phi \mid P_{[a,b]}\phi \mid A_{[a,b]}\phi \mid x^i \leq c \mid x^i \geq c$$

$$\mathscr{F}^0 = \{x^i \sim p_i \mid \sim \in \{ <, > \}, i = 1,\ldots,N\} \cup \{\mathbf{T}\}$$

$$\begin{aligned}\mathscr{F}^n = & \{\neg\phi \mid \phi \in \mathscr{F}^{n-1}\} \\ & \cup \{P_{[p_a,p_b]}\phi \mid \phi \in \mathscr{F}^{n-1}\} \\ & \cup \{A_{[p_a,p_b]}\phi \mid \phi \in \mathscr{F}^{n-1}\} \\ & \bigcup_{i=1}^{n-1} \{\phi_1 \ \wedge \phi_2 \mid \phi_1 \in \mathscr{F}^i, \phi_2 \in \mathscr{F}^{n-i-1}\} \\ & \bigcup_{i=1}^{n-1} \{\phi_1 \ \vee \phi_2 \mid \phi_1 \in \mathscr{F}^i, \phi_2 \in \mathscr{F}^{n-i-1}\} \\ & \bigcup_{i=1}^{n-1} \{\phi_1 S_{[p_a,p_b)} \phi_2 \mid \phi_1 \in \mathscr{F}^i, \phi_2 \in \mathscr{F}^{n-i-1}\}\end{aligned}$$

$$\mathscr{F}^{\leq n} = \cup_{i=0}^{n} \mathscr{F}^i$$

Greedy Search for Formula Synthesis



Find ϕ minimizing cost

$$\mathscr{F}^{\leq n} = \cup_{i=0}^{n} \mathscr{F}^{i}$$

Given an operator limit, run parameter optimization for each

$$\phi^{p} \in \mathscr{F}^{\leq n}$$

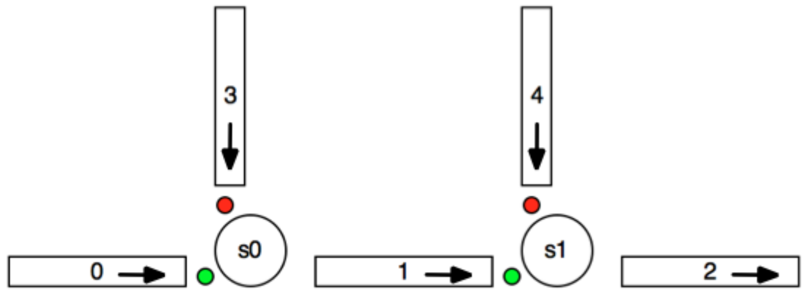
$$\phi = T \mid \phi_1 S_{[a,b]}\, \phi_2 \mid \phi_1 \wedge \phi_2 \mid \neg \phi \mid P_{[a,b]}\phi \mid A_{[a,b]}\phi \mid x^i \leq c \mid x^i \geq c$$

Parameter	Limits	
c^i	Lc^i	Uc^i
a	La	Ua
b	La	Ub

Given a parametric formula ϕ^{p}, and parameter limits, run grid search.

Mert Ergurtuna, Ebru Aydin Gol. An Efficient Formula Synthesis Method with Past Signal Temporal Logic. 5th IFAC International Conference on Intelligent Control and Automation Science, (ICONS) 2019

Greedy Search for Formula Synthesis - Example



$$x^0, x^1, x^2, x^3, x^4, s^0, s^1$$

$$x^0, x^1, x^2 \in [0,40]$$
$$x^3, x^4 \in [0,20]$$
$$s^0, s^1 \in \{0,1\}$$

Minimize F 0.3

Simulate, assign label 1 when a link has more vehicles than %75 of its capacity

$$x^0 < 30 \wedge x^1 < 30 \wedge x^2 < 30 \wedge x^3 < 15 \wedge x^4 < 15$$

Identify it, before it happens: $P_{[1,1]}\phi^p, \phi^p \in \mathcal{F}^{\leq n}$

Operator count limit 0 (x^i </> c), 14 formulas.

$P_{[1,1]} s_0 = 0$ `fp: 307 fn: 256 tp: 599 tn: 638, f03: 0.664`

Operator count limit 1, 14 + 156 formulas.

DOES NOT SCALE

$P_{[1,1]}(x^3 \geq 10.0 \wedge s^0 = 0)$ `fp: 0 fn: 375 tp: 480 tn: 945, f03: 0.939`

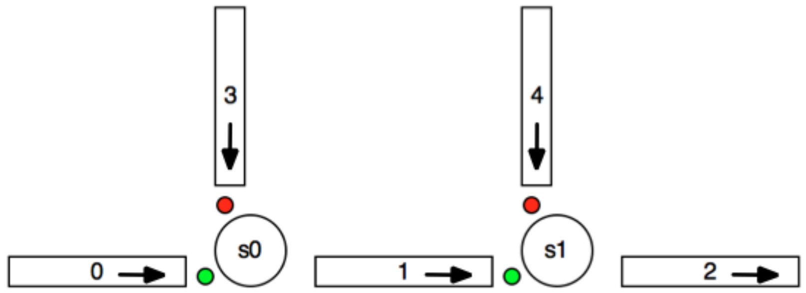
Operator count limit 2, 14 + 156 + 5532 formulas.

