Self-Driving Cars

Jonathan Sprinkle, Ph.D.

Litton Industries John M. Leonis
Distinguished Associate Professor
@sprinkletoday @jmscslgroup

THE UNIVERSITY
OF ARIZONA

Chronicle / Kurt Rogers

* 5 teams complete race

Finalist Locations

23 teams from 13 states

11 university teams

- 2004 Grand Challenge Team
- 2005 Grand Challenge New Entry

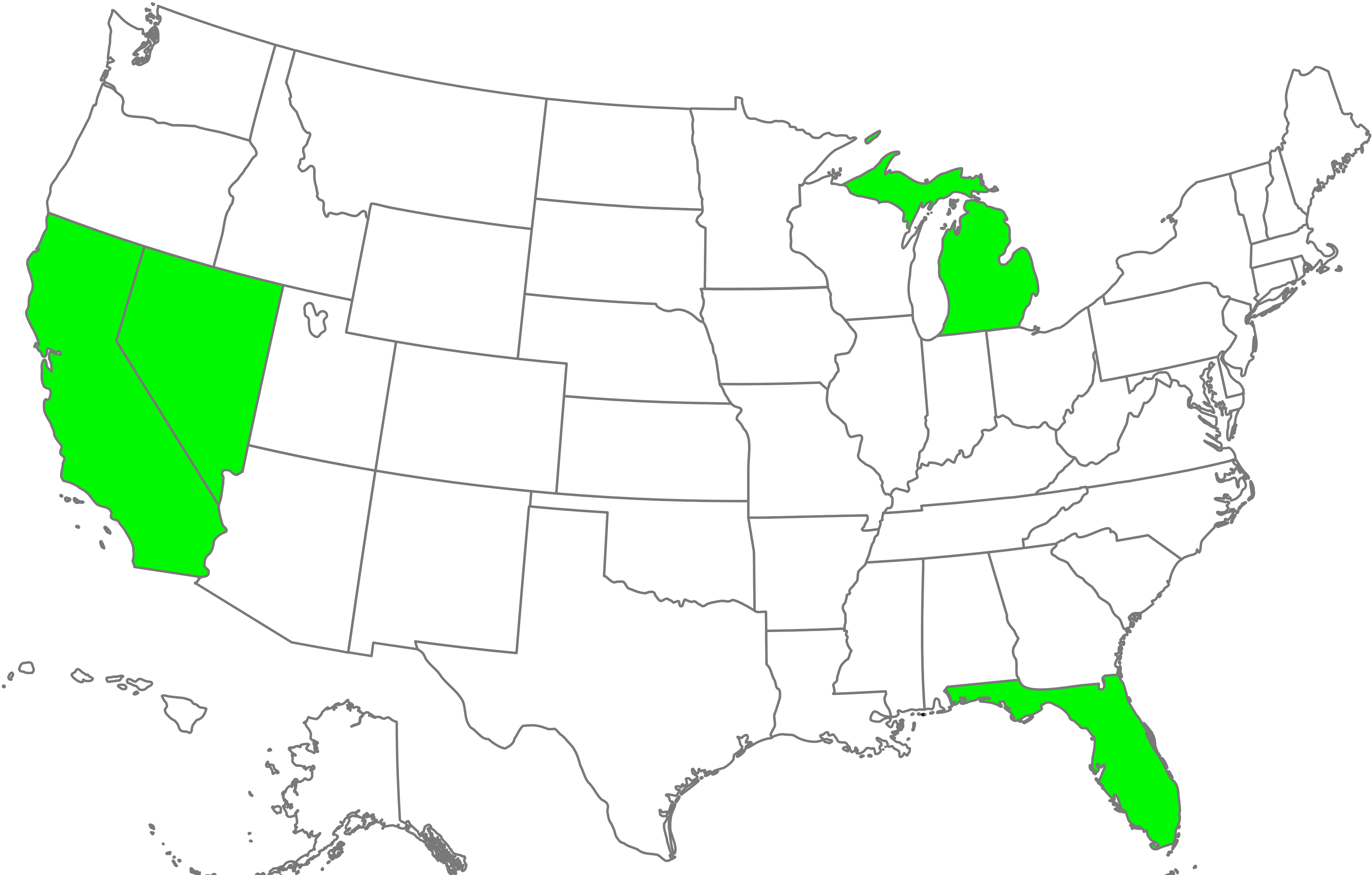

URBAN
CHALLENGE
FINISH
URBAN
CHALLENGE
URBAN
CHALLENGE
3
intel
Red Bull
MDV
NXP

2007 DARPA Urban Challenge Semifinalist Teams

* 6 teams complete race

35 Teams from 22 States

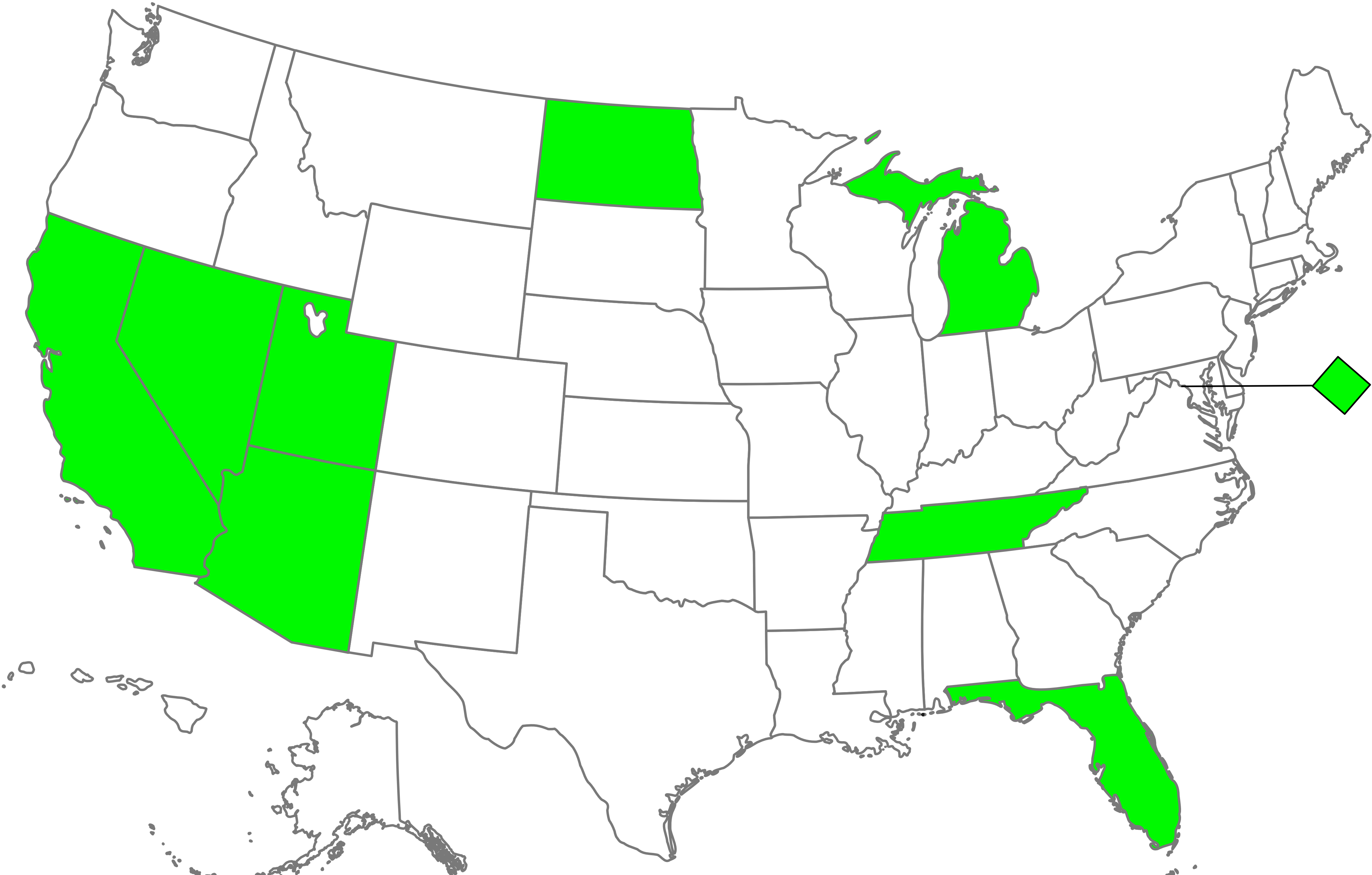
States with permits for self-driving cars (2014)



@sprinkletoday

Source: National Conference of State Legislatures

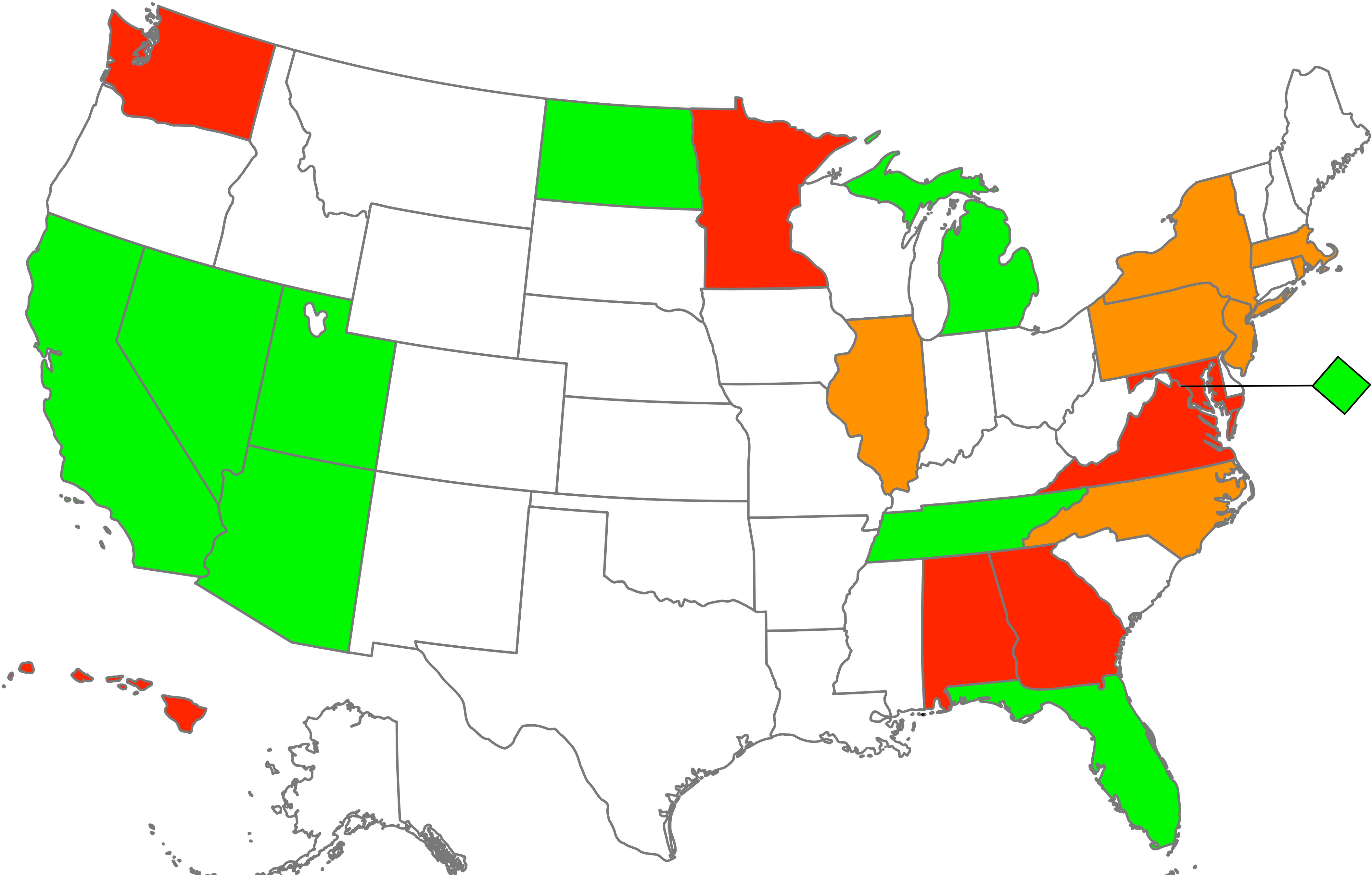
States with permits for self-driving cars (2016)



@sprinkletoday

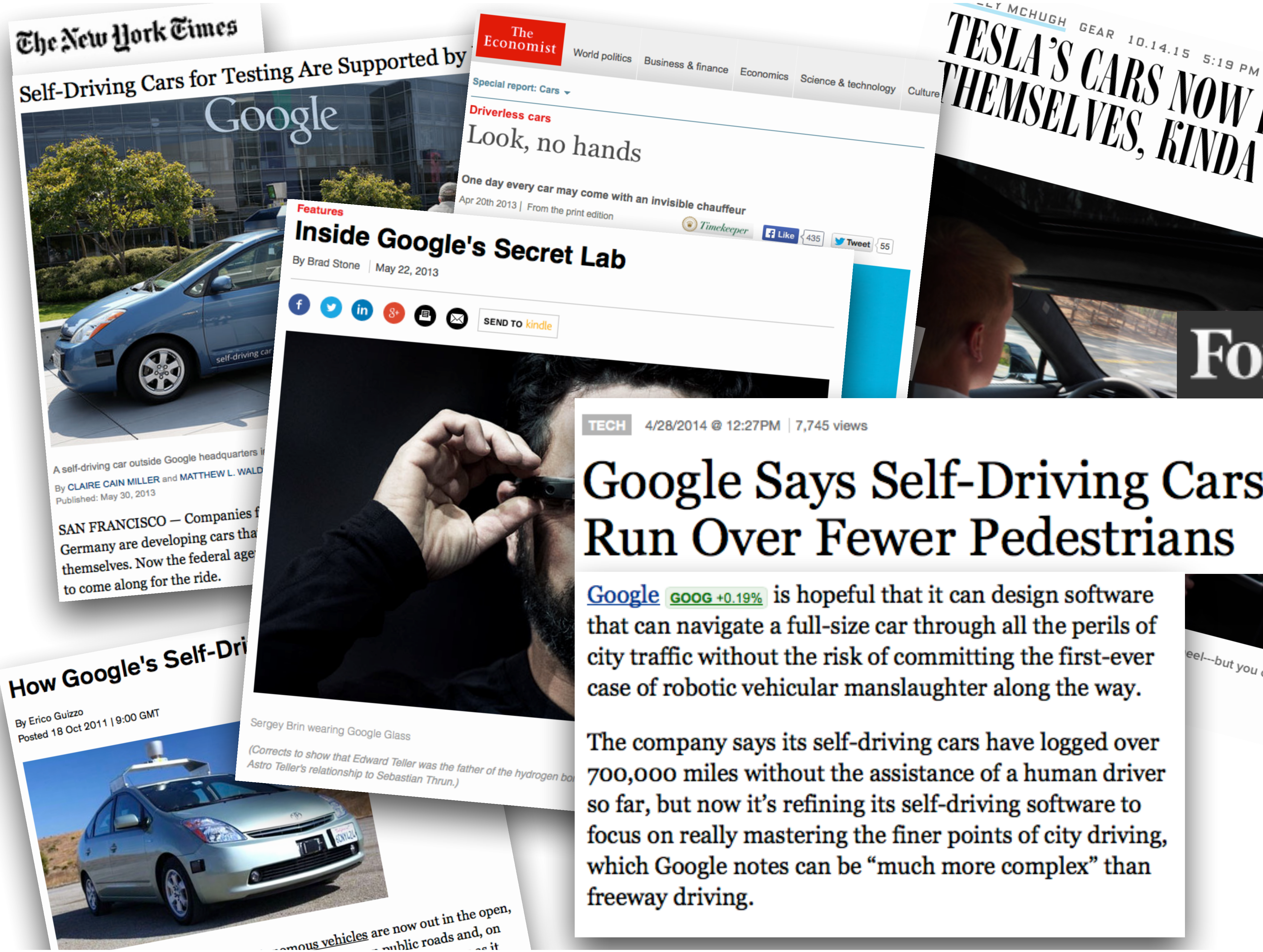
Source: National Conference of State Legislatures

States who've *tried* self-driving cars legislation (2016)



@sprinkletoday

Source: National Conference of State Legislatures



The New York Times

Self-Driving Cars for Testing Are Supported by

A self-driving car outside Google headquarters i

By CLAIRE CAIN MILLER and MATTHEW L. WALD

Published: May 30, 2013

SAN FRANCISCO — Companies f
Germany are developing cars tha
themselves. Now the federal age
to come along for the ride.

The Economist

World politics | Business & finance | Economics | Science & technology | Culture

Special report: Cars

Driverless cars

Look, no hands

One day every car may come with an invisible chauffeur

Apr 20th 2013 | From the print edition

Timekeeper | Like 435 | Tweet 55

TESLA'S CARS NOW
THEMSELVES, KINDA

MCHUGH GEAR 10.14.15 5:19 PM

Features

Inside Google's Secret Lab

By Brad Stone | May 22, 2013

SEND TO kindle

Sergey Brin wearing Google Glass

(Corrects to show that Edward Teller was the father of the hydrogen bo
Astro Teller's relationship to Sebastian Thrun.)

How Google's Self-Dri

By Erico Guizzo

Posted 18 Oct 2011 | 9:00 GMT

omous vehicles are now out in the open,
public roads and, on

TECH 4/28/2014 @ 12:27PM | 7,745 views

Google Says Self-Driving Cars Run Over Fewer Pedestrians

Google GOOG +0.19% is hopeful that it can design software that can navigate a full-size car through all the perils of city traffic without the risk of committing the first-ever case of robotic vehicular manslaughter along the way.

The company says its self-driving cars have logged over 700,000 miles without the assistance of a human driver so far, but now it's refining its self-driving software to focus on really mastering the finer points of city driving, which Google notes can be "much more complex" than freeway driving.

eel—but you

Volvo breaks new ground with amazi
new self-driving car tech

IN DEPTH We experience Volvo's cutting edge self-driving ca
tech, coming next year

By Jeremy Laird July 22nd 2013

1 C

SHARE 122 | TWEET 0 | SHARE | EMAIL

Look, no hands! Volvo's autonomous cars are coming soon.

Are self-driving cars for real? Or just a shallow distraction, a kind of Hollywood-style robo-chic?

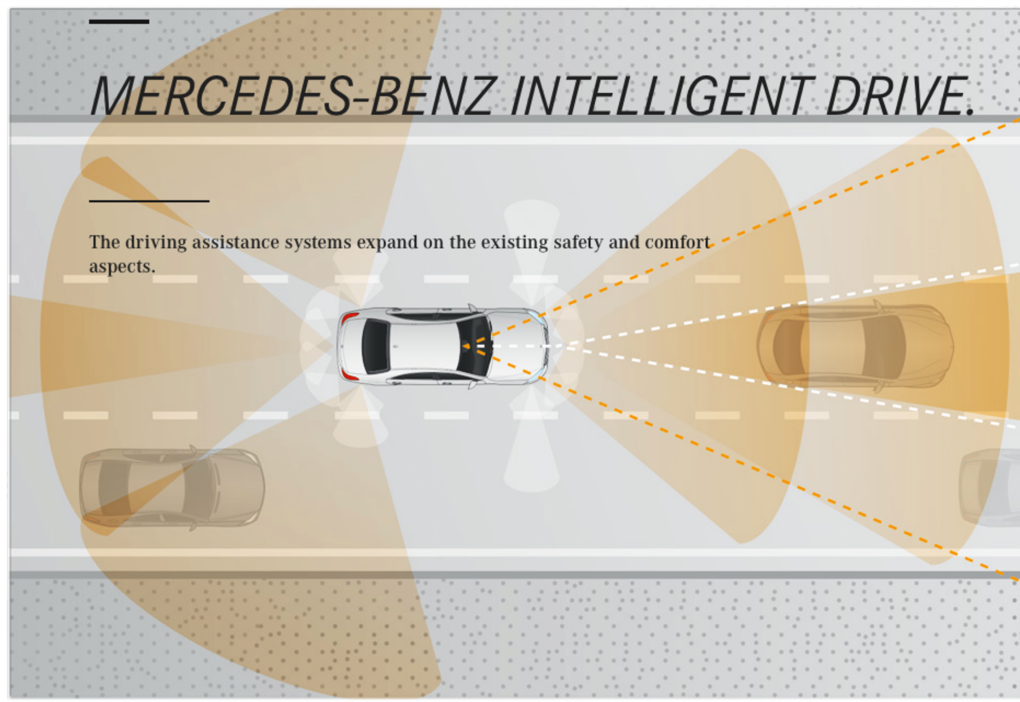
If our recent trip to a test facility near Gothenburg, Sweden courtesy of Volvo is anything to go, it's very serious stuff. In