$P_{[1,1]}(x^3 \geq 10.0 \wedge s^0 = 0)$ `fp: 0 fn: 375 tp: 480 tn: 945, f03: 0.939`

Operator count limit3, 14 + 156 + 5532 + 96414 formulas.

$P_{[1,1]}((x^4 \geq 10 \wedge s^1 = 0) \vee (x^3 \geq 10 \wedge s^0 = 0))$ `fp: 0 fn: 70 tp: 785 tn: 945, f03:0.993`

Greedy Search for Formula Synthesis - Example



$$x^0, x^1, x^2, x^3, x^4, s^0, s^1$$

$$x^0, x^1, x^2 \in [0,40]$$
$$x^3, x^4 \in [0,20]$$
$$s^0, s^1 \in \{0,1\}$$

Minimize F 0.3

Simulate, assign label 1 when a link has more vehicles than %75 of its capacity

$$x^0 < 30 \wedge x^1 < 30 \wedge x^2 < 30 \wedge x^3 < 15 \wedge x^4 < 15$$

$$P_{[1,1]}((x^4 \geq 10 \wedge s^1 = 0) \vee (x^3 \geq 10 \wedge s^0 = 0))$$

```
fp: 0 fn: 70 tp: 785 tn: 945, f03:0.993
```

misclassification rate: 3.9 %

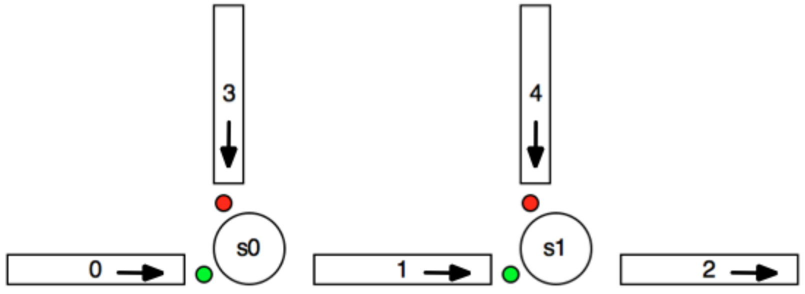
- There can be multiple causes.
- Increasing the operator count does not scale.

Iterative Formula Search-Heuristic 1

- There can be multiple causes.
- Increasing the operator count does not scale.
- Iterative cause finding ?

THE IDEA

- Given upper and lower bounds on operator count
- Found formulas: $\Phi^\star = False$
- Start with n=lower bound, until n > upper bound
  - For each $\phi^p \in \mathscr{F}^n$
    - Perform parameter optimization for $P_{[1,1]}(\phi^p \vee \Phi^\star)$
  - Get the optimal one $\phi^\star$
    - If there is sufficient improvement, update the found formula $\Phi^\star = \Phi^\star \vee \phi^\star$
    - Otherwise increment n



1 n=0, best formula $P_{[1,1]} s_0 = 0$ `f03: 0.664`

Insufficient, increment n

2 n=1, best formula $P_{[1,1]}(x^3 \geq 10.0 \wedge s^0 = 0)$ `f03: 0.939`

Update $\Phi^\star = P_{[1,1]}(x^3 \geq 10.0 \wedge s^0 = 0)$

3 n=1, best formula $P_{[1,1]}(x^4 \geq 10.0 \wedge s^1 = 0)$ `f03: 0.993`

valuation of the combined formula

Update $\Phi^\star = P_{[1,1]}((x^3 \geq 10.0 \wedge s^0 = 0) \vee (x^4 \geq 10.0 \wedge s^1 = 0)$

4 n=1, best formula $P_{[1,1]}(x^0 \geq 25 \wedge s^1 = 1)$ `f03: 0.995`

Insufficient, increment n

fp: 0 fn: 70 tp: 785 tn: 945

Iterative Formula Search-Heuristic 2

- There can be multiple causes.
- Increasing the operator count does not scale.
- Iterative cause finding ?

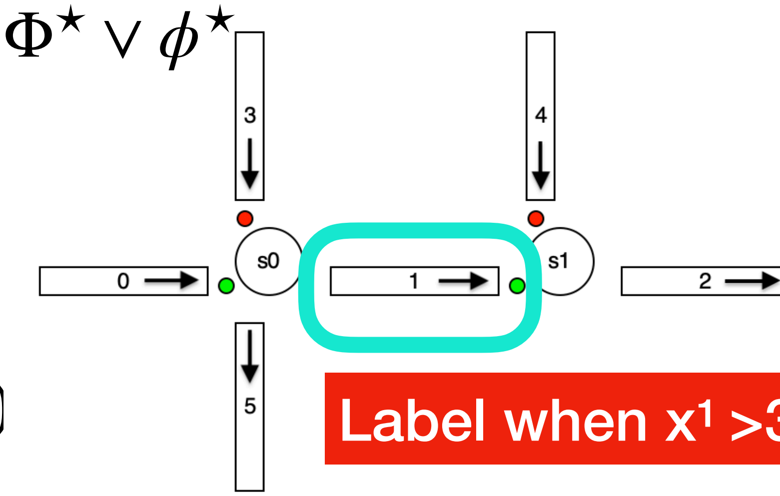
THE IDEA

Optimization is performed once

Monotonic

- Given upper bound on operator count n
- Found formulas: $\Phi^\star = False$
- For each $\phi^p \in \mathscr{F}^n$
  - Perform parameter optimization for $P_{[1,1]}\phi^p$
- While the sub-formula limit is not exceeded
  - Select $\phi^\star$ maximizing $TP(\Phi^\star \vee \phi^\star)$ and set $\Phi^\star = \Phi^\star \vee \phi^\star$
  - Stop when the improvement is insufficient

Maximize TP limit FP



Label when $x^1 > 30$

1 First iteration $\phi_1 = P_{[1,1]}(x^1 > 15 \wedge s^0 = 0 \wedge s^1 = 1)$

2 Second iteration $\phi_2 = P_{[1,1]}(x^1 \geq 25 \wedge s^1 = 1)$

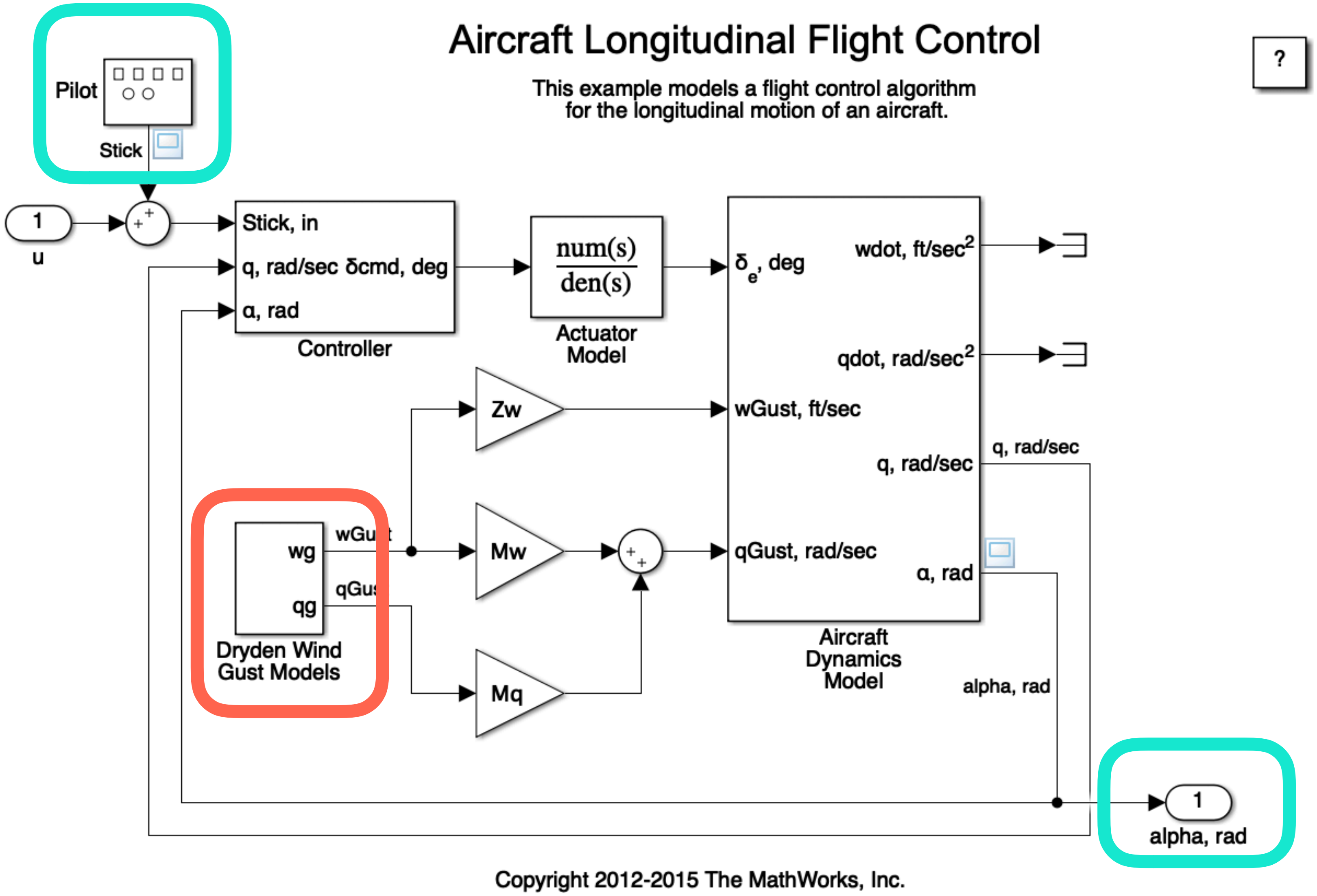
FP limit 20

3 Third iteration $\phi_3 = P_{[1,1]}(x^4 \leq 10 \wedge s^0 = 0 \wedge s^1 = 1)$