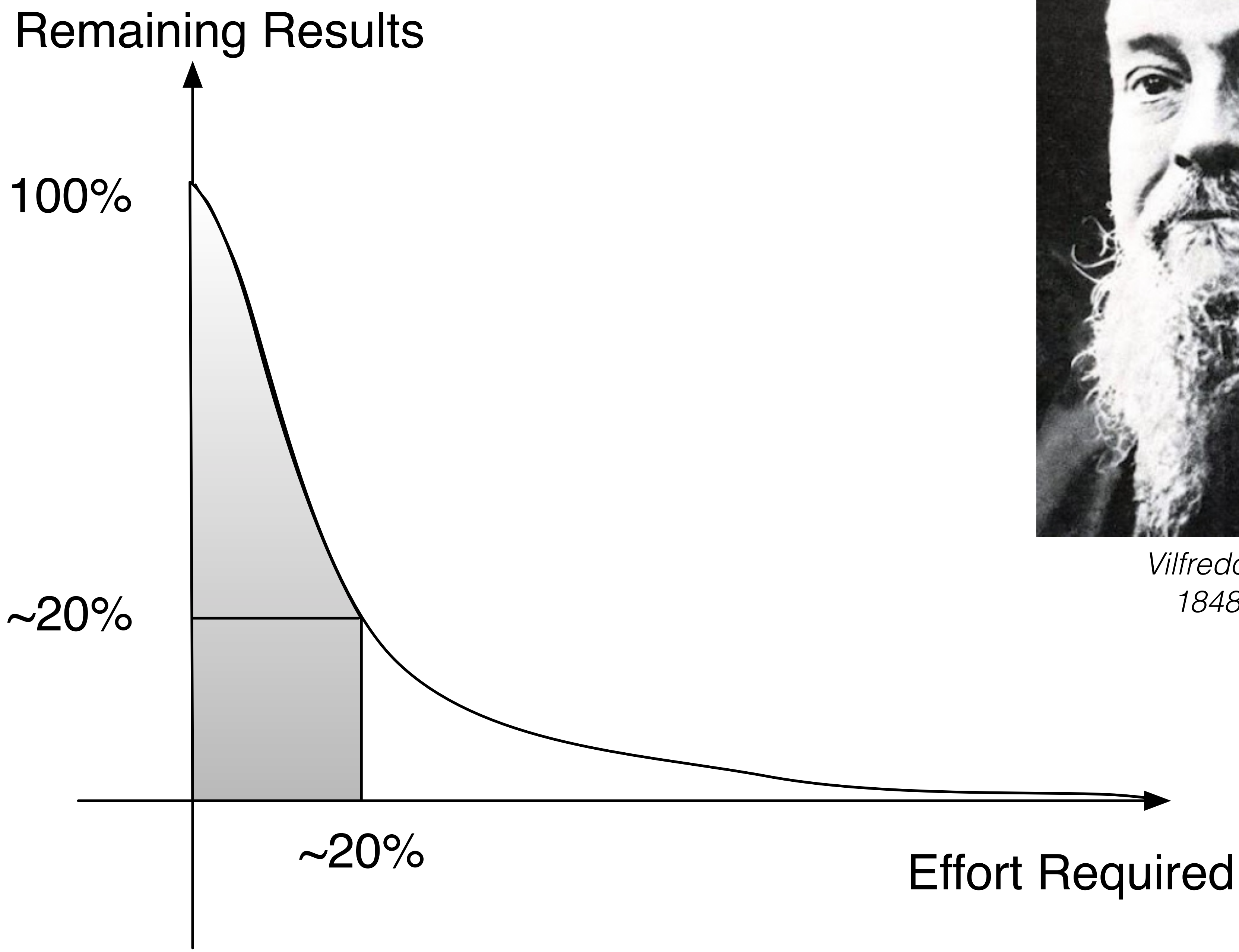
Related stories

Google's self-driving cars are smarter, but they're

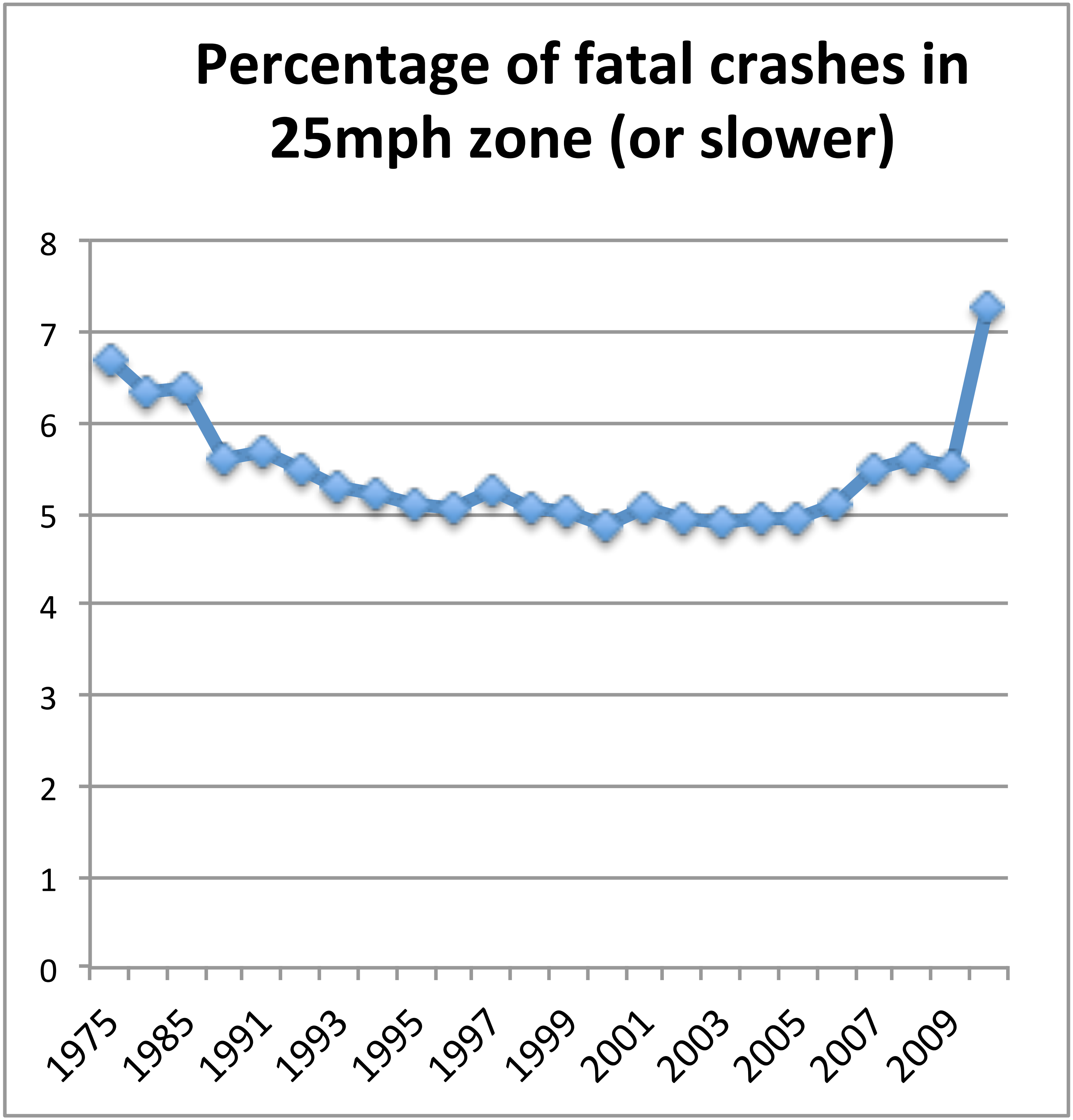
That's right, Volvo's ambition is to ensure nobo
even seriously injured in its cars. And the plan
cars that can achieve that aim by 2020.

technologies, many of which fall into the self-driving category. And we've driven prototypes featuring all of them. Or not driven them, if you see what we mean.





Vilfredo Pareto
1848-1923


Percentage of fatal crashes in 25mph zone (or slower)
8
7
6
5
4
3
2
1
0
1975
1985
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009


Primary GPS
Secondary GPS
Camera System
Mobileye
Image Processing
System
IMU
Sick LMS–221
Laser Rangefinder
MACom
SRS Radar
Ibeo Alasca XP
Laser Rangefinder
MACom
SRS Radar

Estimated cost of equipment only: $250,000

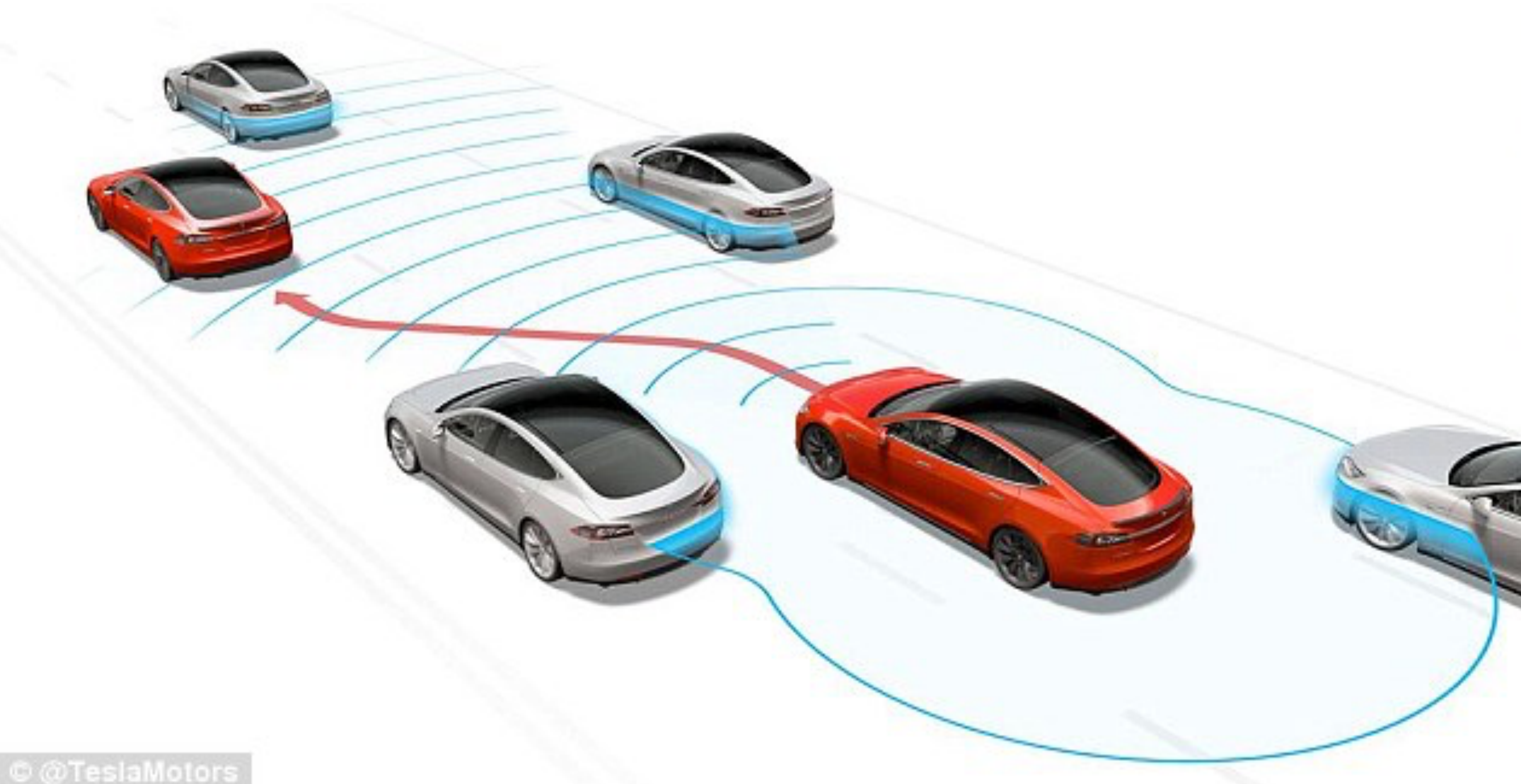
TESLA MODEL S MODEL X MODEL 3 CHARGING ENERGY UPDATES SUPPORT FIND US SHOP MY TESLA

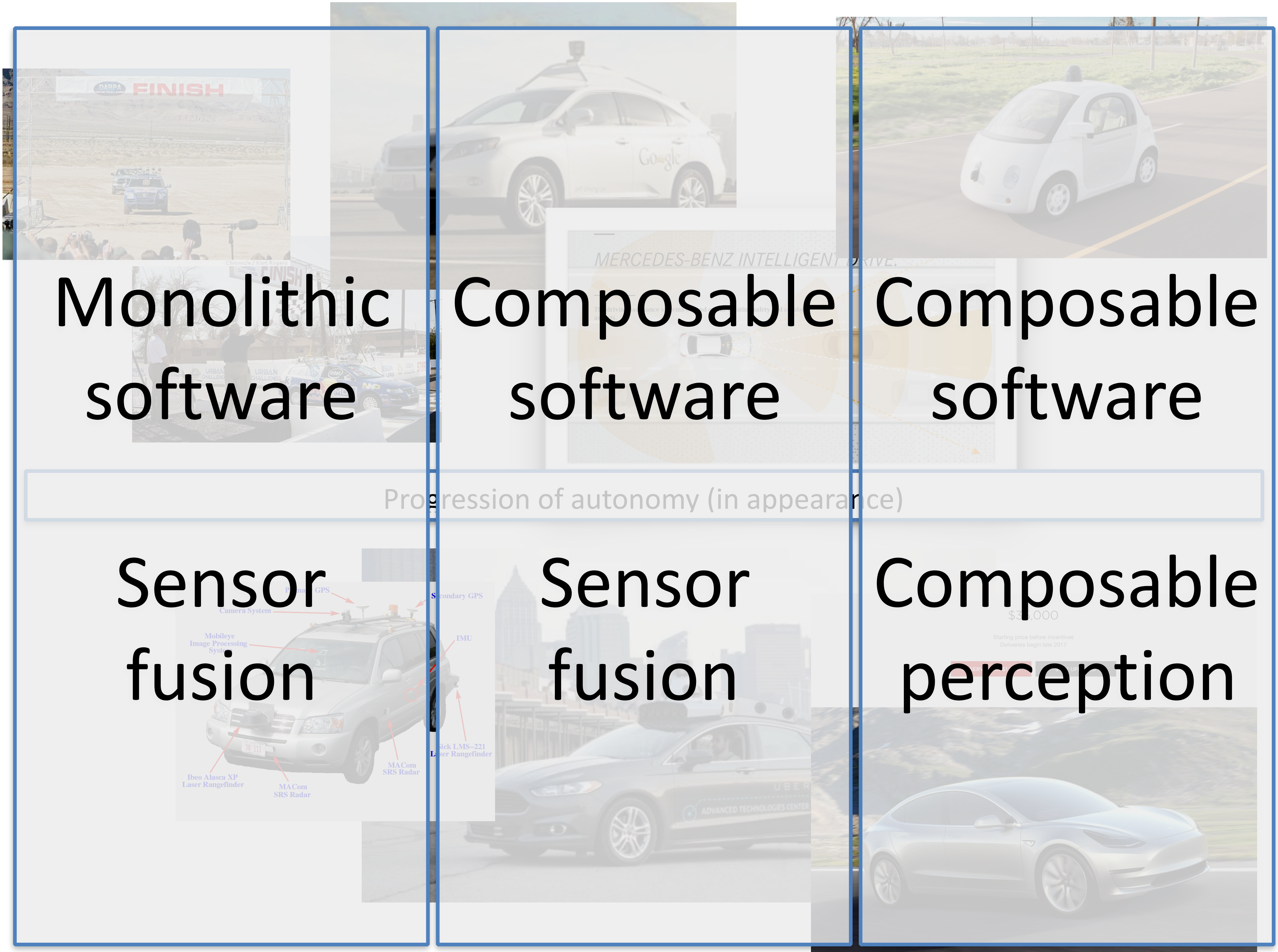
$35,000

Starting price before incentives
Deliveries begin late 2017

RESERVE FOR $1,000 STAY UPDATED

@sprinkletoday

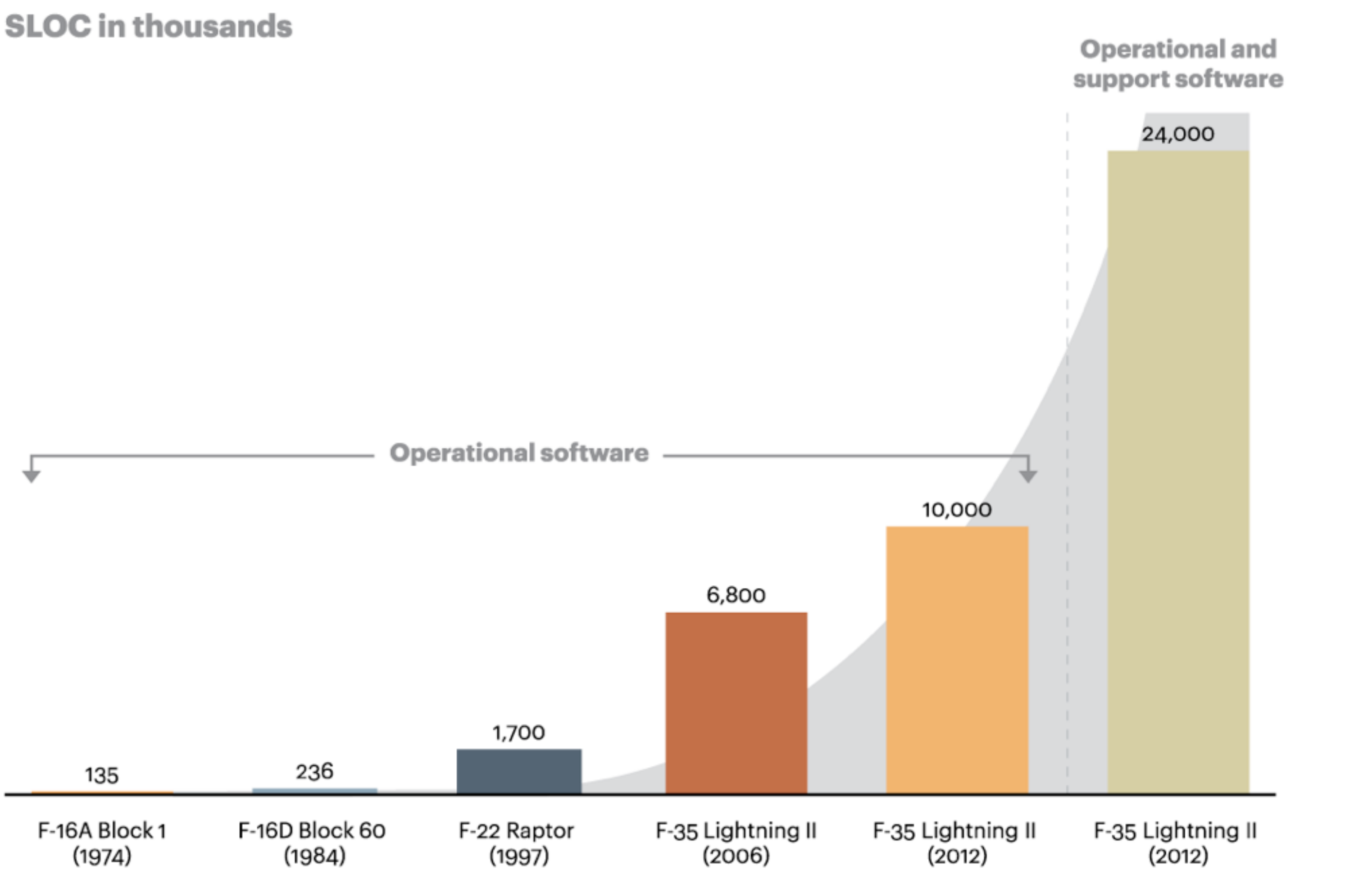

© @TeslaMotors



@sprinkletoday

Figure 1

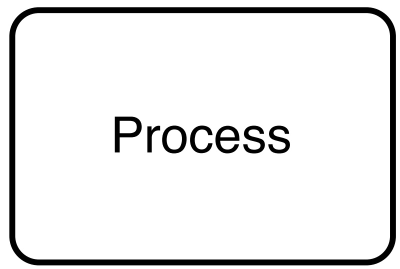
The number of source lines of code (SLOC) has exploded in avionics software



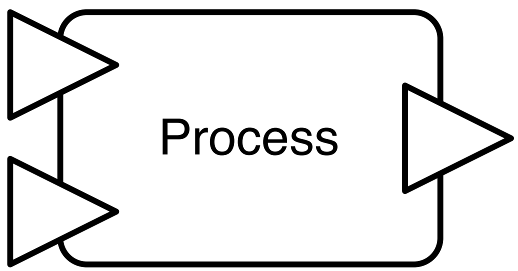
Notes: SLOC for F-16 and F-22 are at first operational flight. F-35 SLOC figures are from first test flight and current estimates/sources.

Sources: P. Judas and L.E. Prokop, "A historical compilation of software metrics with applicability to NASA's Orion spacecraft flight software sizing," Innovations in Systems and Software Engineering, vol. 7 issue 3, September 2011. p. 161–170; Andrea Shalal-Esa, "Pentagon focused on resolving F-35 software issues," Reuters, March 2012; Robert N. Charette, "F-35 Program Continues to Struggle with Software," IEEE Spectrum, September 2012