$\phi_1 \vee \phi_2 \vee \phi_3$ **fp: 30 fn: 2 tp: 454 tn: 1314, mr = 1.8%**

Computation: a few minutes

Iterative Formula Search-Heuristic 2 - Example

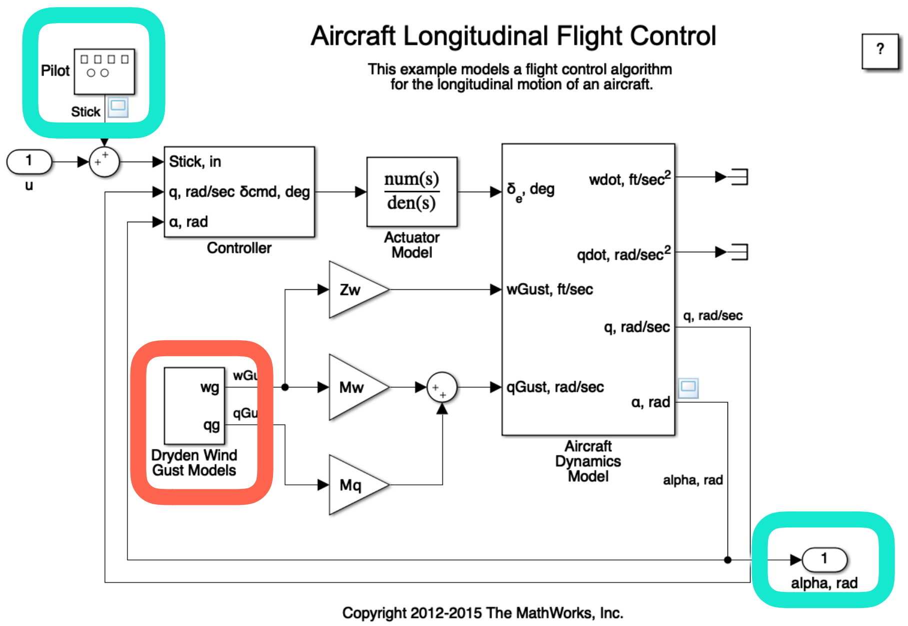


When the aircraft's longitudinal motion disturbs?

alpha⁰ : no wind

alpha¹ : wind (random)

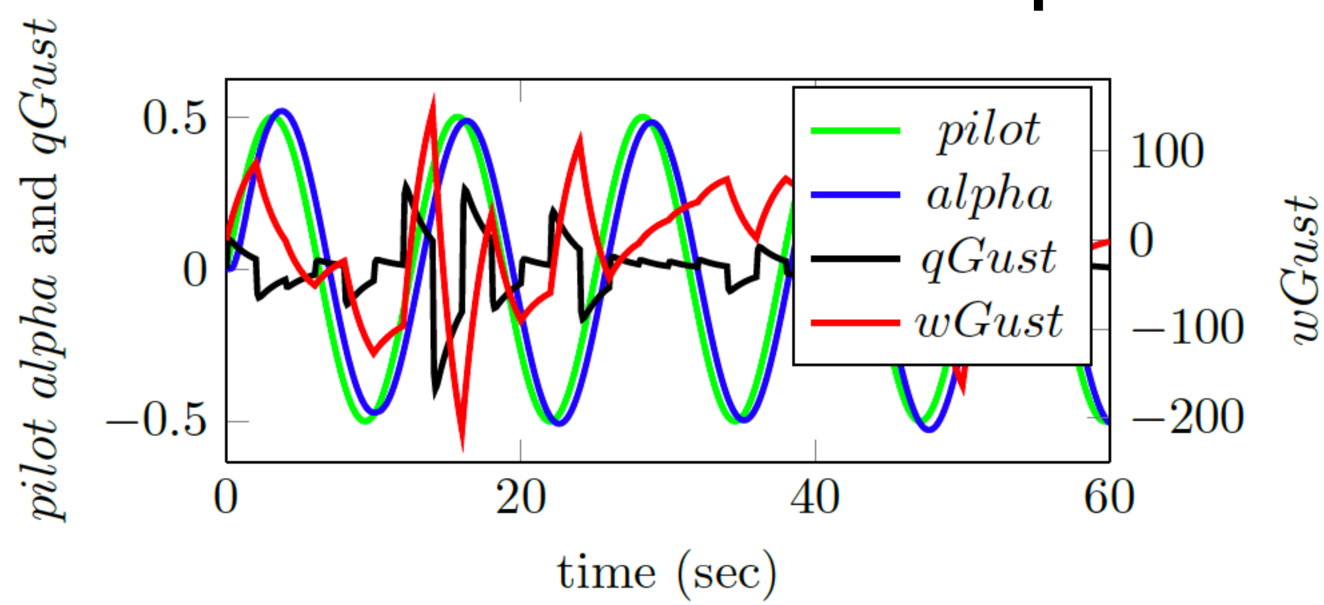
Iterative Formula Search-Heuristic 2 - Example