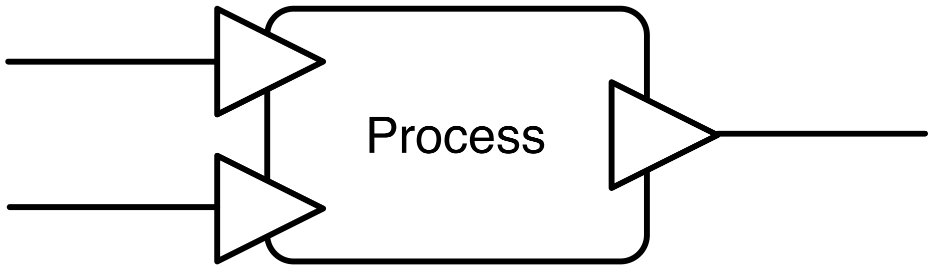
Composable software



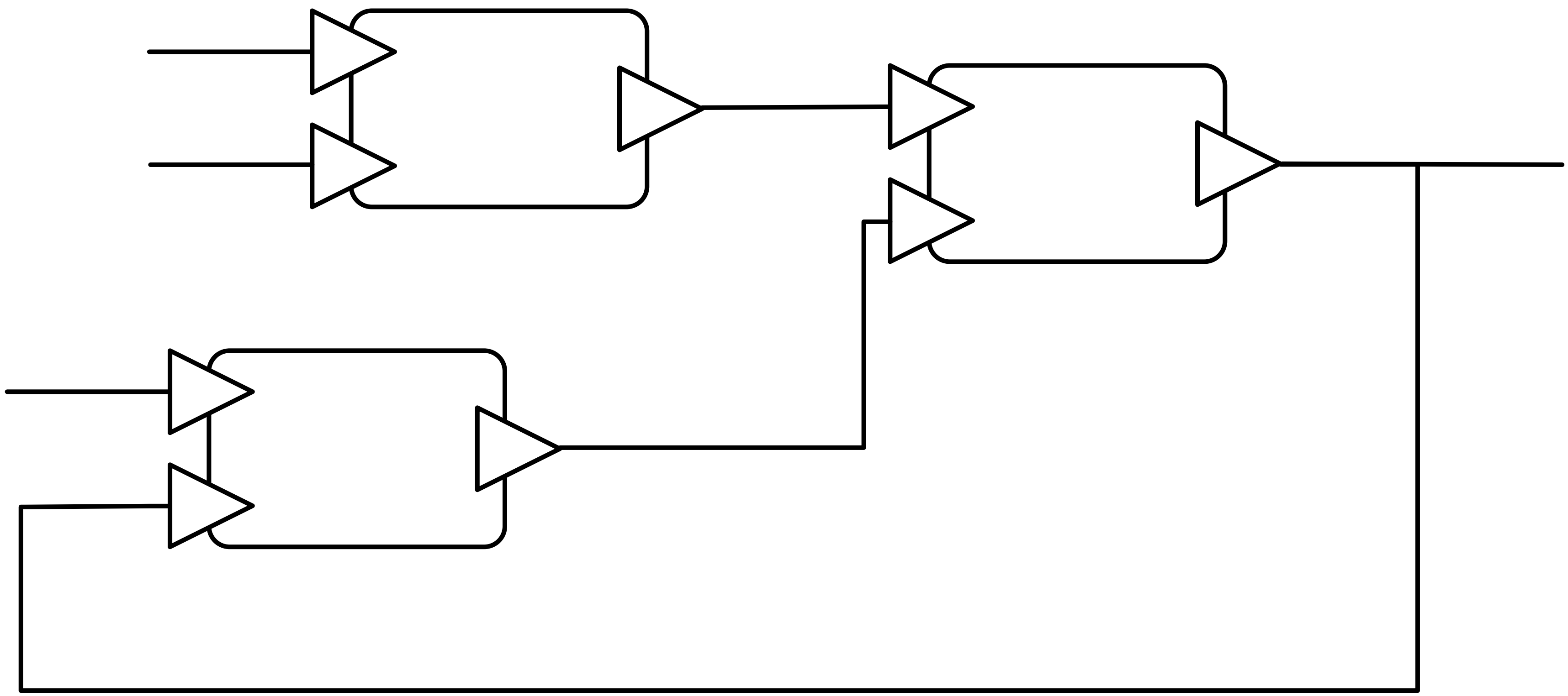
Composable software



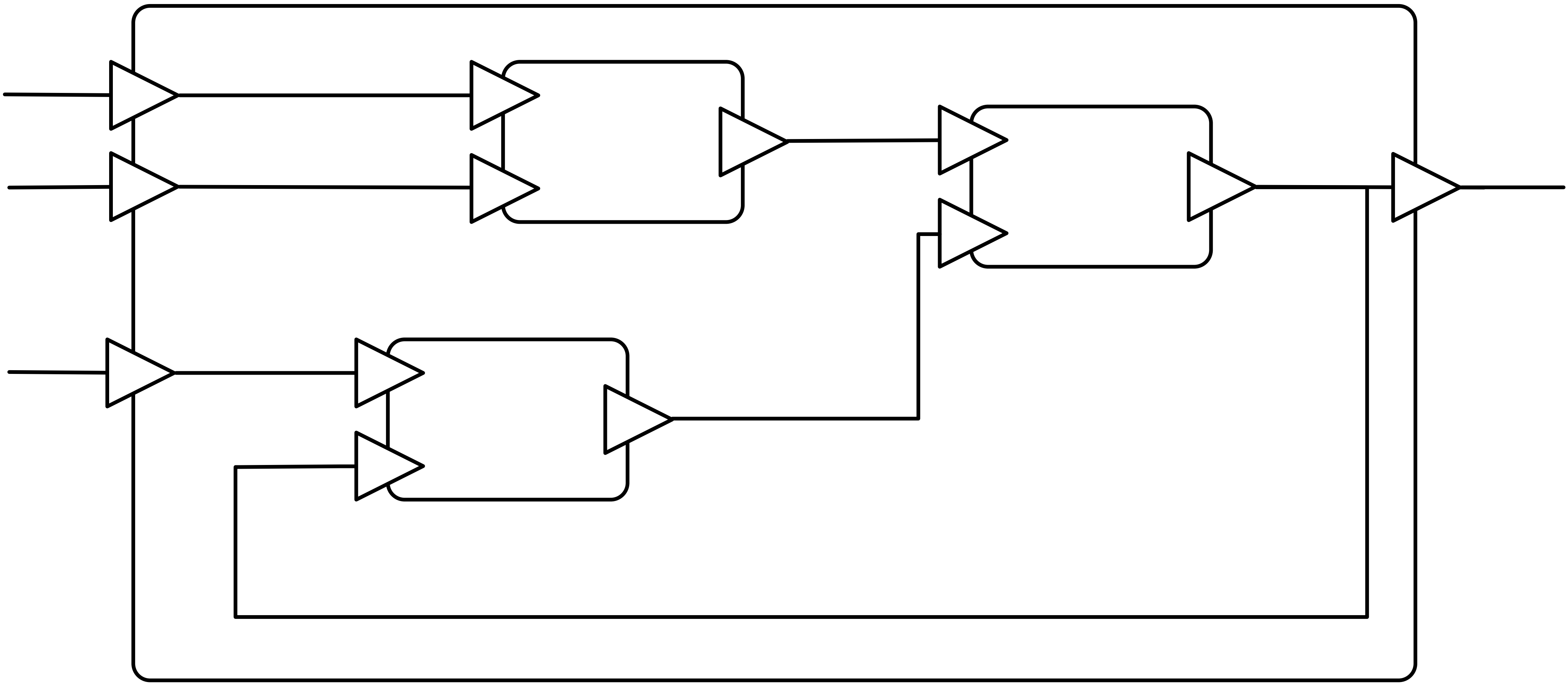
Composable software



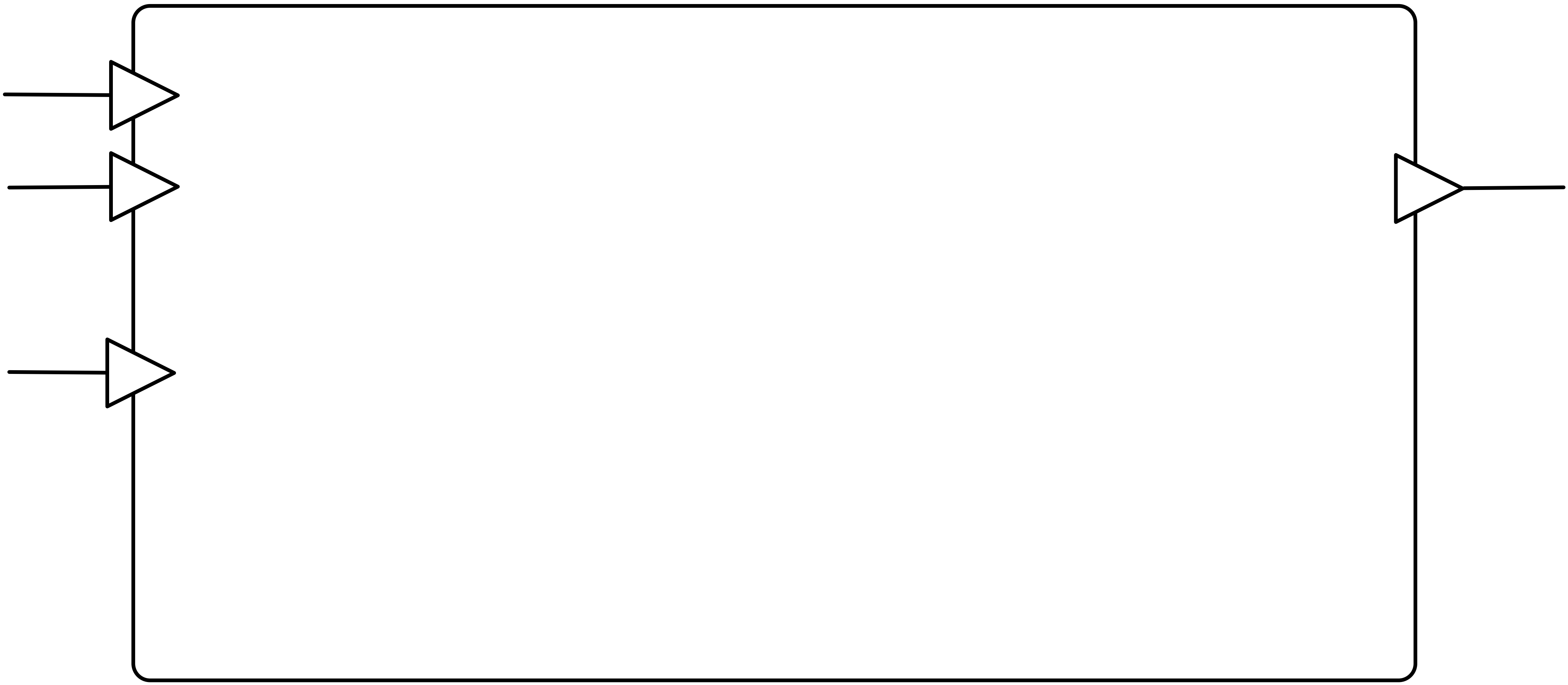
Composable software



Composable software



Composable software



Composable software

While functional behaviors may be (fairly) easy to test, **nonfunctional behaviors rarely compose**—and these behaviors are the ones that must be guaranteed for complex cyber-physical systems that interact with humans.

GIZMODO

Search

Steve Wozniak Explains That Faulty Software Caused His Car Troubles

Rosa Golijan
Filed to: CARS 2/02/10 1:33am

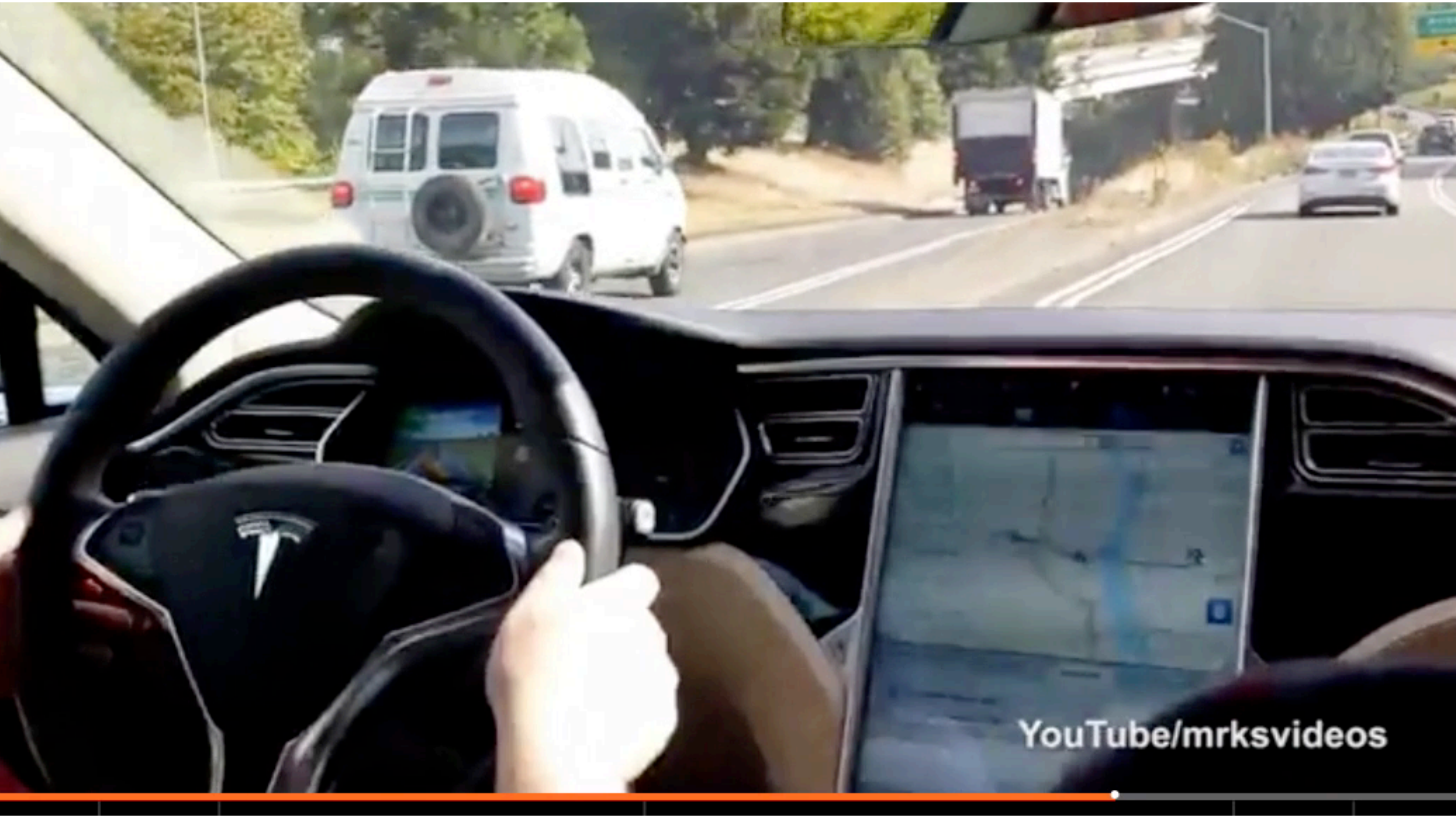
44,263

Uh oh. Steve Woz is having some "very scary" trouble with his 2010 Toyota Prius. At a recent event in San Francisco he went off topic and talked about how faulty software is to blame for his car's accelerator troubles:

> *Toyota has this accelerator problem we've all heard about. Well, I have many models of Prius that got recalled, but I have a new model that didn't get recalled. This new model has an accelerator that goes wild but only under certain conditions of cruise control. And I can repeat it over and over and over again—safely. This is software. It's not a bad accelerator pedal. It's very scary, but luckily for me I can hit the brakes.*

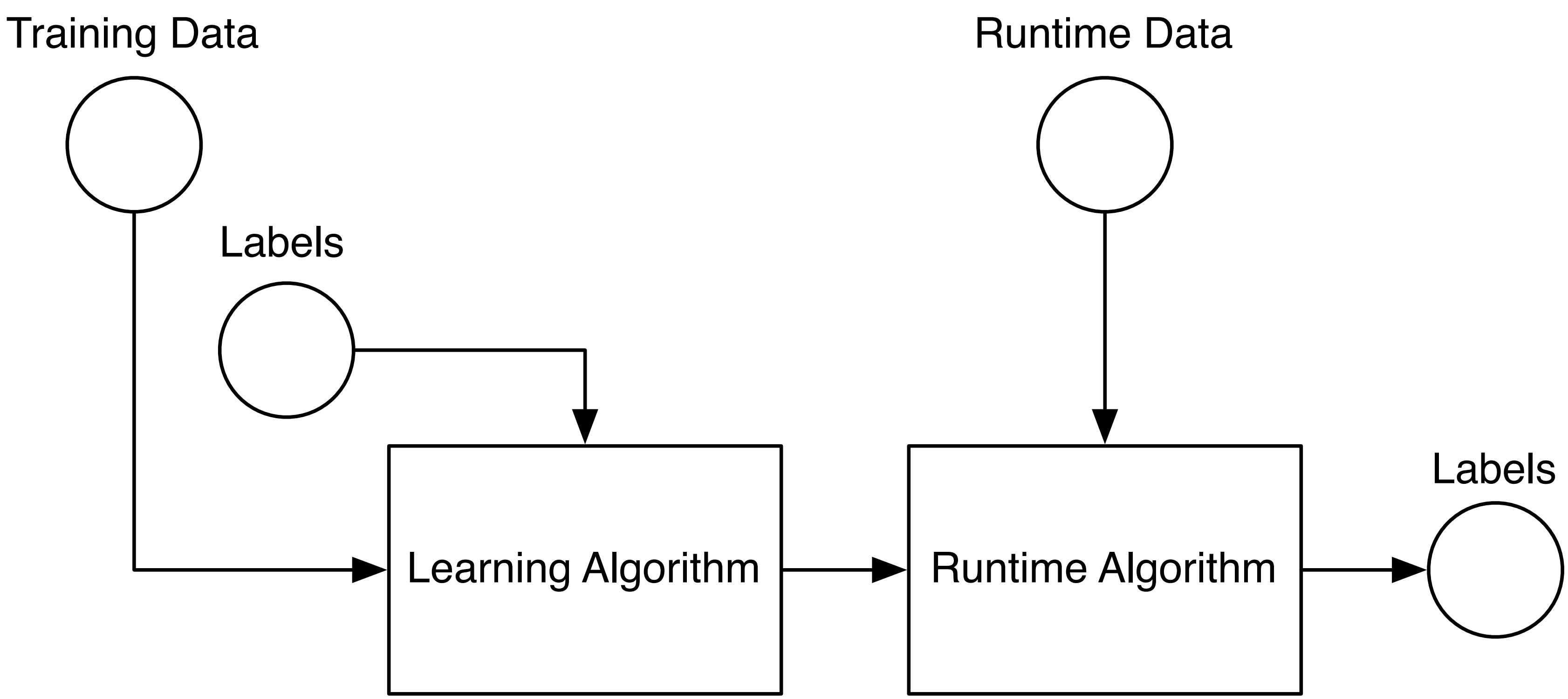
@sprinkletoday

http://www.dailymail.co.uk/sciencetech/article-3281562/Tesla-autopilot-fail-videos-emerge-Terrifying-footage-shows-happens-autonomous-driving-goes-wrong.html

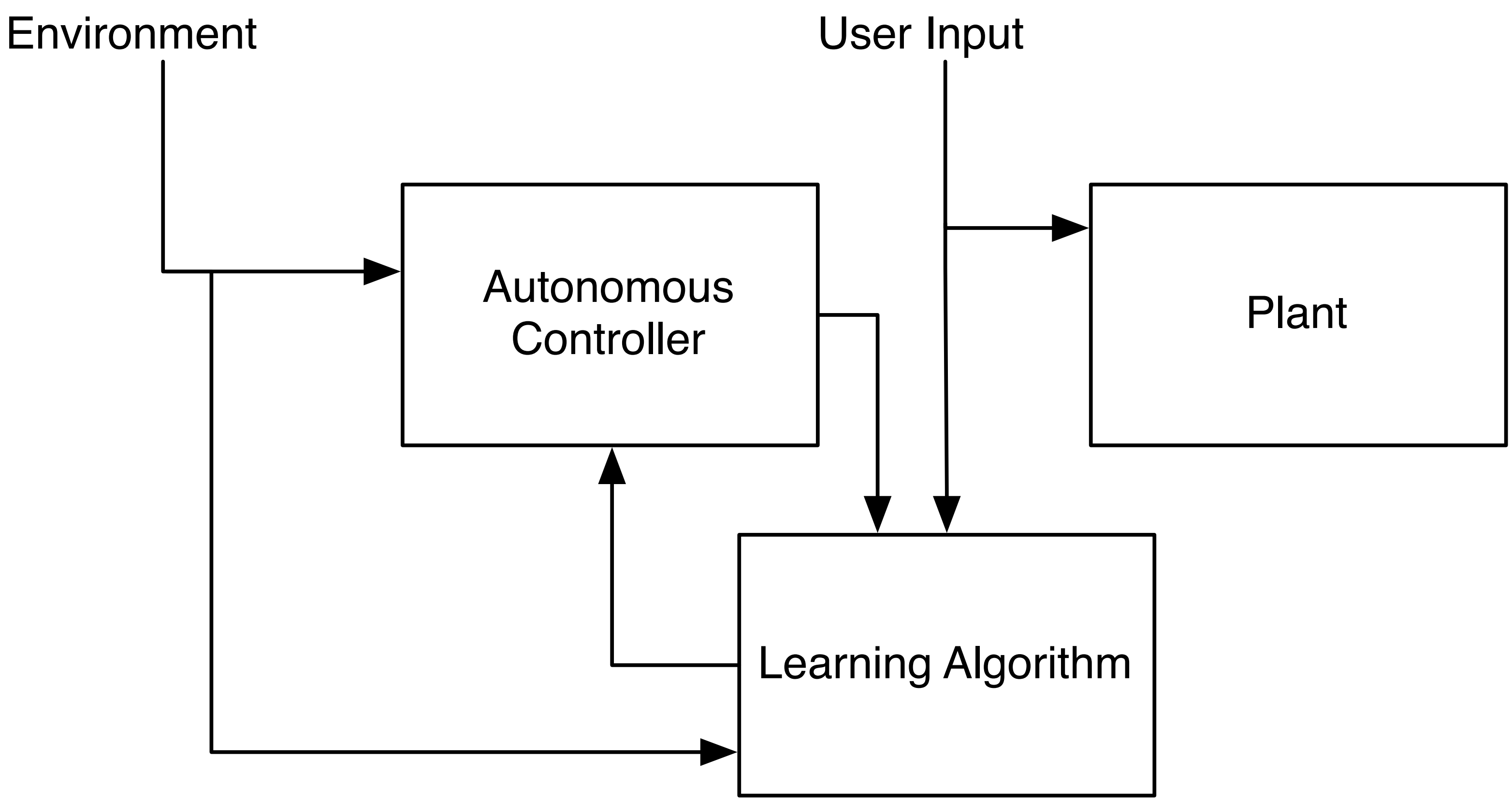


http://www.dailymail.co.uk/sciencetech/article-3281562/Tesla-autopilot-fail-videos-emerge-Terrifying-footage-shows-happens-autonomous-driving-goes-wrong.html

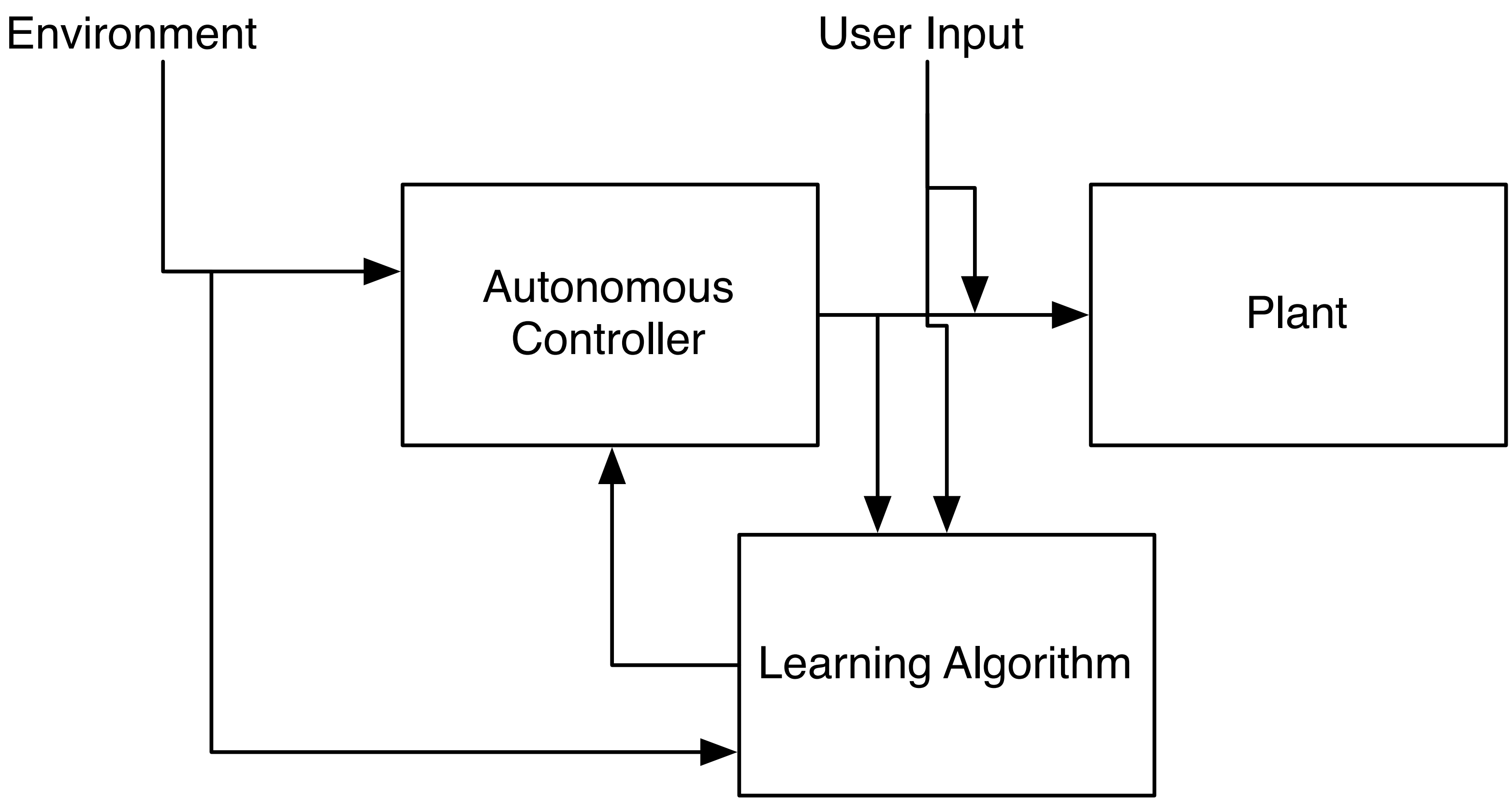
Generic Machine Learning Architecture



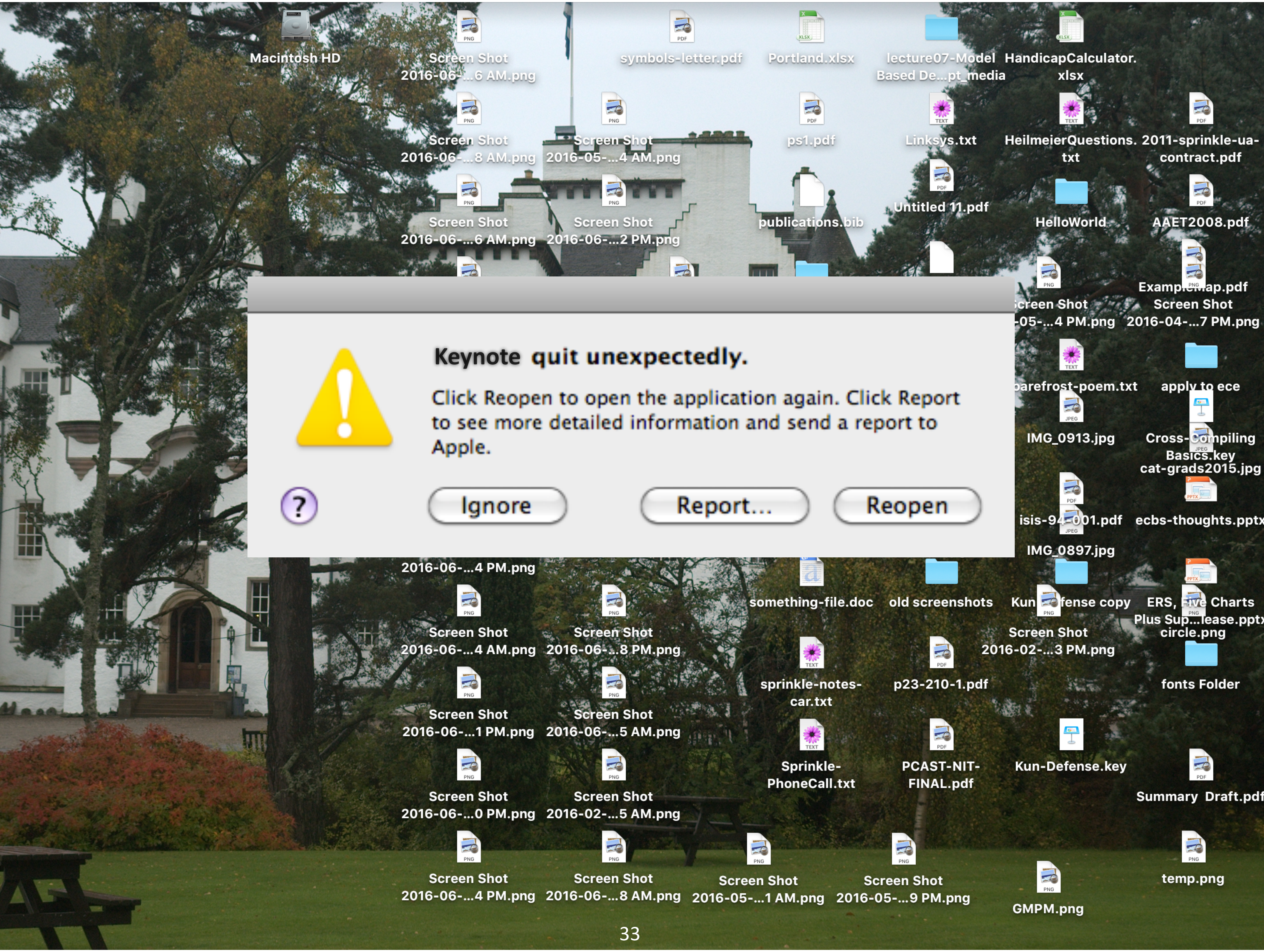
Train offline with data from human driver