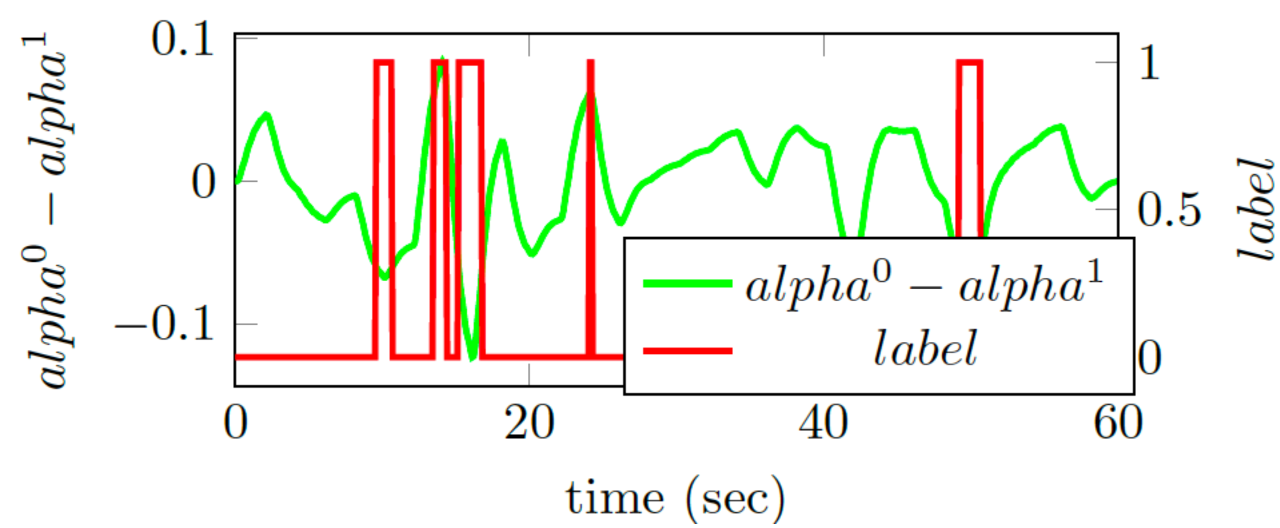


alpha^0 : no wind
alpha^1 : wind (random)

When the aircraft's longitudinal motion disturbs?

alpha^1



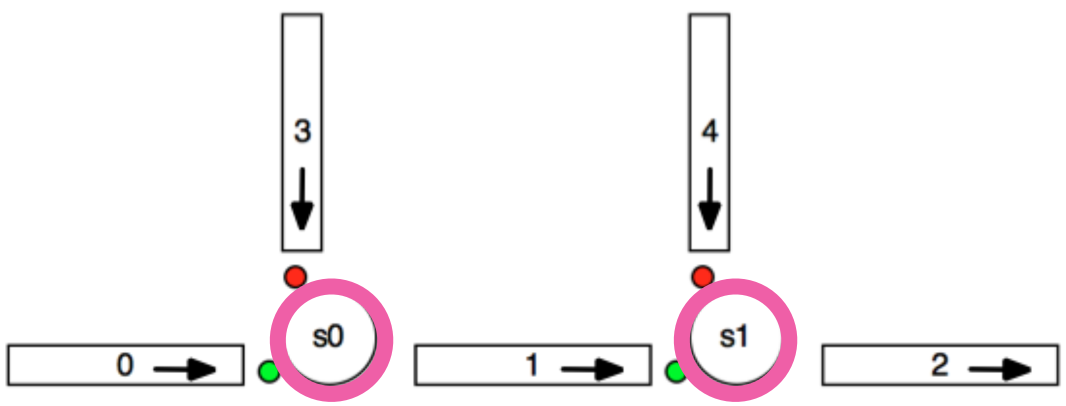


1. $\phi_1 = P_{[4,10]}(qGust \leq 0 \wedge wGust \leq -120)$
2. $\phi_2 = wGust \geq 120 \wedge A_{[14,14]}(pilot \geq -0.4)$
3. $\phi_3 = P_{[2,2]}(alpha \leq 0.3 \wedge wGust - \leq 120)$
4. $\phi_4 = (A_{[2,6]} qGust \geq 0.1) \wedge pilot \leq -0.4$

$\phi_1 \vee \phi_2 \vee \phi_3 \vee \phi_4$ **fp: 18 fn: 58 tp: 419 tn: 2505, mr=2.5%**

Controllable Formula Search (*ongoing work*)

Find the cause and update the system to avoid it in fully automated way.



s^0 and s^1 are controllable

$\Phi_1 \vee \ldots \vee \Phi_p$

$\Phi_i := (A_{[1,b_i]} u^j = c_i) \wedge (P_{[1,1]} \phi_i)$

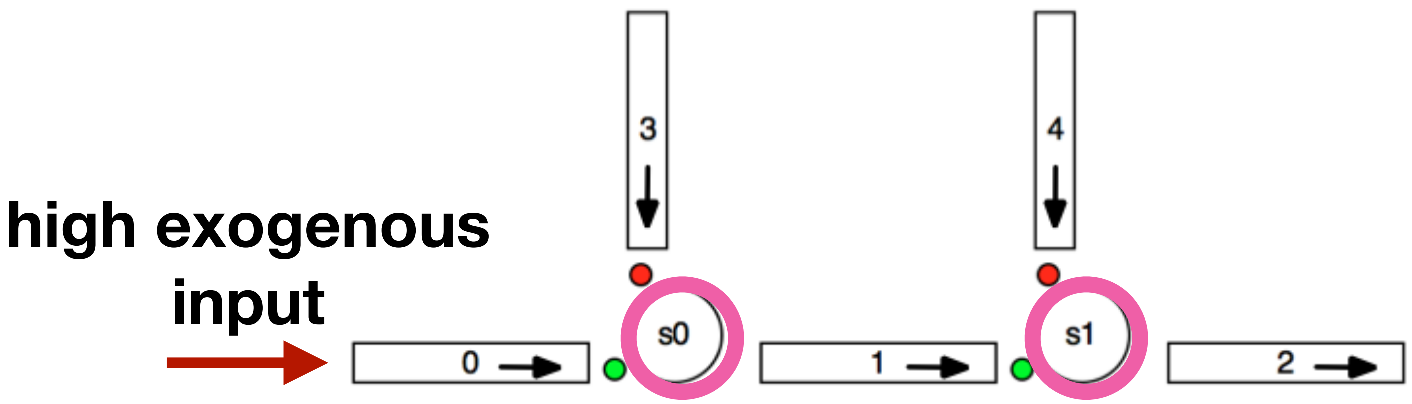
Controller: Select u that violates each cause