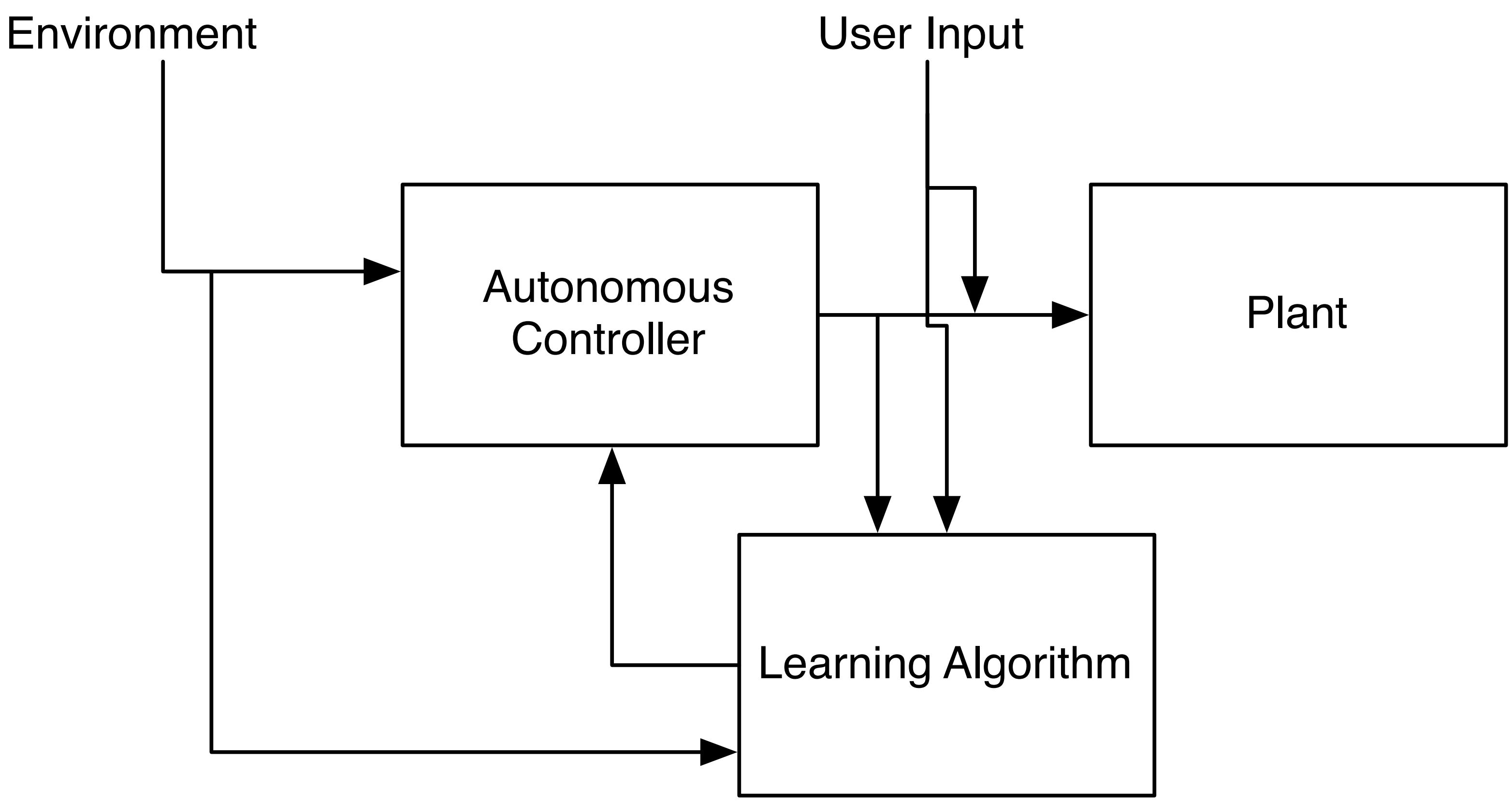
Generate new exception criteria and data for regression test when user intervenes



System must be robust at runtime in order to do this.


Keynote quit unexpectedly.
Click Reopen to open the application again. Click Report to see more detailed information and send a report to Apple.
Ignore
Report...
Reopen
Macintosh HD
Screen Shot 2016-06-...6 AM.png
symbols-letter.pdf
Portland.xlsx
lecture07-Model Based De...pt_media
HandicapCalculator.xlsx
Screen Shot 2016-06-...8 AM.png
Screen Shot 2016-05-...4 AM.png
ps1.pdf
Linksys.txt
HeilmeierQuestions.txt
2011-sprinkle-ua-contract.pdf
Untitled 11.pdf
Screen Shot 2016-06-...6 AM.png
Screen Shot 2016-06-...2 PM.png
publications.bib
HelloWorld
AAET2008.pdf
IMG_0913.jpg
IMG_0897.jpg
2016-06-...4 PM.png
something-file.doc
old screenshots
Screen Shot 2016-06-...4 AM.png
Screen Shot 2016-06-...8 PM.png
Screen Shot 2016-02-...3 PM.png
sprinkle-notes-car.txt
p23-210-1.pdf
fonts Folder
Screen Shot 2016-06-...1 PM.png
Screen Shot 2016-06-...5 AM.png
Sprinkle-PhoneCall.txt
PCAST-NIT-FINAL.pdf
Kun-Defense.key
Summary Draft.pdf
Screen Shot 2016-06-...0 PM.png
Screen Shot 2016-02-...5 AM.png
Screen Shot 2016-06-...4 PM.png
Screen Shot 2016-06-...8 AM.png
Screen Shot 2016-05-...1 AM.png
Screen Shot 2016-05-...9 PM.png
GMPM.png
temp.png

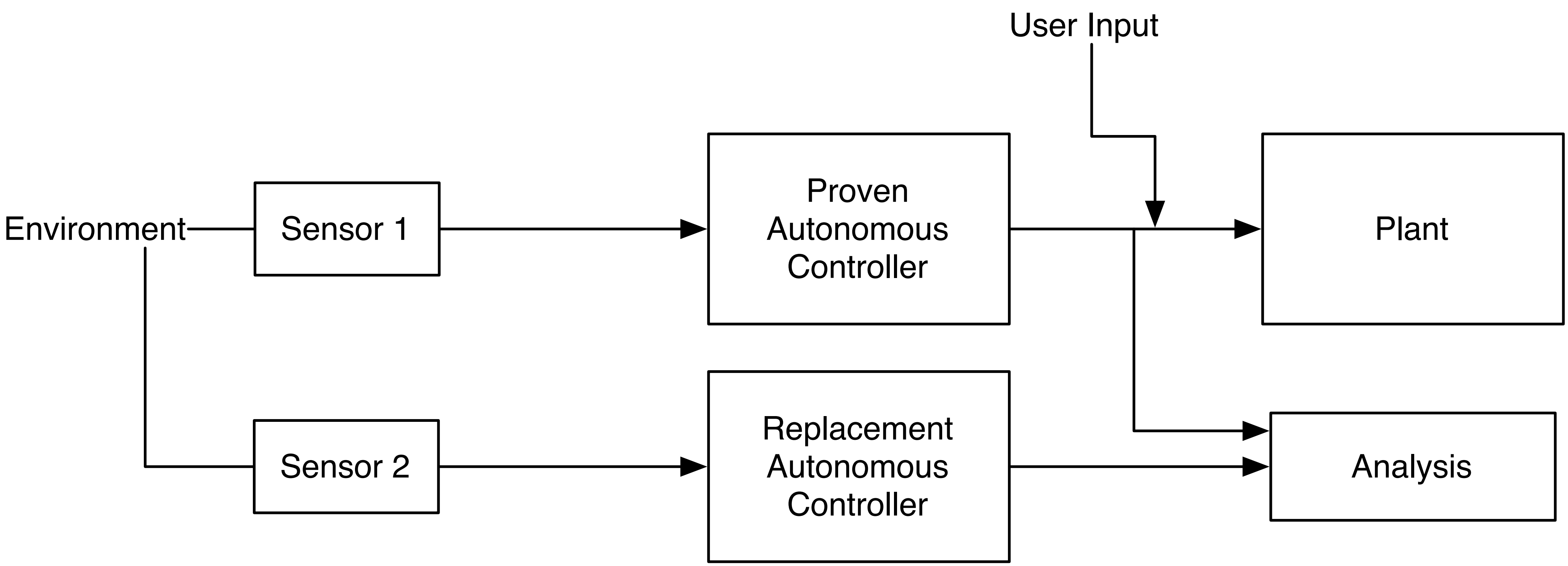
Generate new exception criteria and data for regression test when user intervenes



<u>What's the good of a counterexample for your test case, if irretrievable damage is done when you get those data?</u>

@sprinkletoday

Run replacement controller (or replacement sensor) live in the loop, but not hooked up to the plant.



Check the functional (and nonfunctional) viability of a cheaper sensor, or alternative controller, and upload analysis data nightly.

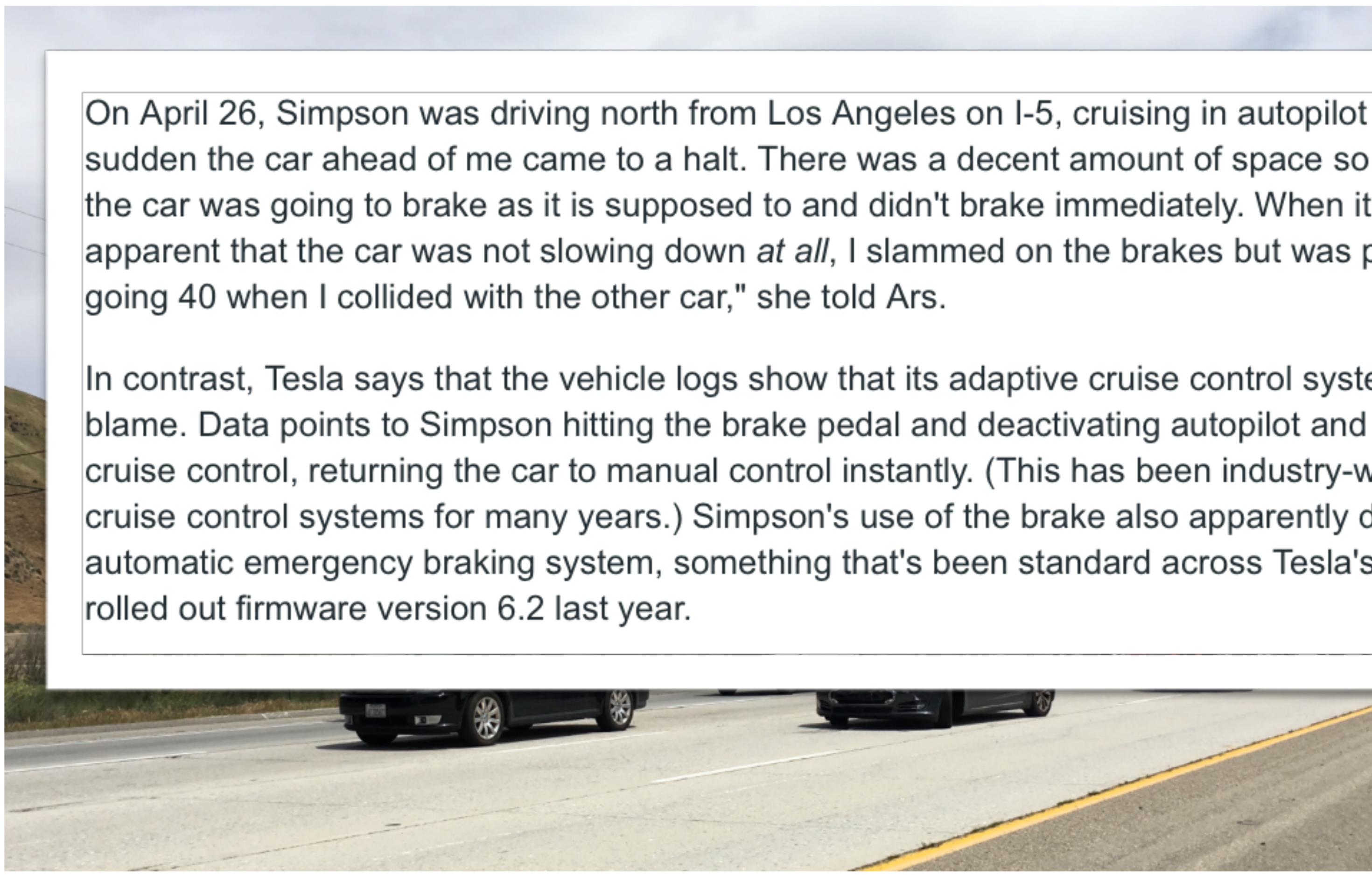
CARS TECHNICA / ALL THINGS AUTOMOTIVE

Another driver says Tesla's autopilot failed to brake; Tesla says otherwise

Mode confusion

Second recent autonomous accident is also blamed on driver error.

by **Jonathan M. Gitlin** - May 13, 2016 10:30pm CEST

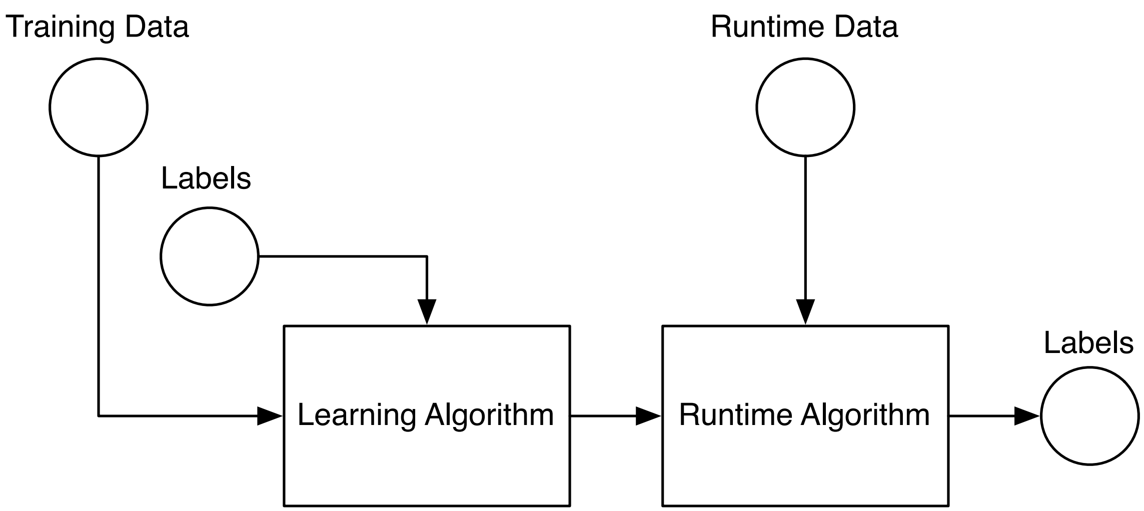


On April 26, Simpson was driving north from Los Angeles on I-5, cruising in autopilot mode. "All of a sudden the car ahead of me came to a halt. There was a decent amount of space so I figured that the car was going to brake as it is supposed to and didn't brake immediately. When it became apparent that the car was not slowing down *at all*, I slammed on the brakes but was probably still going 40 when I collided with the other car," she told Ars.

In contrast, Tesla says that the vehicle logs show that its adaptive cruise control system is not to blame. Data points to Simpson hitting the brake pedal and deactivating autopilot and traffic aware cruise control, returning the car to manual control instantly. (This has been industry-wide practice for cruise control systems for many years.) Simpson's use of the brake also apparently disengaged the automatic emergency braking system, something that's been standard across Tesla's range since it rolled out firmware version 6.2 last year.

Arianna Simpson's Model S after the crash outside Lebec, CA.

Arianna Simpson



Unclassified runtime data. Opaque models.

Issues of liability.

Another driver says Tesla's autopilot failed to brake; Tesla says otherwise

Second recent autonomous accident is also blamed on driver error.

by **Jonathan M. Gitlin** - May 13, 2016 10:30pm CEST

Share Tweet Email 342

Sensor degradation.

Sensor cost decline.

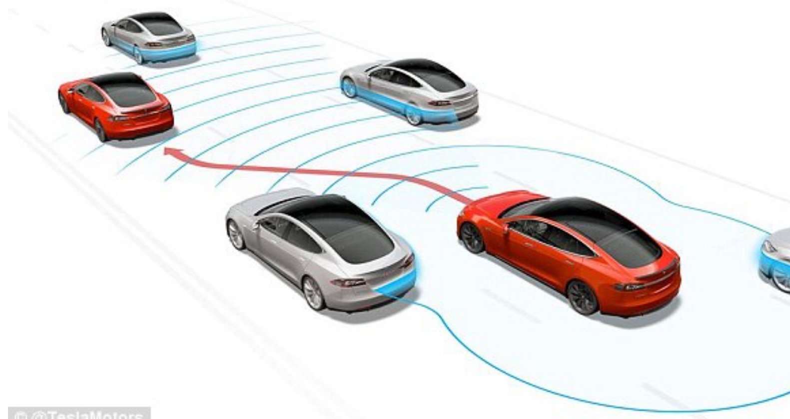
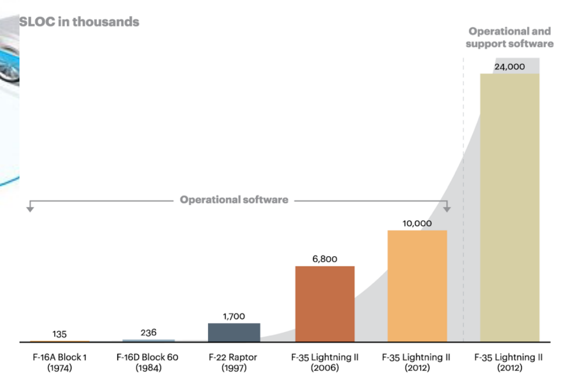


Figure 1
The number of source lines of code (SLOC) has exploded in avionics software



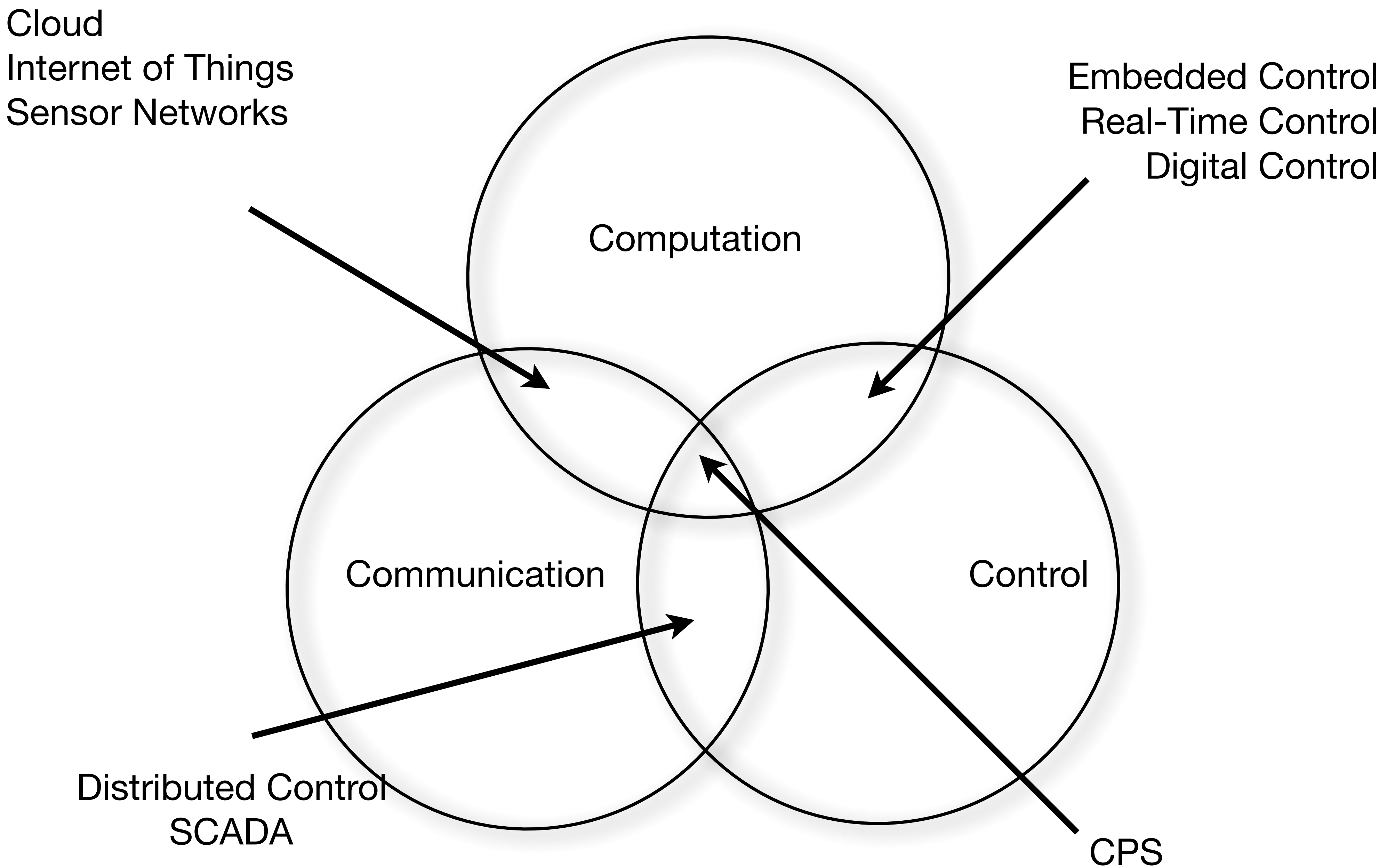
Notes: SLOC for F-16 and F-22 are at first operational flight. F-35 SLOC figures are from first test flight and current estimates/sources.
Sources: P. Judas and L.E. Prokop, "A historical compilation of software metrics with applicability to NASA's Orion spacecraft flight software sizing," Innovations in Systems and Software Engineering, vol. 7 issue 3, September 2011. p. 161–170; Andrea Shalal-Esa, "Pentagon focused on resolving F-35 software issues," Reuters, March 2012; Robert N. Charette, "F-35 Program Continues to Struggle with Software," IEEE Spectrum, September 2012

Software certification.

These are big questions.

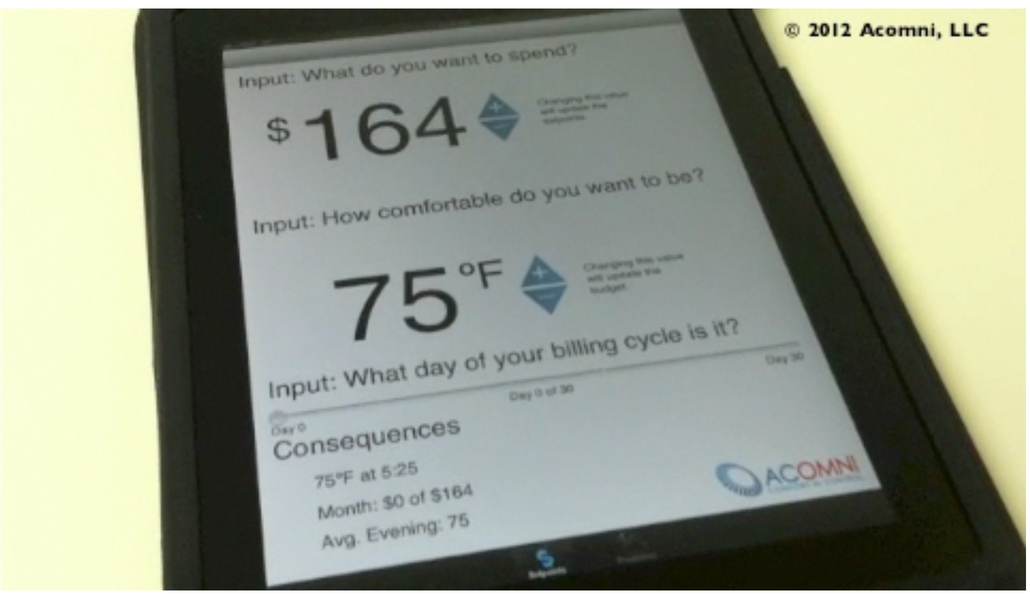
What role does research play to get better answers?

Cyber-Physical Systems

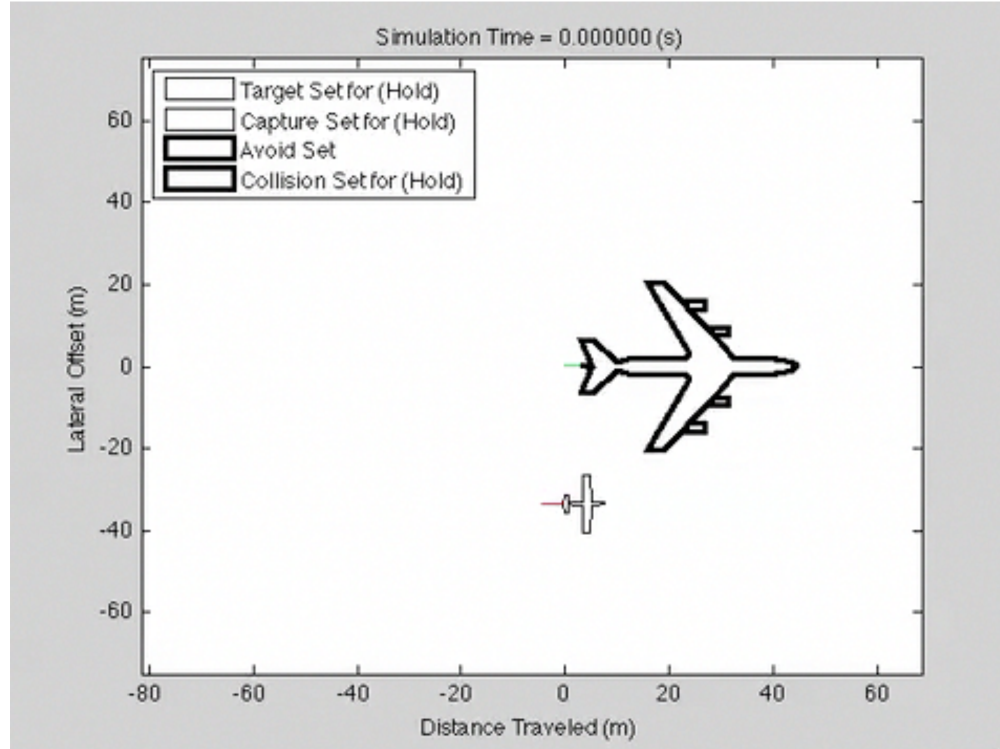


CPS Design Competition

http://cps-vo.org/group/vortex/competition

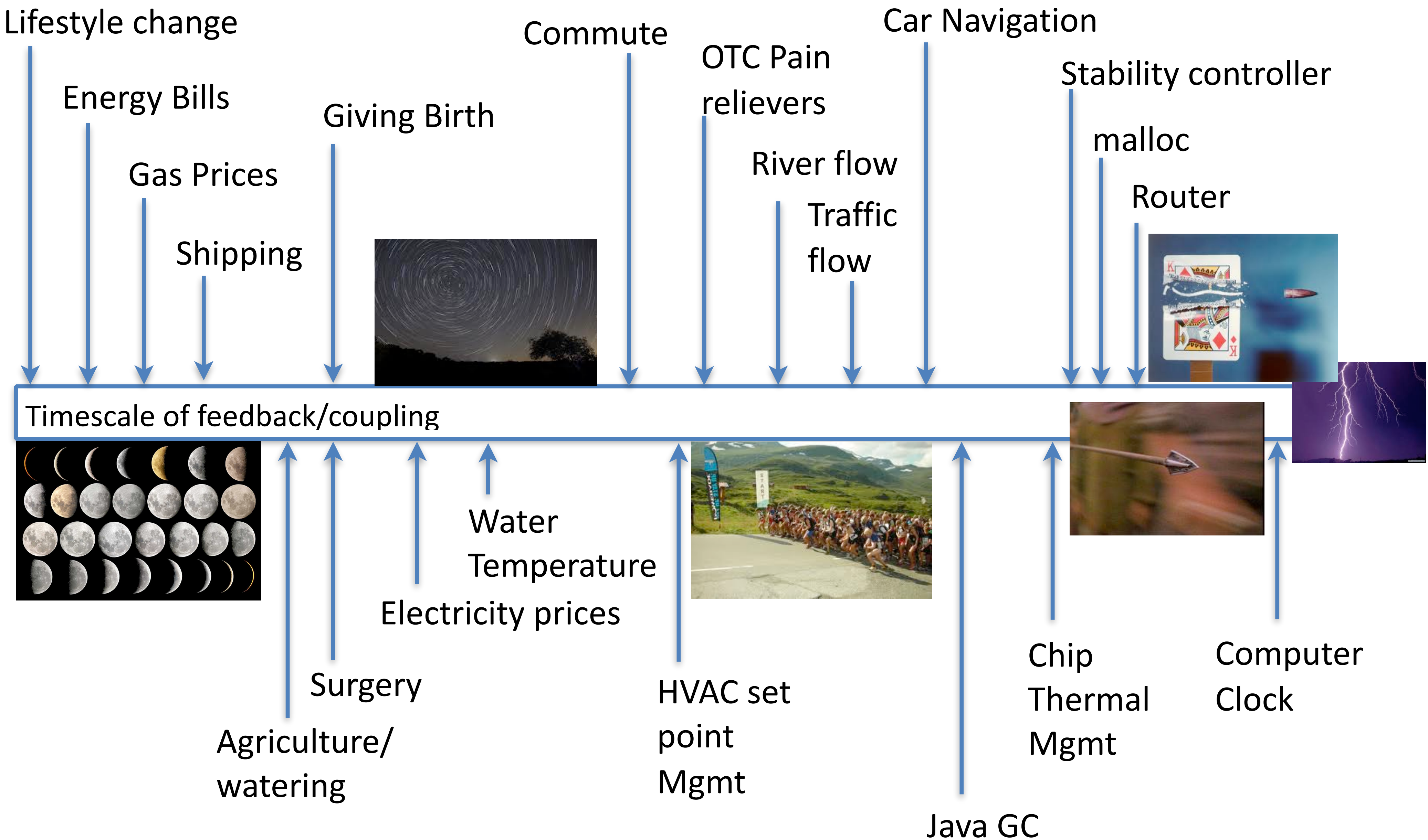


Safe maneuvers of aircraft



Water quality sensing

Different timescales*



* Not to scale. It's not like I plotted this in MATLAB or anything...

Different timescales*

Lifestyle change

Energy Bills

Gas Prices

Shipping

Giving Birth

Commute

OTC Pain relievers

River flow

Traffic flow

Car Navigation

Stability controller

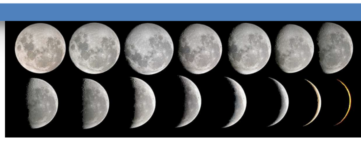
malloc

Router

Regulation and/or public comment

Ingenuity and choice

Only possible through automation



Water

Temperature

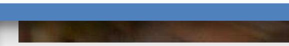
Electricity prices

Surgery

Agriculture/ watering

HVAC set point Mgmt

Java GC

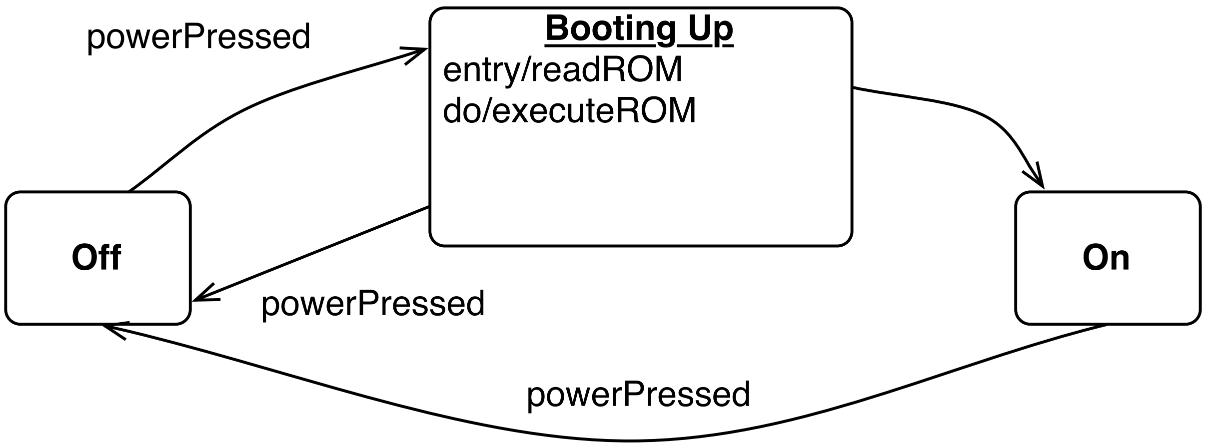


Chip Thermal Mgmt

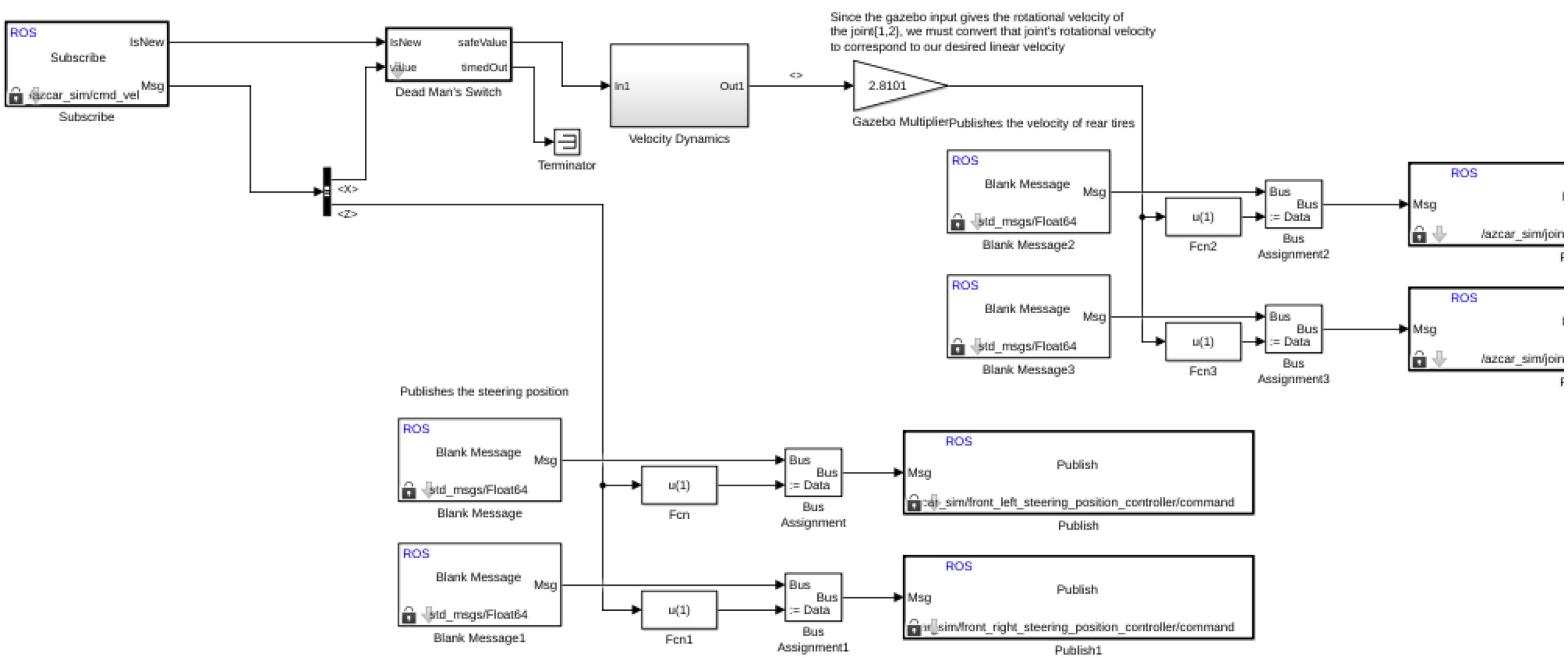
Computer Clock

* Not to scale. It's not like I plotted this in MATLAB or anything...

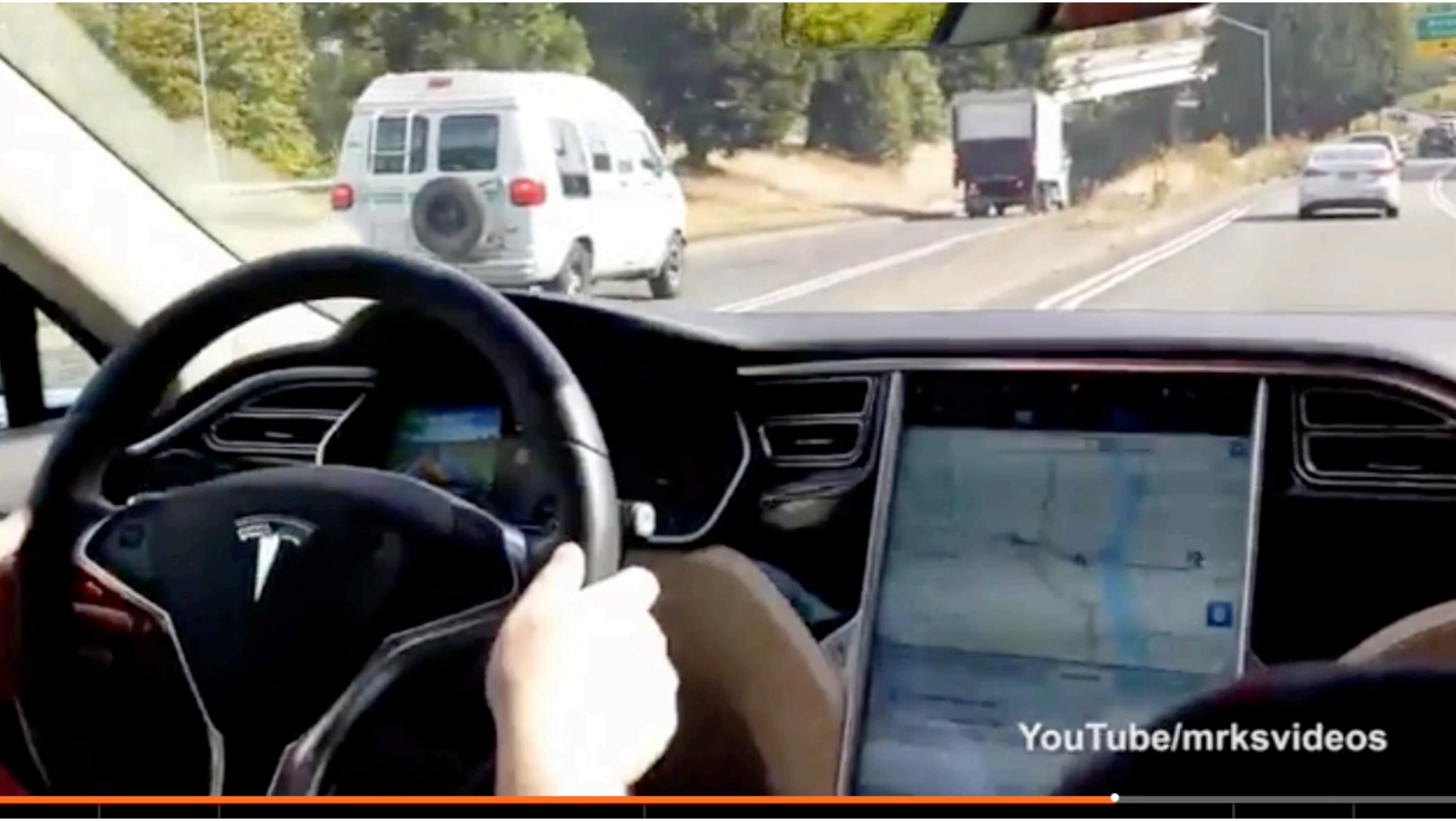
Event-triggered (reactive) models



Time-triggered (functional) models

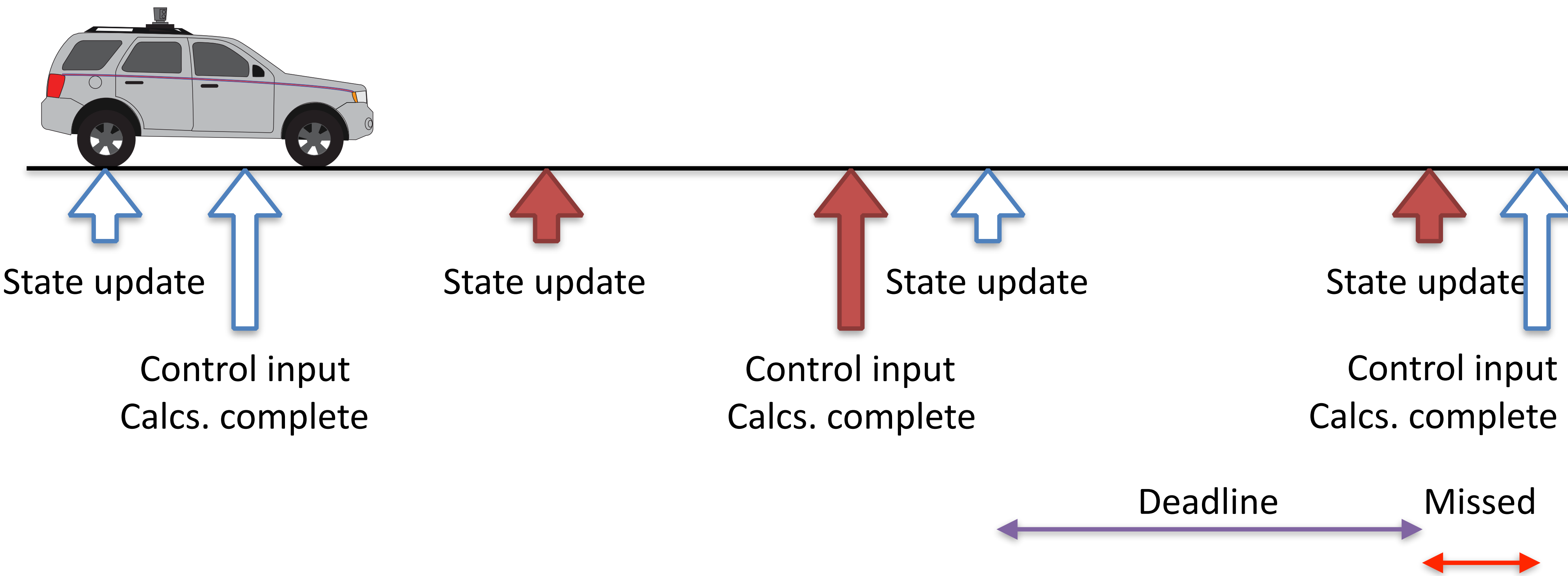


How much time do you have to act, as a controller?

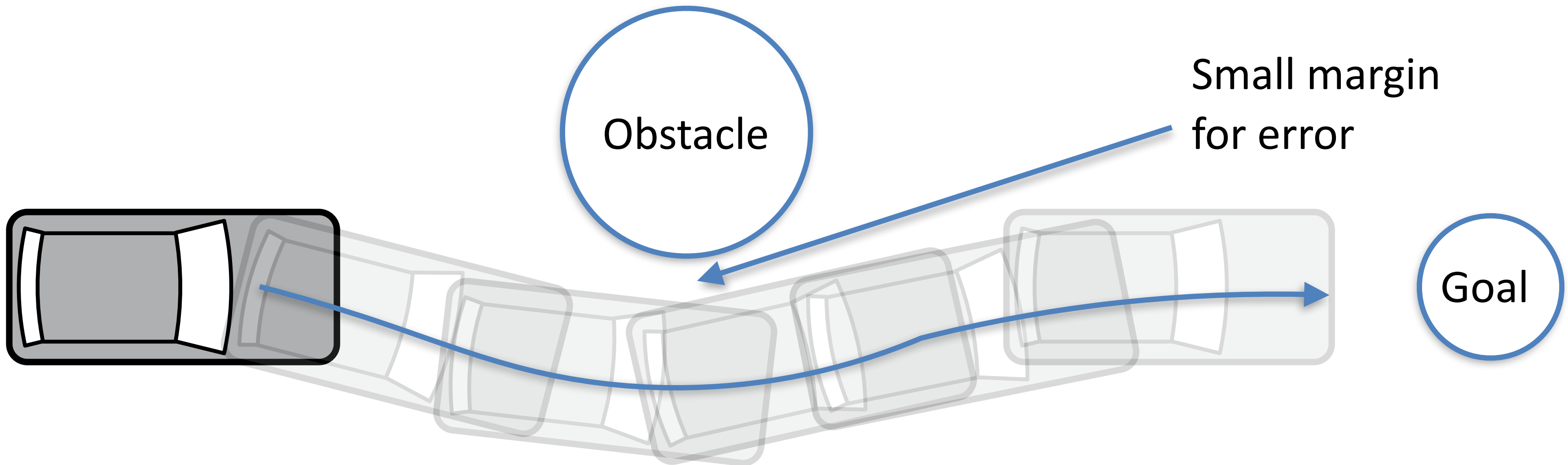


http://www.dailymail.co.uk/sciencetech/article-3281562/Tesla-autopilot-fail-videos-emerge-Terrifying-footage-shows-happens-autonomous-driving-goes-wrong.html

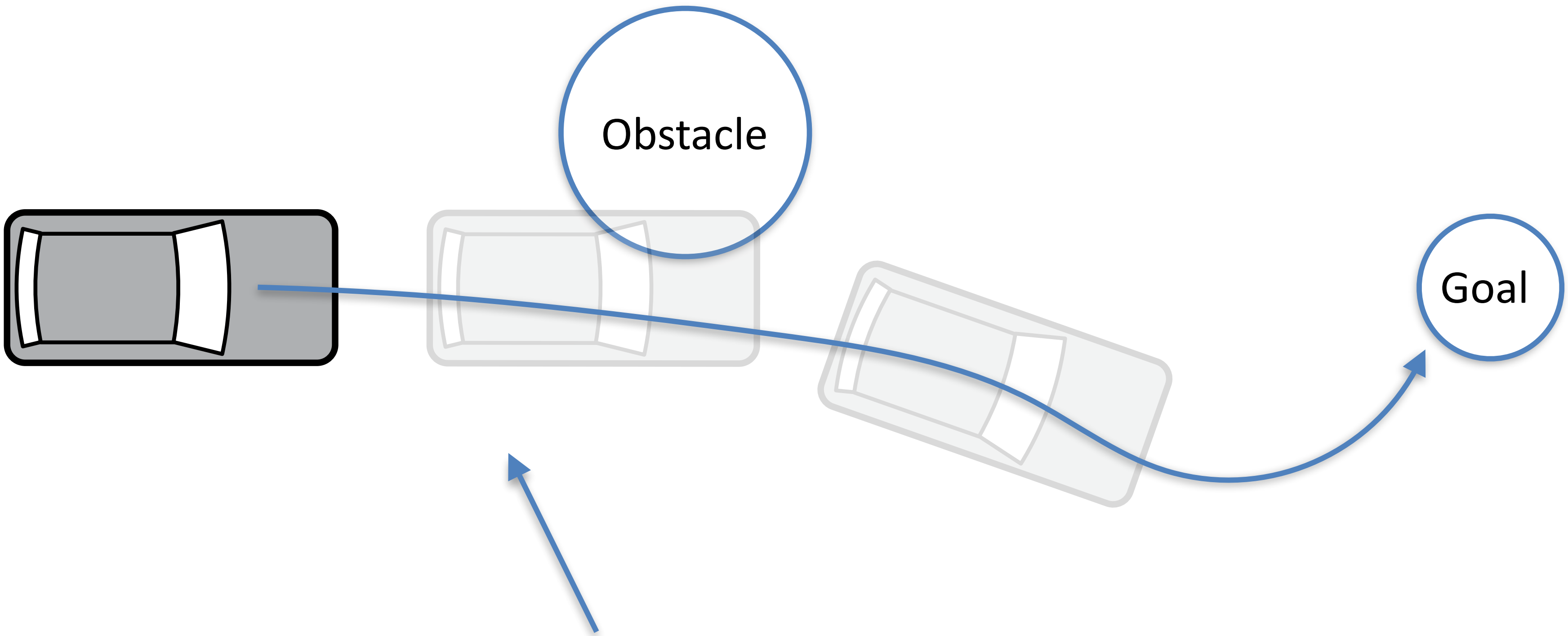
When computing a control decision…



Model-Predictive Control: Plan Trajectories at Runtime

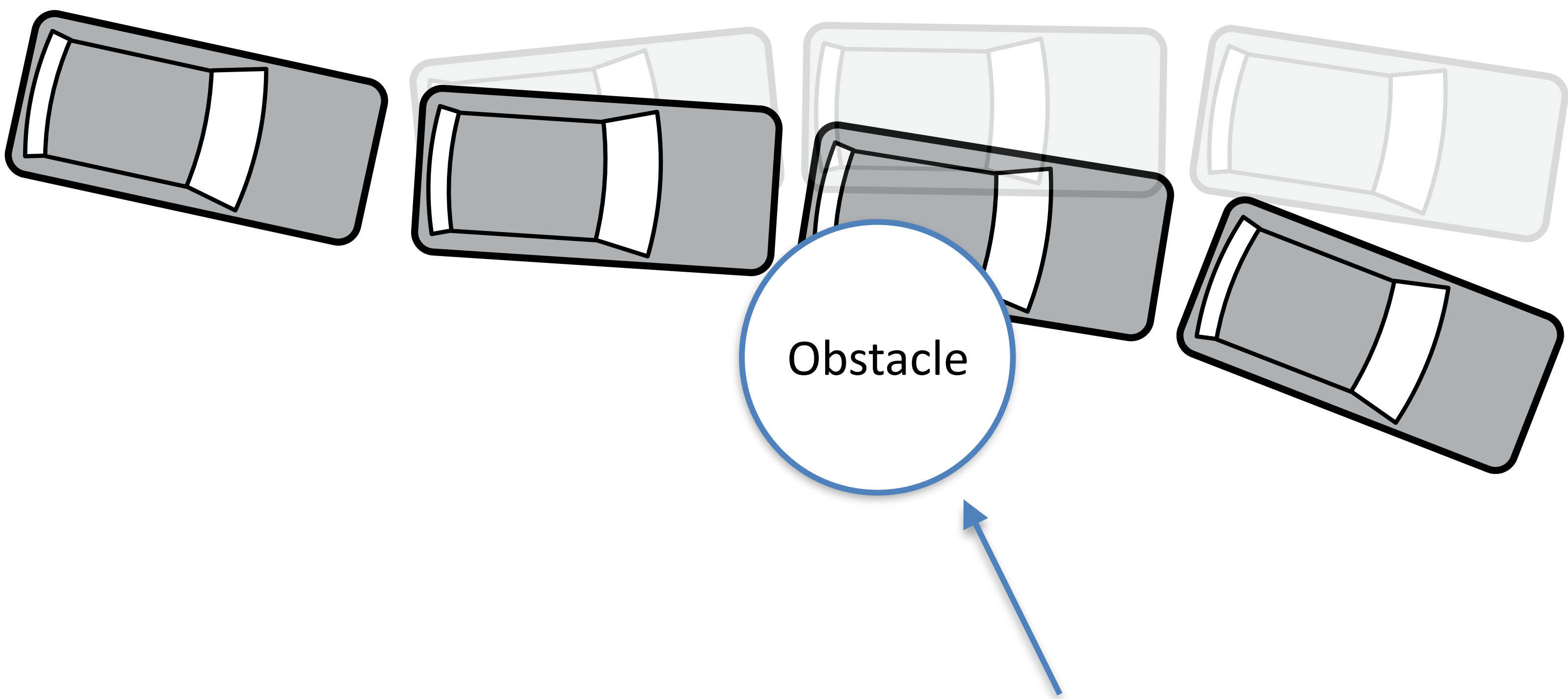


Easy…I'll use an accurate vehicle model to predict the trajectory and avoid the obstacle.