$\mathbb{U}^{cand} = \mathbb{U}$
while $\mathbb{U}^{cand} \neq \emptyset$ **do**
    $u_k = Random(\mathbb{U}^{cand})$
    if $(\mathbf{x}, (x_k, u_k), k) \models (G^{-}_{[0,b_i-1]} u^j = c_i) \wedge \phi_i$ for some Φ_i from Φ **then**
        $\mathbb{U}^{cand} = \mathbb{U}^{cand} \setminus \{u_k\}$
    else **return** u_k
    end if
end while
return $Random(\mathbb{U})$

ITERATIVELY

Find cause
Synthesize controller
Simulate-label

Controllable Formula Search (*ongoing work*)



$$\Phi_1 \vee \ldots \vee \Phi_p$$

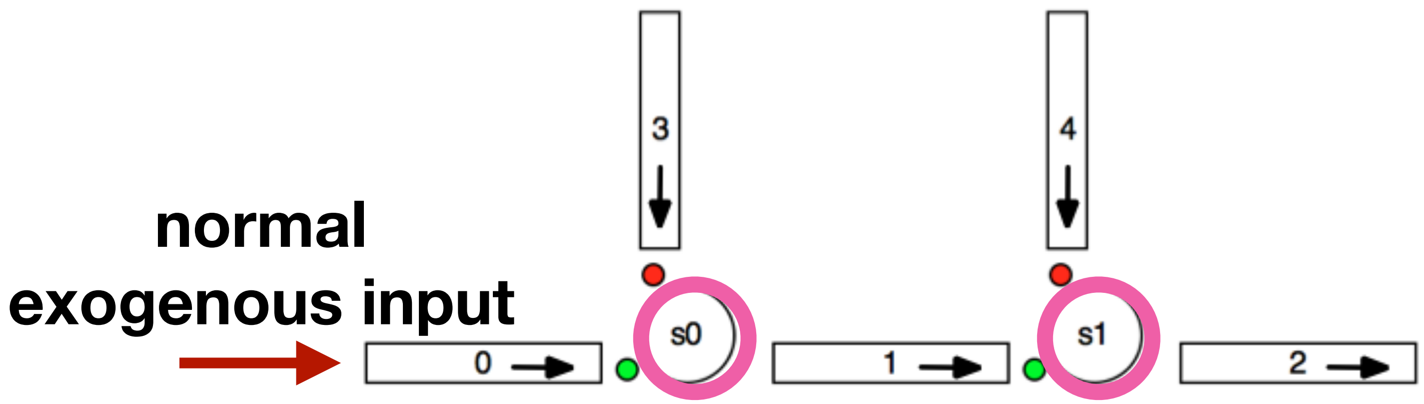
$$\Phi_i := (A_{[1,b_i]} u^j = c_i) \wedge (P_{[1,1]} \phi_i)$$

%79 percent congestion

i	Viol Count	Φ_i	tp	fp
1	1591	$A_{[1,2]}(s^0 = 1) \wedge P_{[1,1]}(x^0 > 20)$	405	0
2	1549	$A_{[1,2]}(s^0 = 0) \wedge P_{[1,1]}(x^3 > 10)$	576	0
3	1557	$A_{[1,2]}(s^1 = 0) \wedge P_{[1,1]}(x^1 > 20)$	465	19
4	1763	$A_{[1,2]}(s^1 = 1) \wedge P_{[1,1]}(x^4 > 10)$	599	3
5	2			

S. Coogan, E. A. Gol, M. Arcak, and C. Belta. Traffic network control from temporal logic specifications, IEEE TCNS (2016)

Controllable Formula Search (*ongoing work*)



$$\Phi_1 \vee \ldots \vee \Phi_p$$

$$\Phi_i := (A_{[1,b_i]} u^j = c_i) \wedge (P_{[1,1]} \phi_i)$$

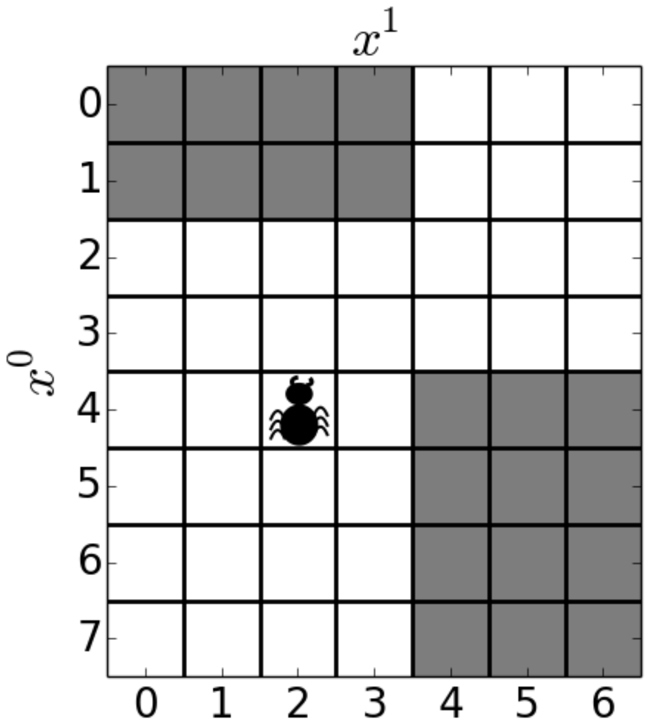
$Ex\#$	time	v_0	v_1	v_2	v_3	v_4	v_5	v_6	v_7
#1	630sec	143	23	5	2	1	0	-	-
#2	320sec	911	530	265	5	6	2	0	-
#3	115sec	911	617	149	80	70	48	10	0