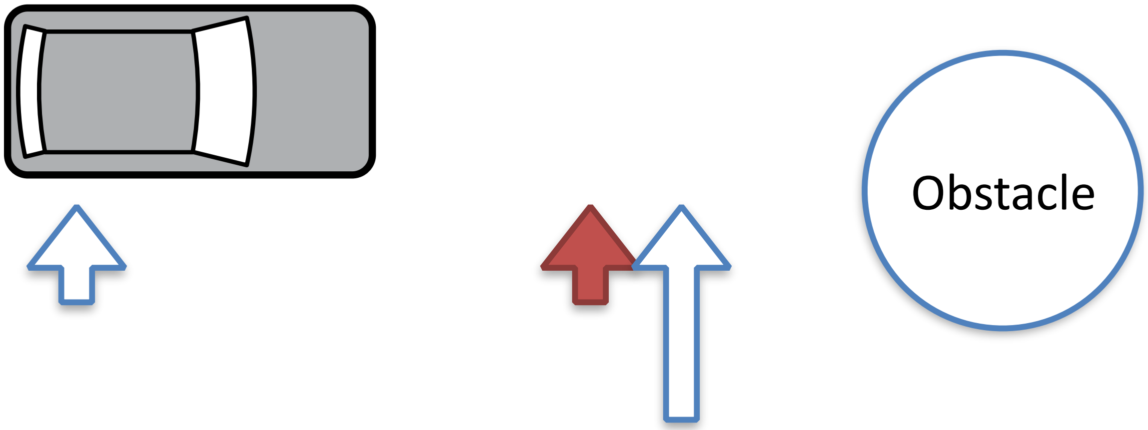
Takes longer to compute control inputs

Easy…I'll pick a simpler vehicle model to make it more likely to return control inputs in time

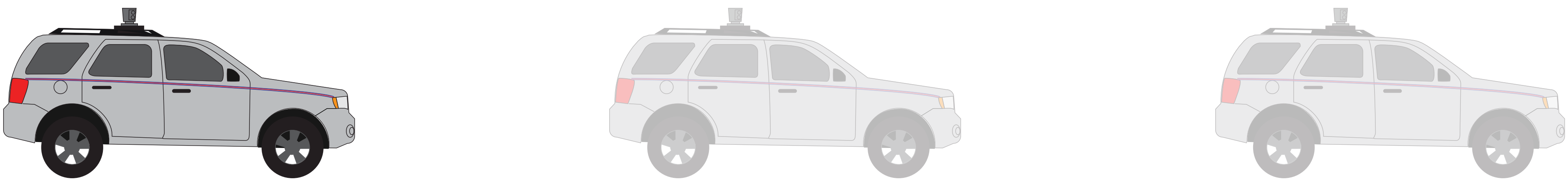


That control input does not mean what you think it means.

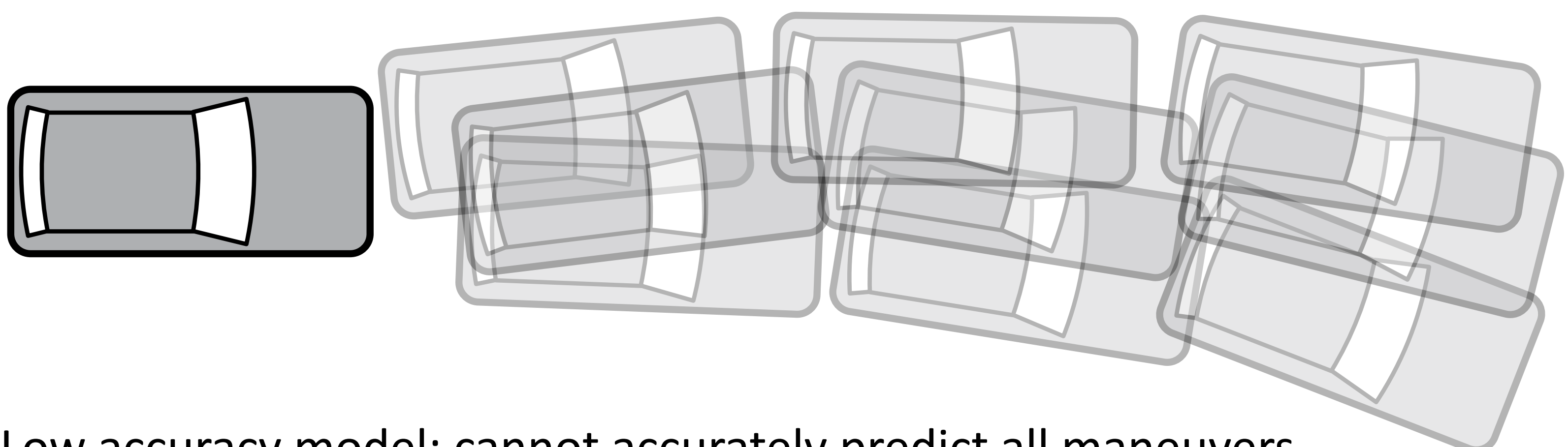
Competing constraints



High accuracy model: takes longer to optimize.



High vehicle speed: cannot tolerate slow return time.



Low accuracy model: cannot accurately predict all maneuvers.

Research: Computationally-Aware CPS

1. Consider the time required to perform the computation.
2. Switch between controllers using accuracy and time as switching criteria.
3. Explore conditions for stability and convergence.

Joint work with Kun Zhang and Ricardo Sanfelice

$$\xi_{k,t+1} = \hat{f}_q(\xi_{k,t}, u_{k,t})$$
$$t \in \{k, k+1, \cdots, k+N-1\}$$

MPC solves the optimization problem $\mathbf{P}^q(\xi_k)$ at time k by using the model $\hat{f}_q$. We denote the input sequence $\{u^q_{k,k}, u^q_{k,k+1}, \cdots, u^q_{k,k+N-1}\}$ by U^q_k, and formulate the following problem:

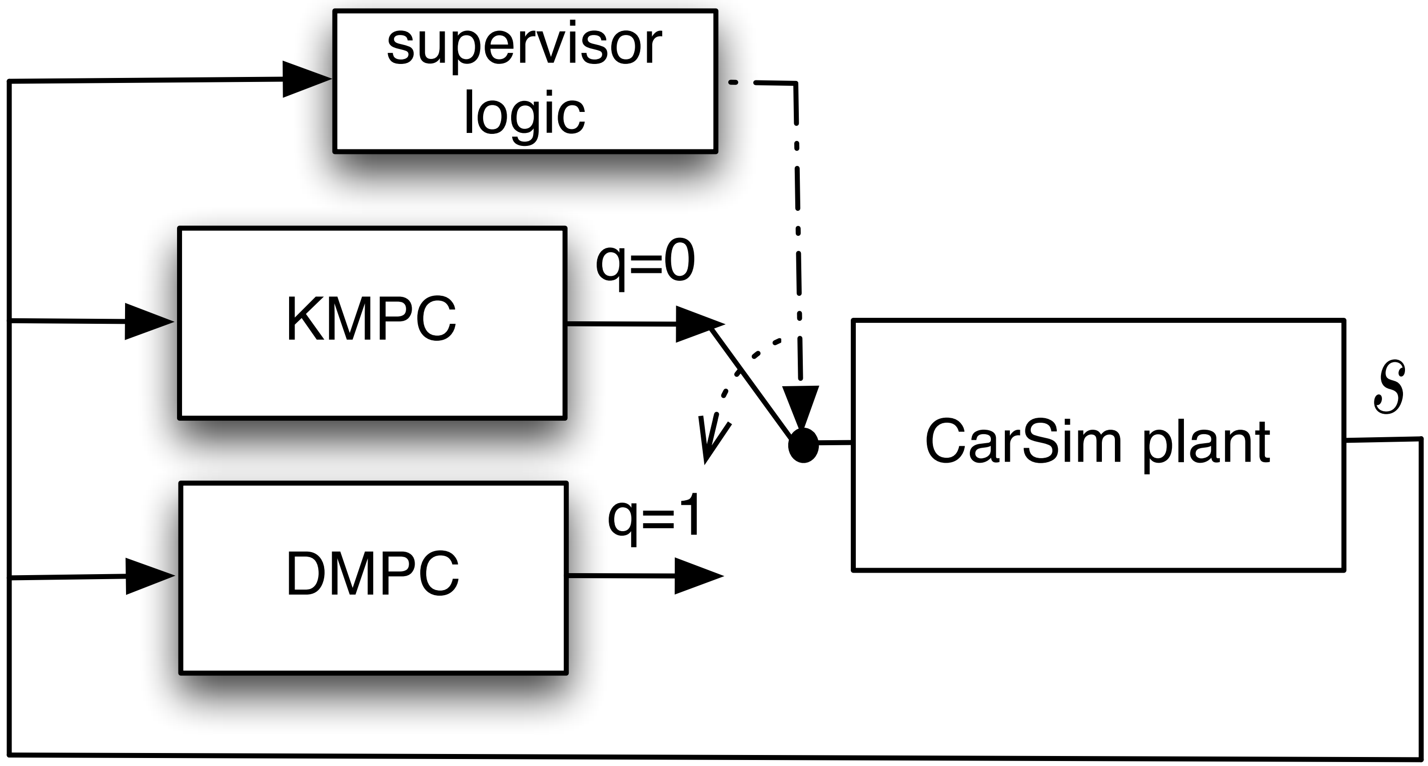
$$\mathbf{P}^q(\xi_k) : \underset{U^q_k}{\operatorname{argmin}}\{J_N(\xi_k, U^q_k) : U^q_k \subset \mathbb{R}^m\}$$

$$J_N(\xi_k, U^q_k) = \sum_{t=k}^{k+N-1} \ell(\xi^q_{k,t}, u^q_{k,t}) + F(\xi^q_{k,k+N})$$

$$U^{q*}_k = \{u^{q*}_{k,k}, u^{q*}_{k,k+1}, \cdots, u^{q*}_{k,k+N-1}\}$$

Problem Statement

Suppose at time $k \in \{0, 1, \cdots\}$, the vehicle state ξ_k is observed for an optimization problem indexed by the predictive model in use (i.e., $\mathbf{P}^q(\xi_k)$), and that two alternative predictive models are available.



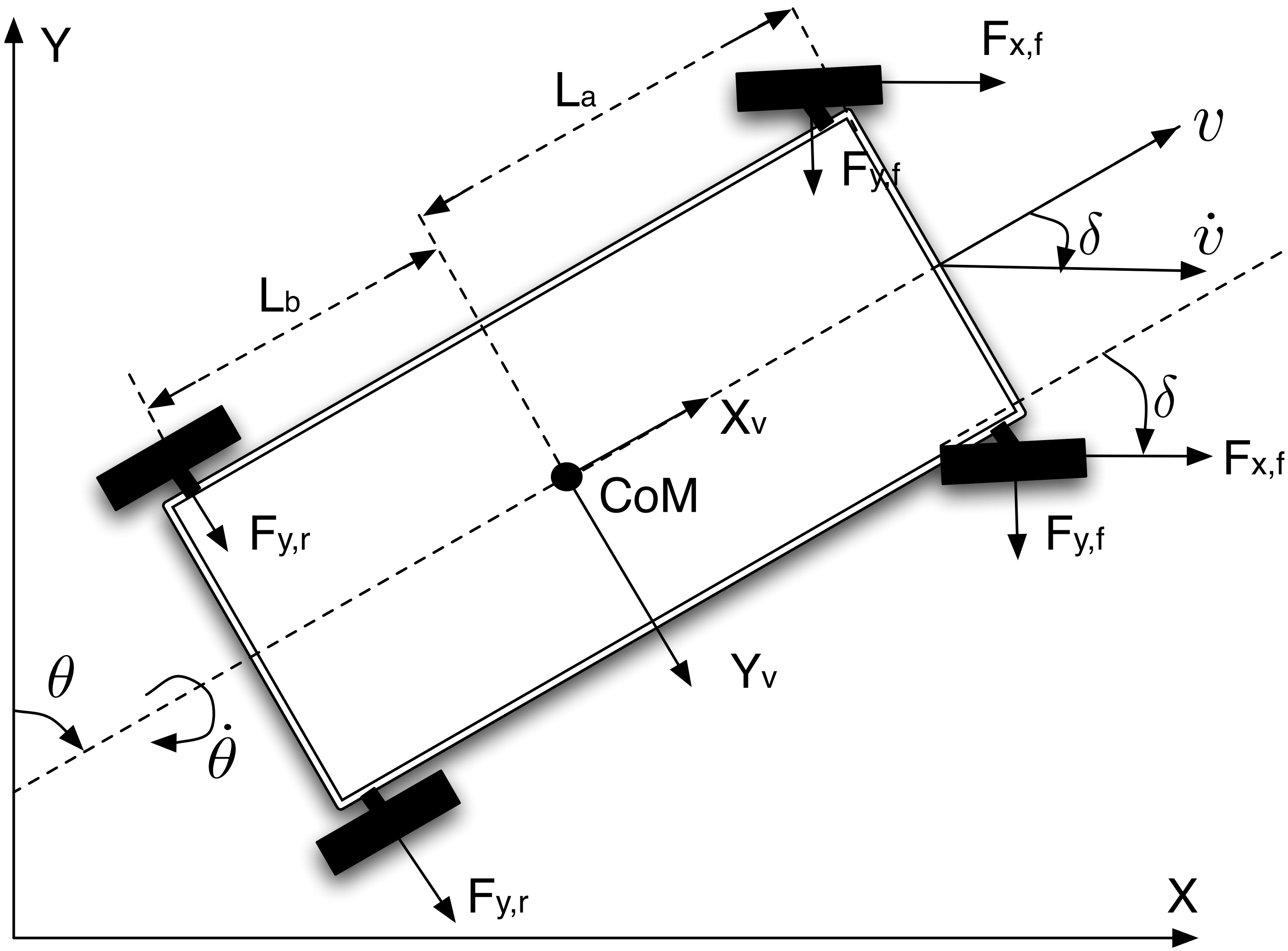
Problem: select the predictive model q such that the divergence of the state at ξ_k from the plant's state with the same inputs is minimized.

Kinematic/Dynamical Models

$$\dot{\xi} = \begin{bmatrix} v\sin\theta \\ v\cos\theta \\ \frac{v\tan\delta}{L} \end{bmatrix}$$

$$\dot{\xi} = \begin{bmatrix} v\sin(\theta) \\ v\cos(\theta) \\ \cos(\delta)a - \frac{2}{m}F_{y,f}\sin(\delta) \\ \varphi \\ \frac{1}{J}\left(L_a\left(ma\sin(\delta) + 2F_{y,f}\cos(\delta)\right) - 2L_bF_{y,r}\right) \\ \omega \end{bmatrix}$$

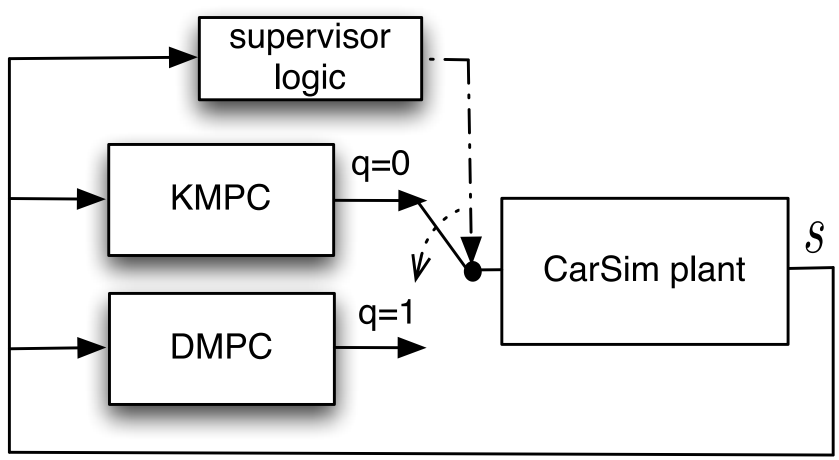
$$\dot{\xi} = \begin{bmatrix} v\sin(\theta) \\ v\cos(\theta) \\ \cos(\delta)a - \frac{2}{m}F_{y,f}\sin(\delta) \\ \varphi \\ \frac{1}{J}\left(L_a\left(ma\sin(\delta) + 2F_{y,f}\cos(\delta)\right) - 2L_bF_{y,r}\right) \\ \omega \end{bmatrix}$$



Hybrid MPC Design

$$\dot{\xi}^{q=0} = \begin{bmatrix} v\sin\theta \\ v\cos\theta \\ \frac{v\tan\delta}{L} \end{bmatrix} \qquad \dot{\xi}^{q=1} = \begin{bmatrix} v\sin(\theta) \\ v\cos(\theta) \\ \cos(\delta)a - \frac{2}{m}F_{y,f}\sin(\delta) \\ \varphi \\ \frac{1}{J}\left(L_a\left(ma\sin(\delta) + 2F_{y,f}\cos(\delta)\right) - 2L_bF_{y,r}\right) \\ \omega \end{bmatrix}$$

$$q = \underset{q}{\operatorname{argmin}} \left\| \xi_{k+1} - \xi_{k,k+1}^{q*} \right\|$$



Hybrid MPC Design

$$q = \underset{q}{\operatorname{argmin}} \left\| \xi_{k+1} - \xi_{k,k+1}^{q*} \right\|$$

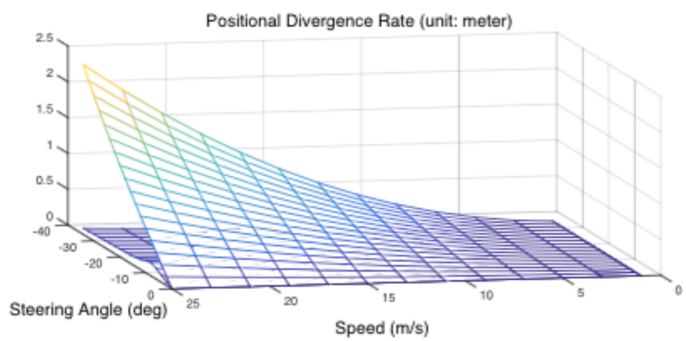
To make this decision, we need to know two things:

(1) Model mismatch **(2) Return time for MPC for this model**

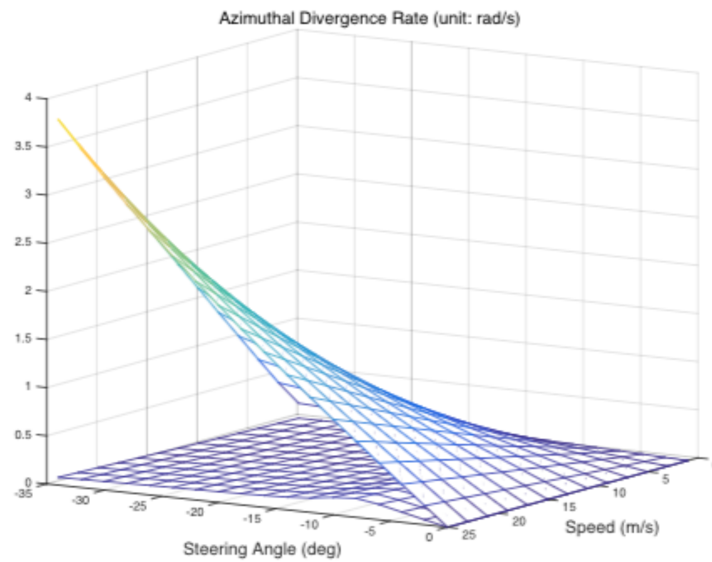
$$\left\| \xi_{k+1} - \xi_{k,k+1}^{q*} \right\| \leqslant \boxed{\left\| \hat{\Gamma}_q(\xi_k) \right\|} + \left\| I + \frac{\partial f\left(\xi_k, \kappa_q(\xi_k)\right)}{\partial \xi} \Delta T \right\| \left\| f\left(\xi_k, \kappa_q(\xi_k)\right) \right\| \boxed{\Delta t_q(\xi_k)}$$

$$\left\| \xi_{k+1} - \xi_{k,k+1}^{q*} \right\| \approx \boxed{\left\| \hat{\Gamma}_q(\xi_k) \right\|} + v \boxed{\Delta t_q(\xi_k)} \sqrt{1 + \left(\frac{\tan \delta}{L} v \Delta T \right)^2}$$

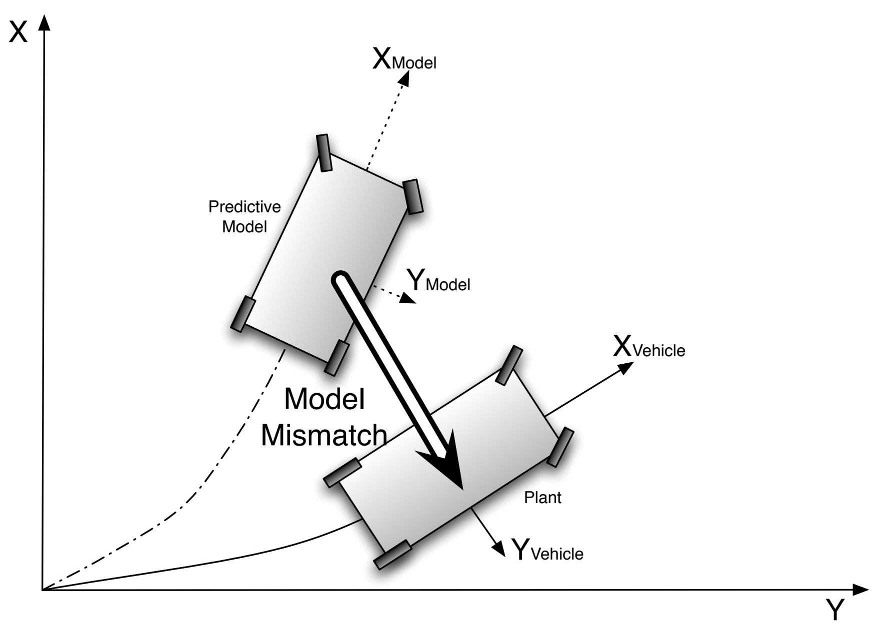
Model Mismatch & Return Time

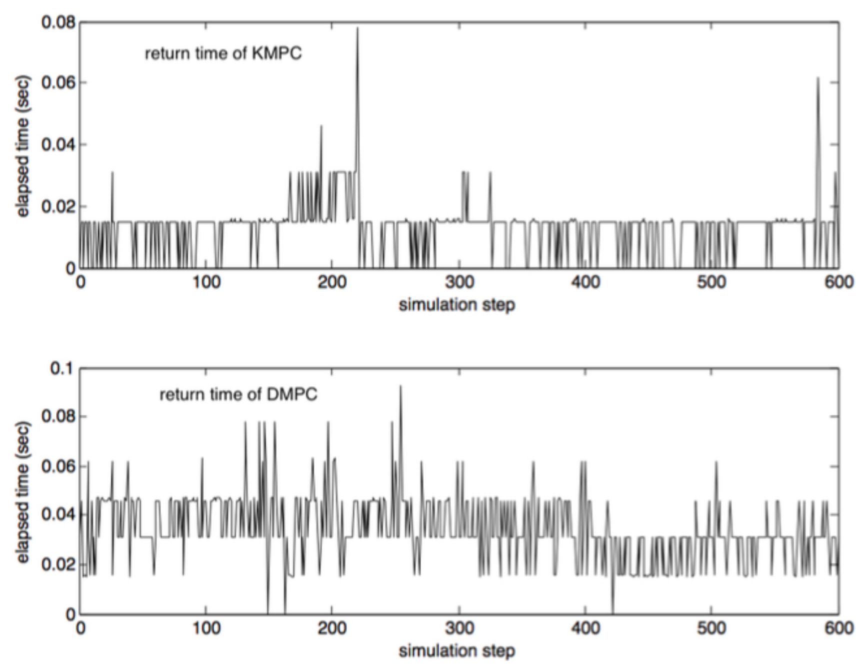


(a)

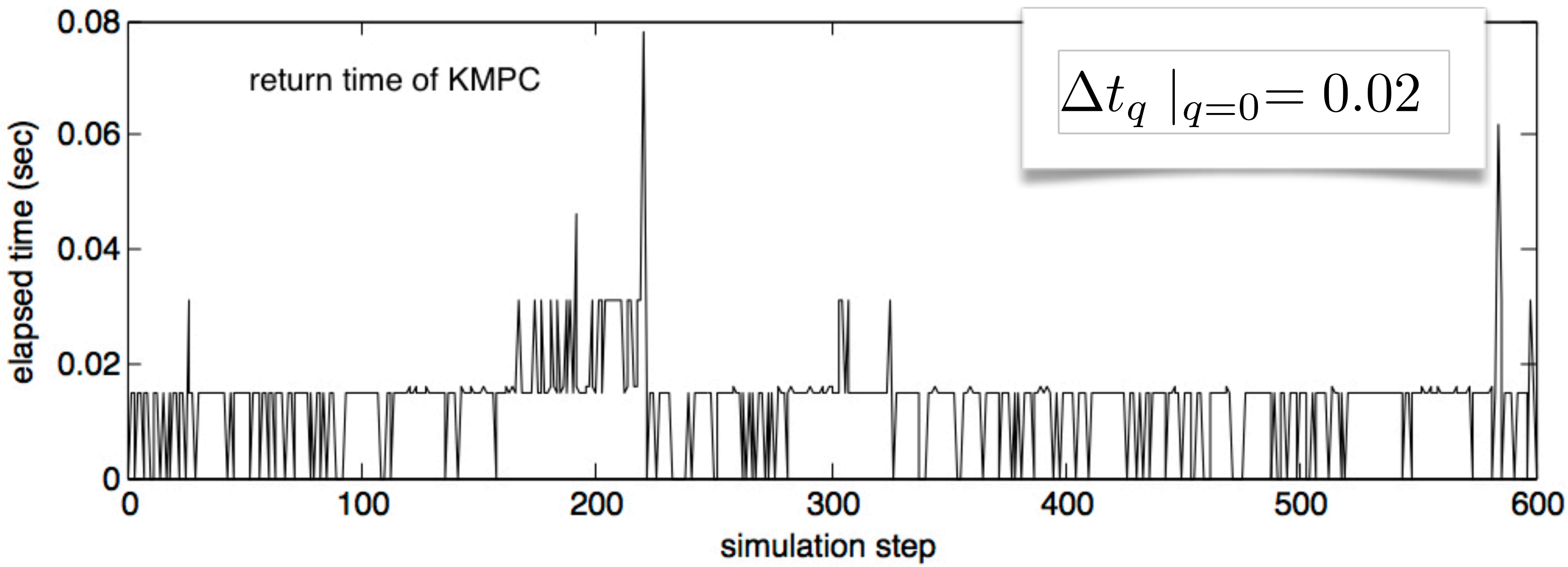


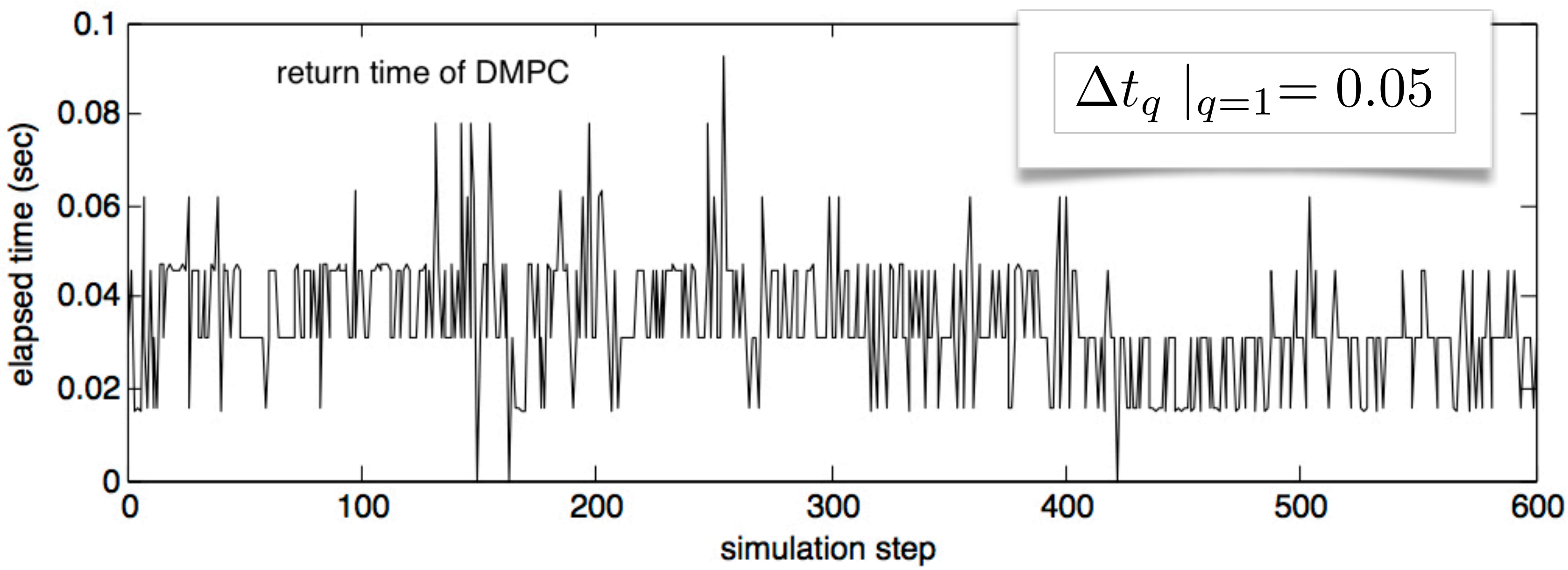
(b)





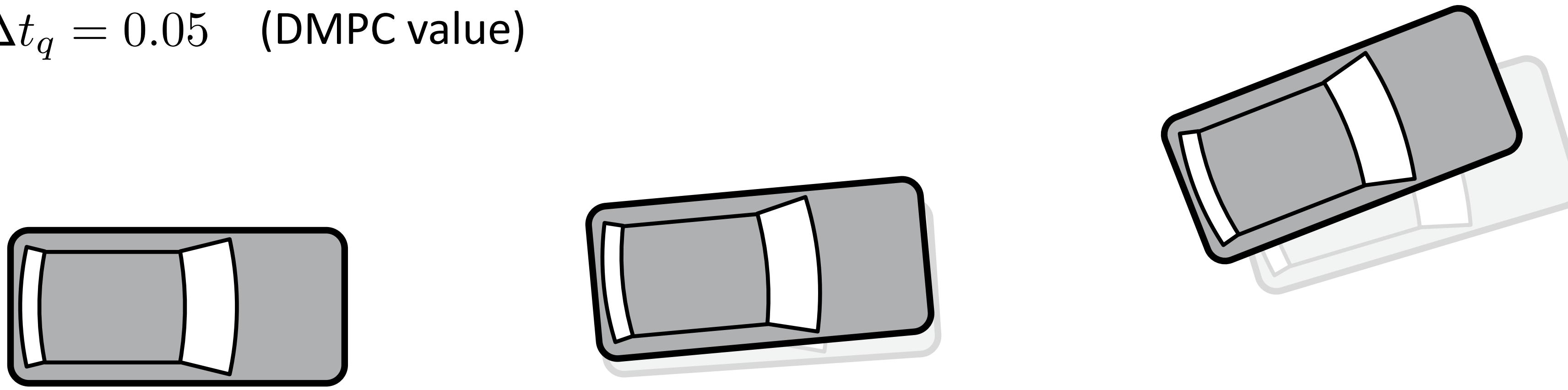
Time to return





Uncontrollable divergence: DMPC

$\Delta t_q = 0.05$ (DMPC value)

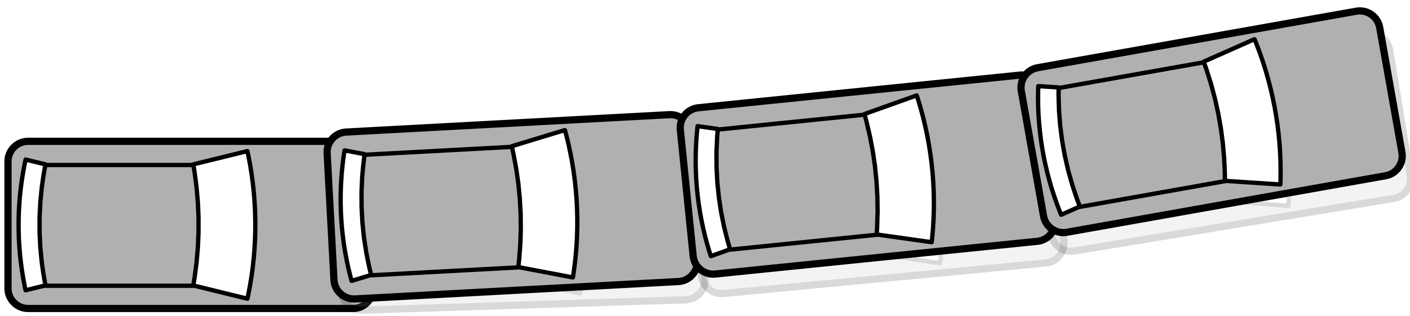


$$\dot{\xi}^{q=1} = \begin{bmatrix} v\sin(\theta) \\ v\cos(\theta) \\ \cos(\delta)a - \frac{2}{m}F_{y,f}\sin(\delta) \\ \varphi \\ \frac{1}{J}\left(L_a\left(ma\sin(\delta) + 2F_{y,f}\cos(\delta)\right) - 2L_bF_{y,r}\right) \\ \omega \end{bmatrix}$$

$$\left\| \xi_{k+1} - \xi^{q*}_{k,k+1} \right\|$$

Uncontrollable divergence: KMPC

$\Delta t_q = 0.02$ (KMPC value...)

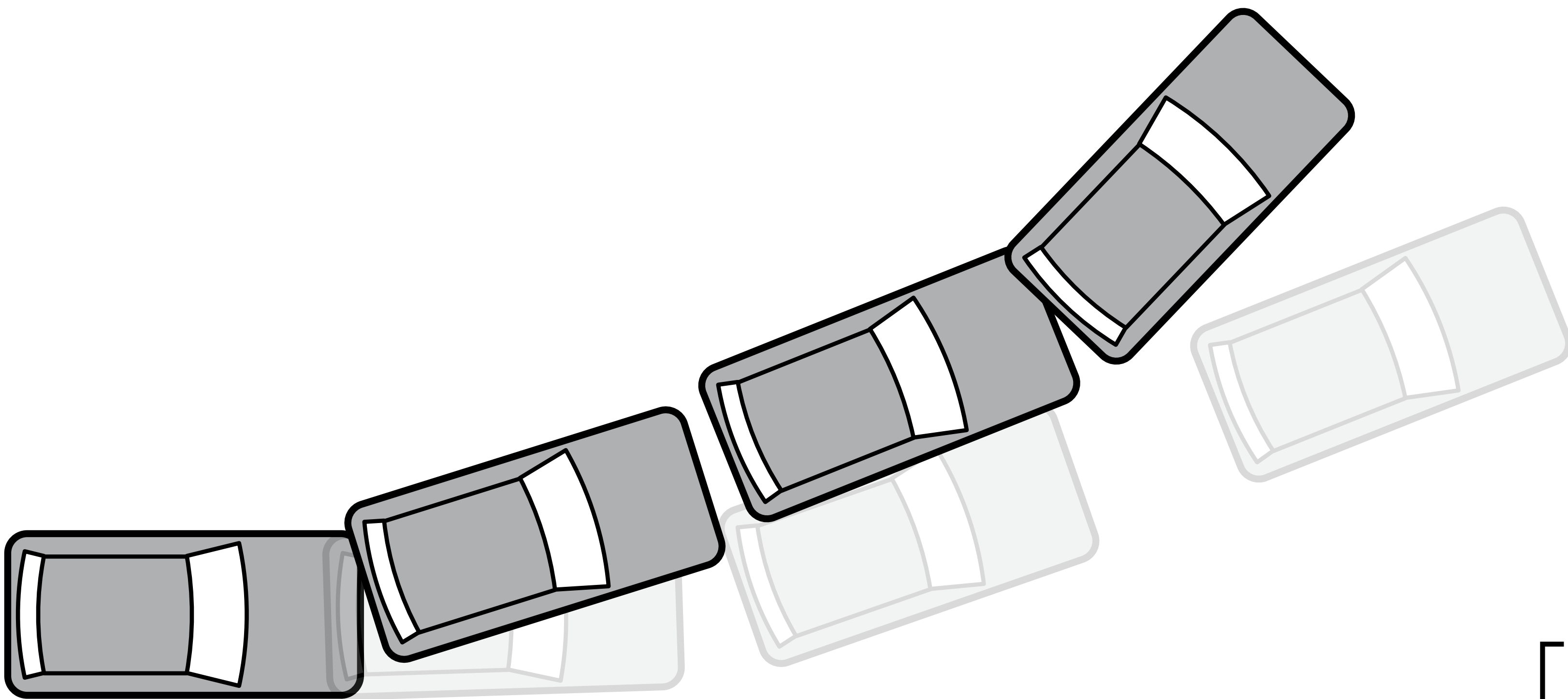


$$\dot{\xi}^{q=0} = \begin{bmatrix} v \sin\theta \\ v \cos\theta \\ \frac{v \tan\delta}{L} \end{bmatrix}$$

$$\left\| \xi_{k+1} - \xi^{q*}_{k,k+1} \right\|$$

Uncontrollable divergence: KMPC with large steering

$\Delta t_q = 0.02$ (KMPC value...)



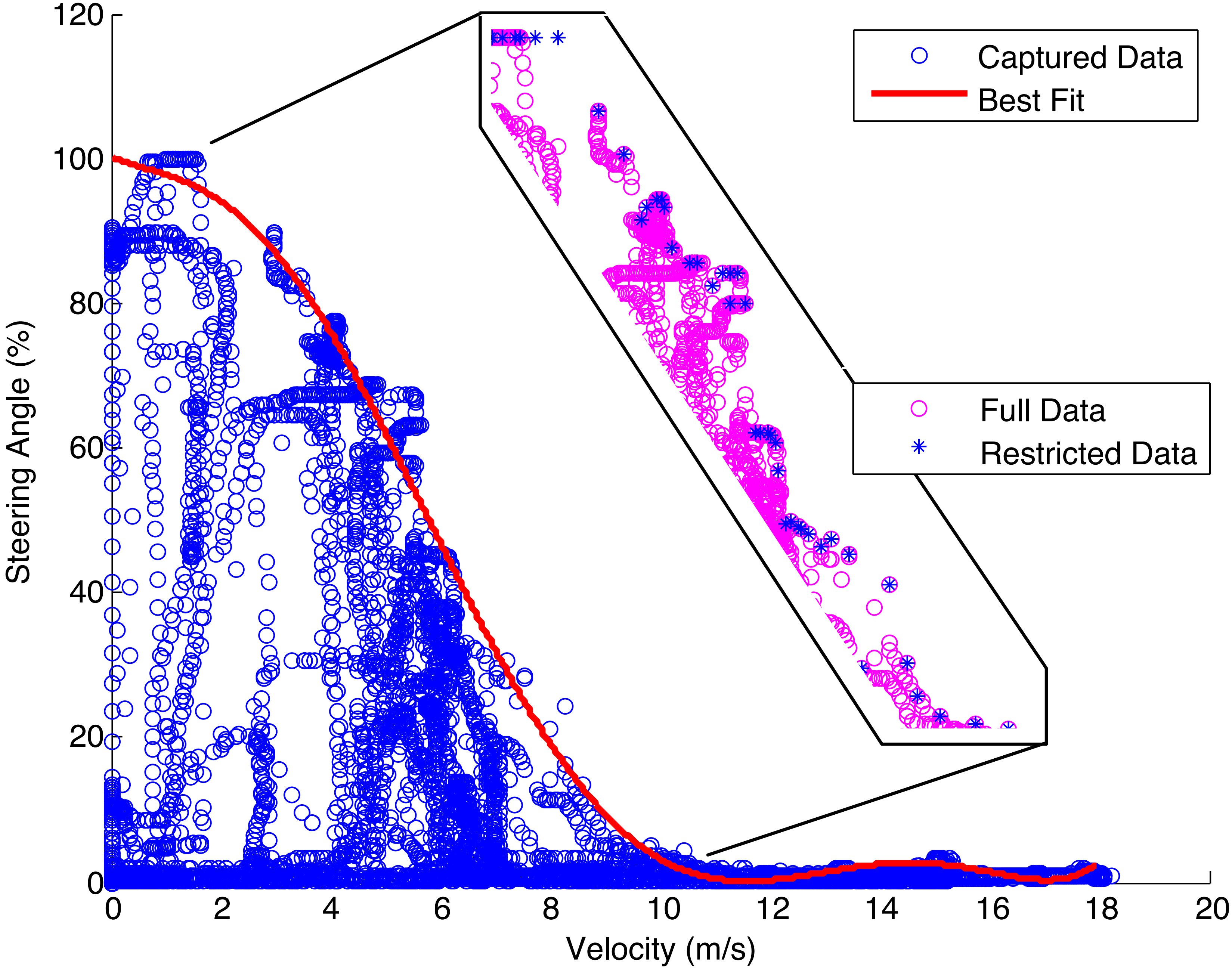
$$\dot{\xi}^{q=0} = \begin{bmatrix} v\sin\theta \\ v\cos\theta \\ \frac{v\tan\delta}{L} \end{bmatrix}$$

$$\left\| \xi_{k+1} - \xi^{q*}_{k,k+1} \right\|$$

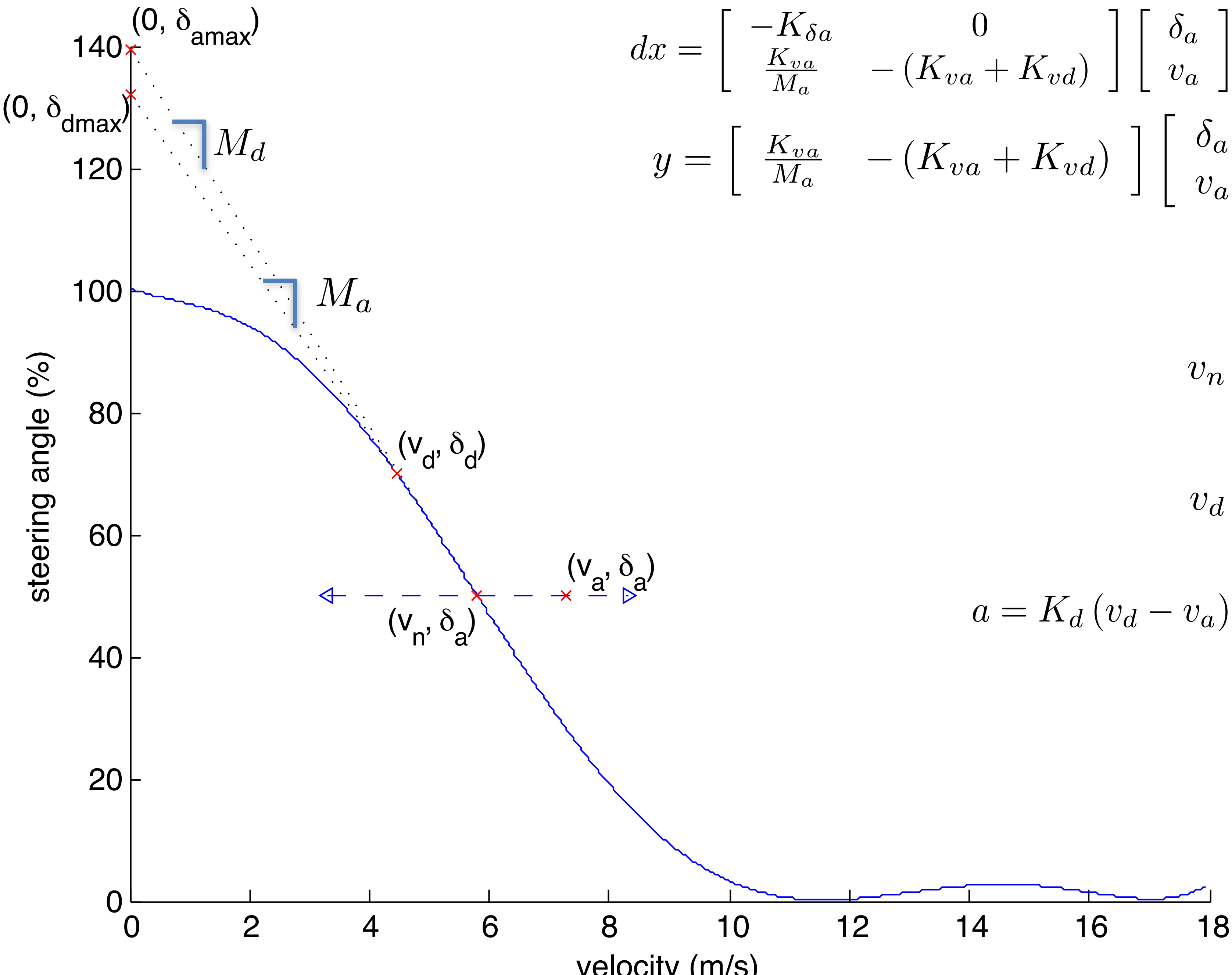
https://youtu.be/-ZDdhjZYP4A

Photo By Twilight Invasion

Fortunate Previous Result from [1]