$Ex\#$	$\underline{oc}$	$\overline{oc}$	$\overline{p}$	$\underline{val}$
#1	0	∞	∞	0.01
#2	0	∞	∞	0.1
#3	0	0	1	0

No formal guarantees, but much faster compared to[1], and applicable to any system

S. Coogan, E. A. Gol, M. Arcak, and C. Belta. Traffic network control from temporal logic specifications, IEEE TCNS (2016)

Controllable Formula Search - Robotic Example



$\Phi_1 \vee \ldots \vee \Phi_p$

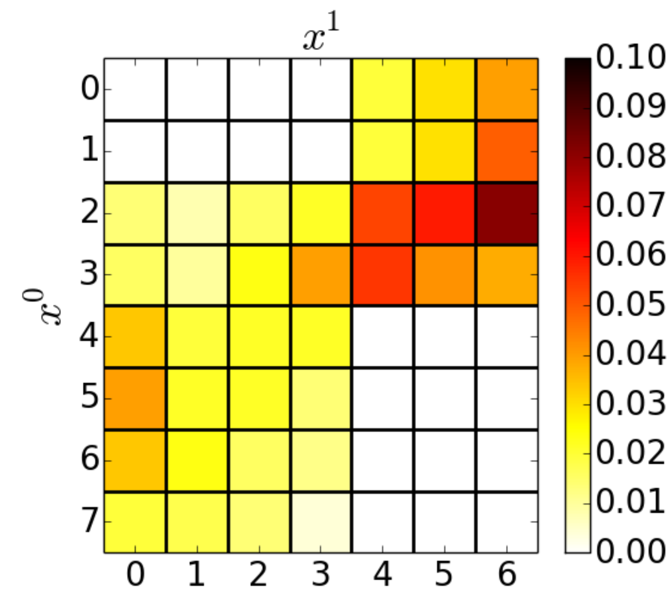
$\Phi_i := (A_{[1,b_i]} u^j = c_i) \wedge (P_{[1,1]} \phi_i)$

Random walk, label - 1 when hits an obstacle

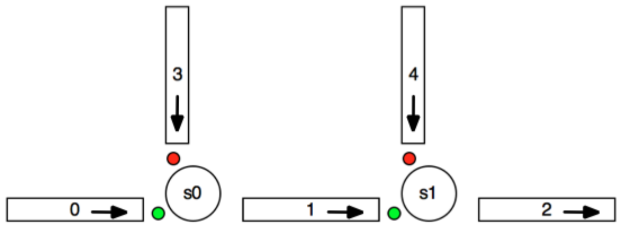
Control actions: S,N,E,W

ongoing work: Generalize control formula with automata based controller.

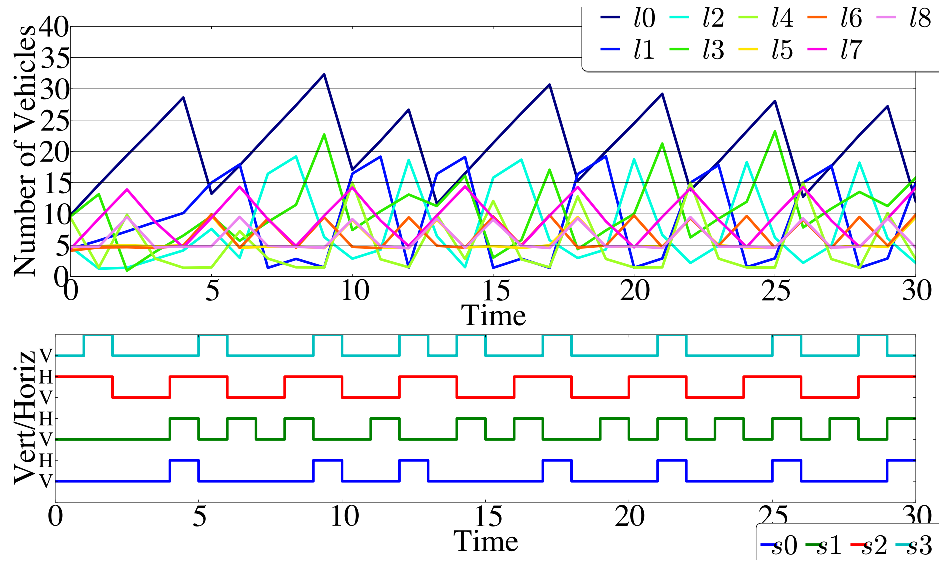
i	v_i	Φ_i	tp	fp
1	705	$(G^-_{[1,1]} u = S) \wedge (F^-_{[1,1]}(x^1 > 3 \wedge x^0 > 2))$	126	0
2	429	$(G^-_{[1,1]} u = N) \wedge (F^-_{[1,1]}(x^1 < 4 \wedge x^0 < 3))$	125	0
3	109	$(G^-_{[1,1]} u = E) \wedge (F^-_{[1,1]}(x^1 > 2 \wedge x^0 > 3))$	42	0
4	77	$(G^-_{[1,1]} u = W) \wedge (F^-_{[1,1]}(x^1 < 5 \wedge x^0 < 2))$	52	0
5	0	–	–	–



Summary: Cause mining with STL



$$x_l[t+1] = x_l[t] + d_l[t] - f_l^{out}(x_l[t]) + \sum_{k \in \mathcal{L}_v^{out}} \beta_{kl} f_k^{out}(x_k[t])$$



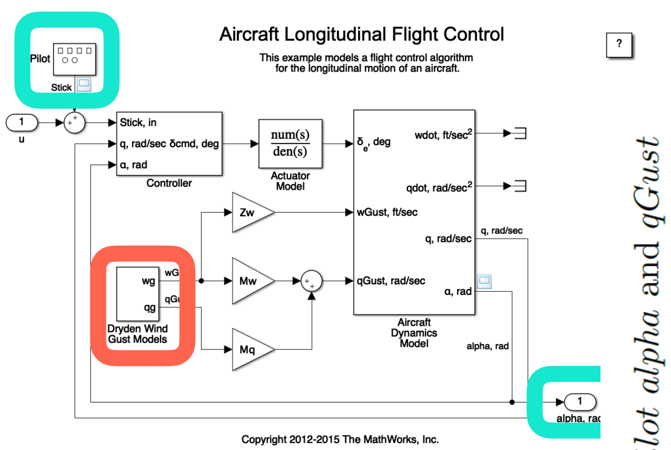
1. $\phi_1 = P_{[1,1]}(x^1 > 15 \wedge s^0 = 0 \wedge s^1 = 1$
2. $\phi_2 = P_{[1,1]}(x^1 \geq 25 \wedge s^1 = 1)$
3. $\phi_3 = P_{[1,1]}(x^4 \leq 10 \wedge s^0 = 0 \wedge s^1 = 1)$

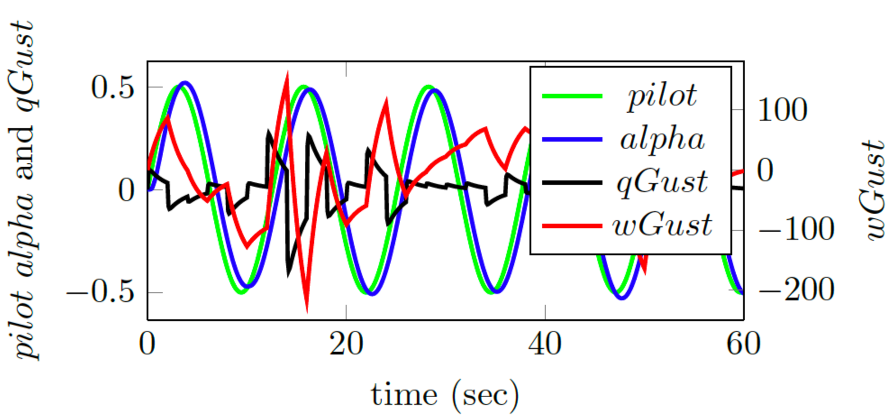
System model

Simulations

Label

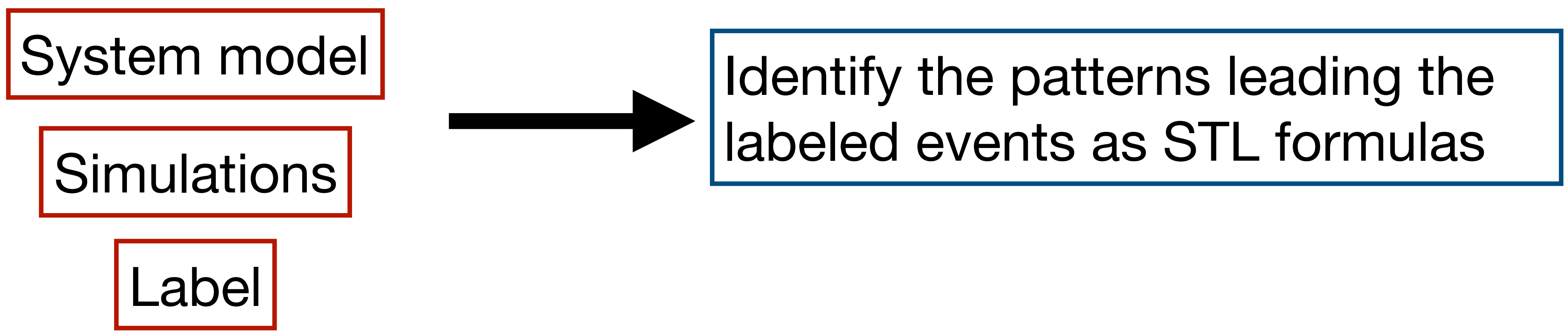
Identify the patterns leading the labeled events as STL formulas





1. $\phi_1 = P_{[4,10]}(qGust \leq 0 \wedge wGust \leq -120)$
2. $\phi_2 = wGust \geq 120 \wedge A_{[14,14]}(pilot \geq -40)$
3. $\phi_3 = P_{[2,2]}(alpha \leq 30 \wedge wGust - \leq 120)$
4. $\phi_4 = (A_{[2,6]}qGust \geq 10) \wedge pilot \leq -40$

Cause mining with STL



- How can we ensure that these are actual causes ?
  - Underlying causes?
  - Symptoms?

- What if there is single label?
  - Somewhere along the simulation a problem occurred.

- Is there a class of systems for which this type of analysis can reveal the causes?

Further questions?