Take the fit data and utilize linearization techniques



$$dx = \begin{bmatrix} -K_{\delta a} & 0 \\ \frac{K_{va}}{M_a} & -(K_{va} + K_{vd}) \end{bmatrix} \begin{bmatrix} \delta_a \\ v_a \end{bmatrix} + \begin{bmatrix} -K_{\delta d} \\ \frac{K_{vd}}{M_d} \end{bmatrix} \delta_d$$

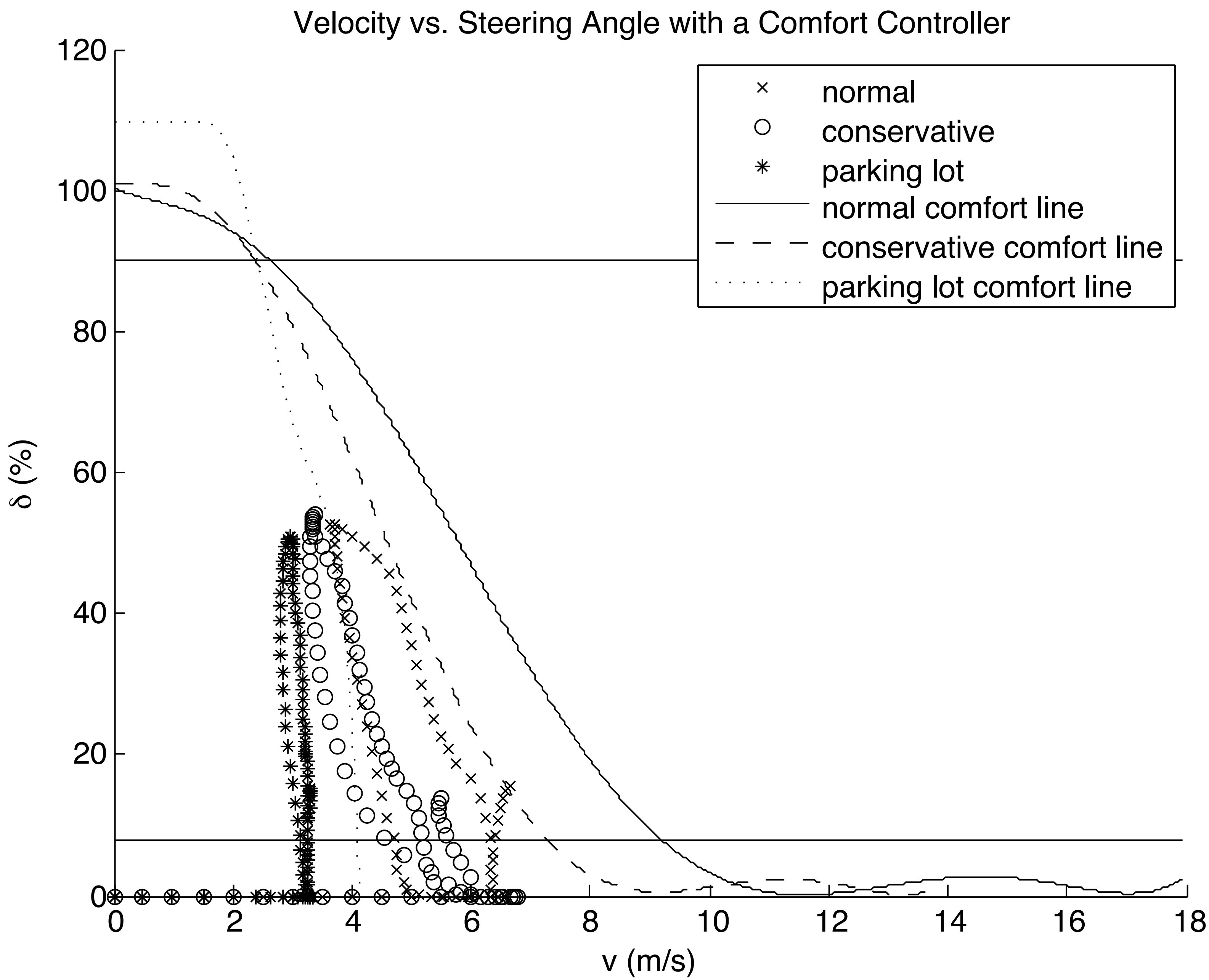
$$y = \begin{bmatrix} \frac{K_{va}}{M_a} & -(K_{va} + K_{vd}) \end{bmatrix} \begin{bmatrix} \delta_a \\ v_a \end{bmatrix} + \begin{bmatrix} \frac{K_{vd}}{M_d} \end{bmatrix} \delta_d$$

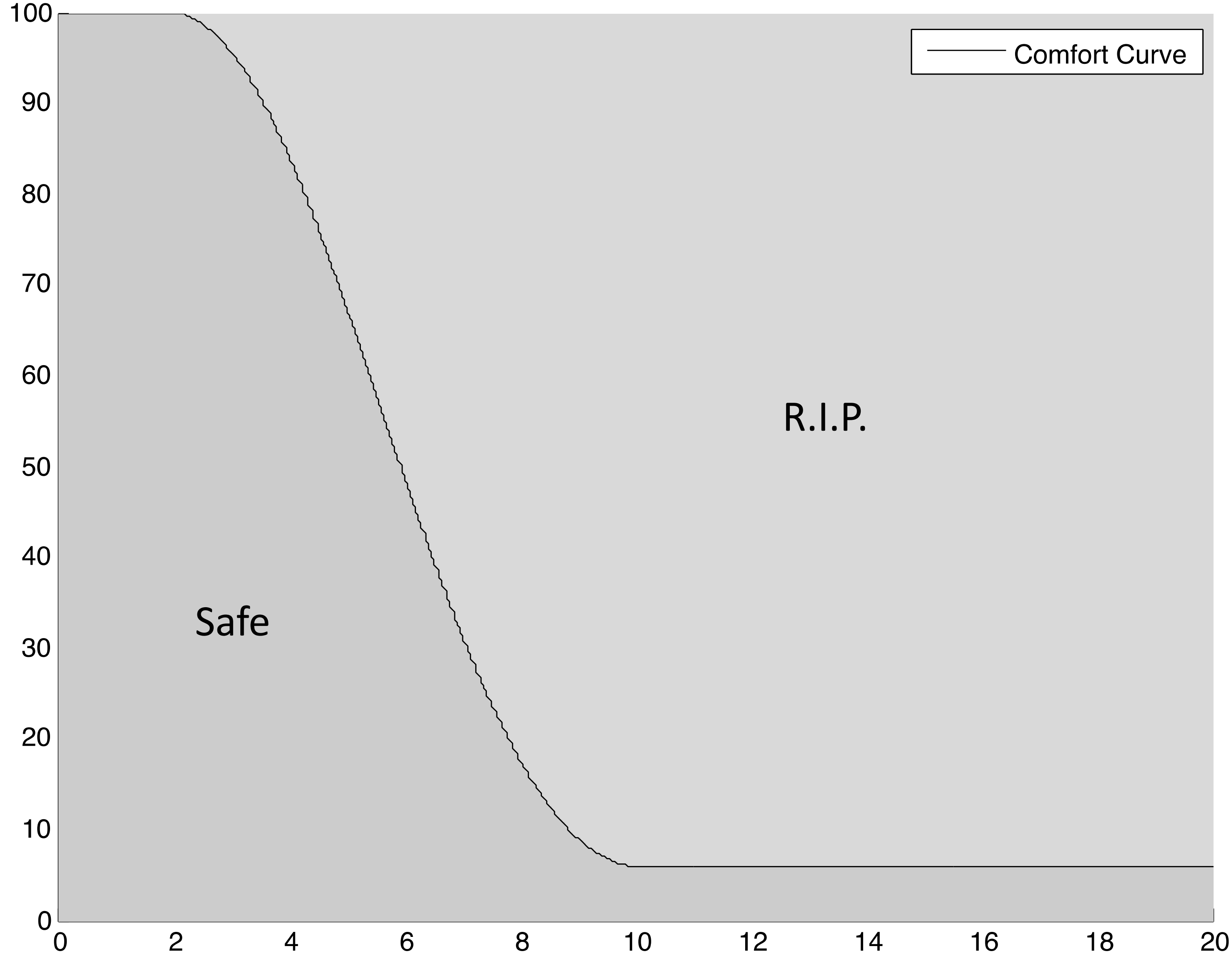
$$v_n = \frac{\delta_a - \delta_{amax}}{M_a}$$

$$v_d = \frac{\delta_d - \delta_{dmax}}{M_d}$$

$$a = K_d (v_d - v_a) + K_a (v_n - v_a)$$

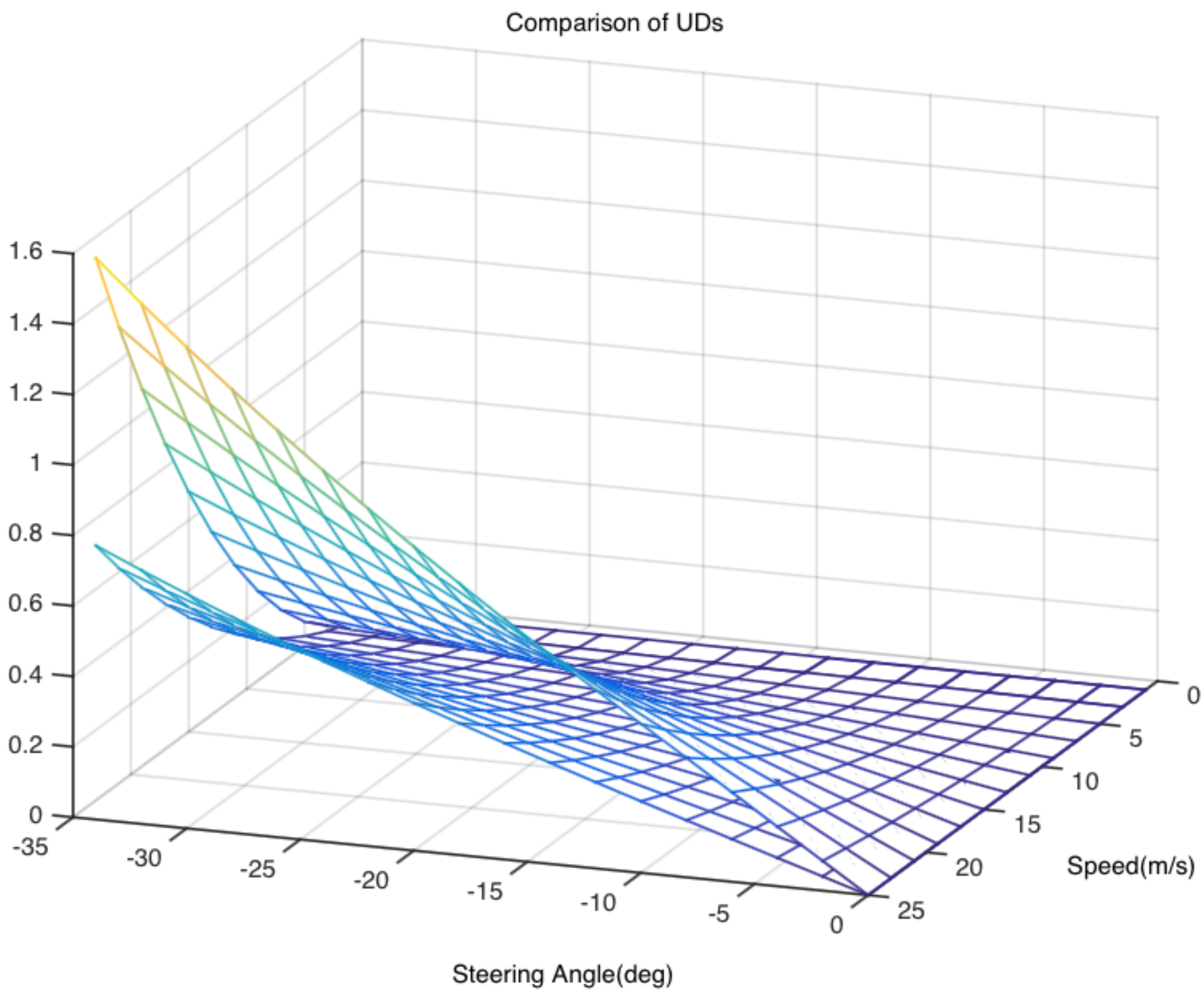
Scatter plot with comfort controller



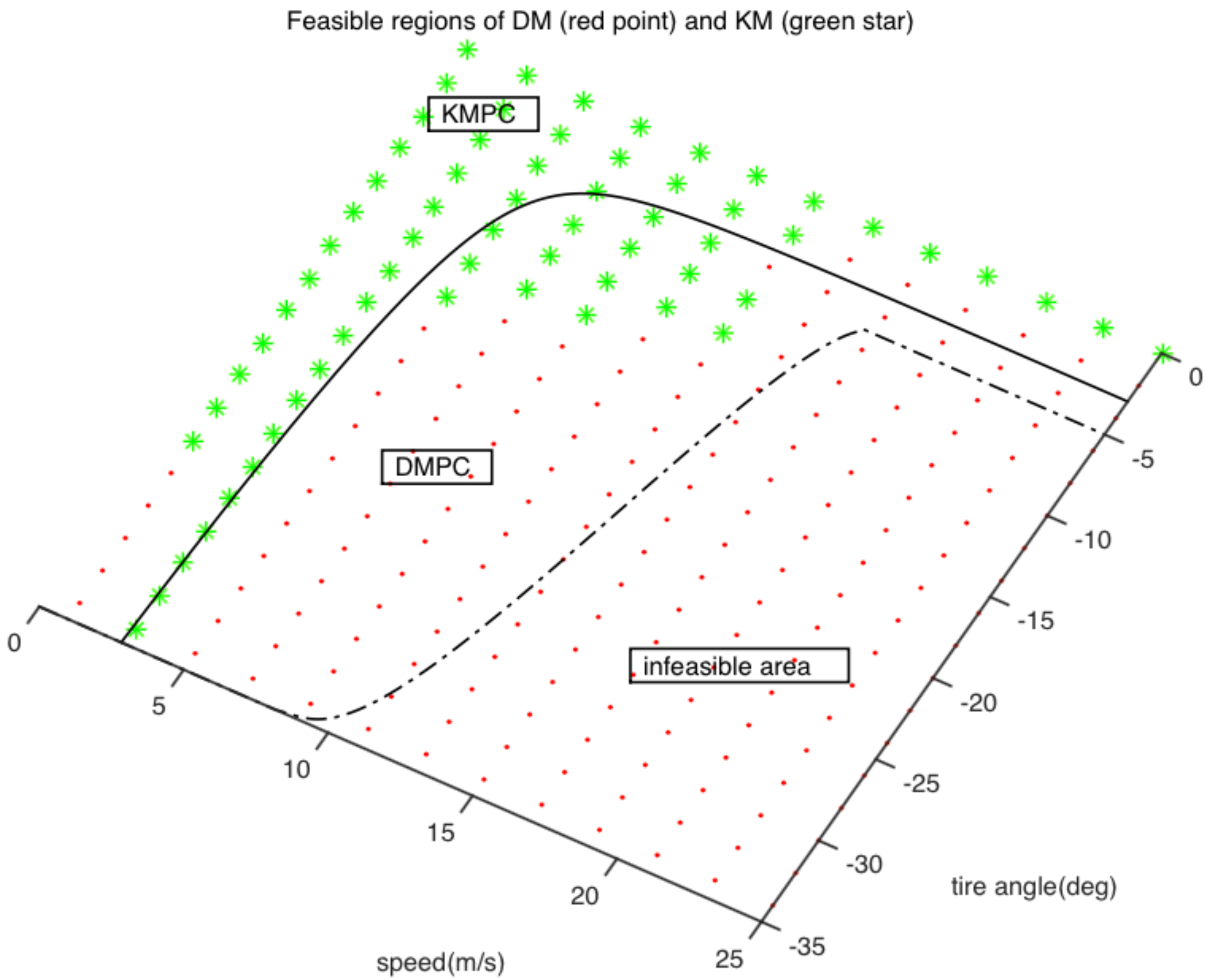


100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
16
18
20
Comfort Curve
R.I.P.
Safe

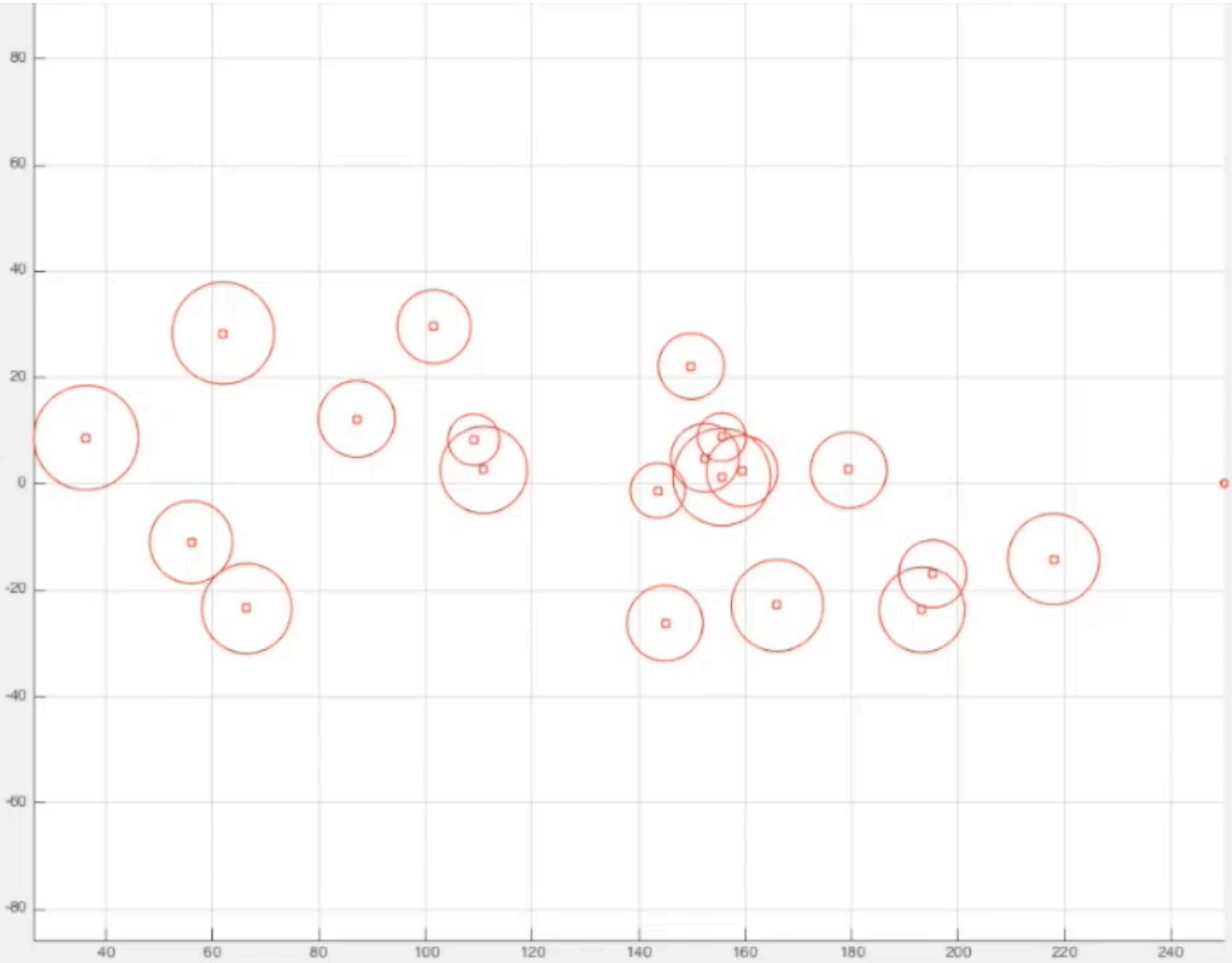
Hybrid MPC Design



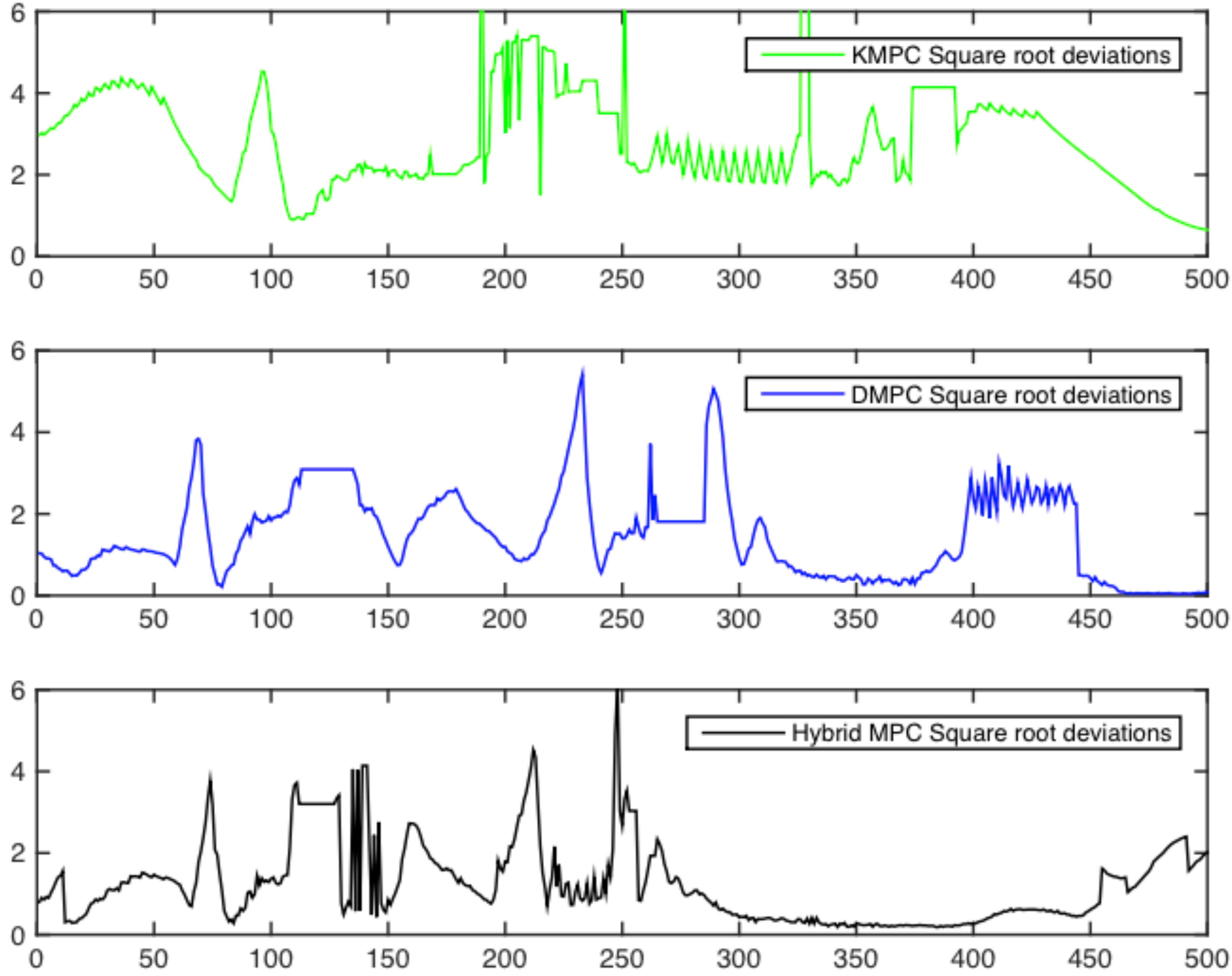
Hybrid MPC Design

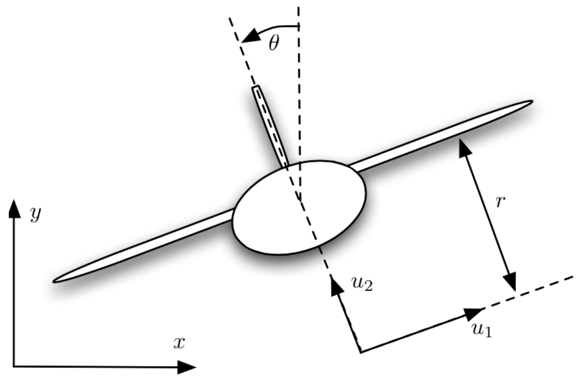


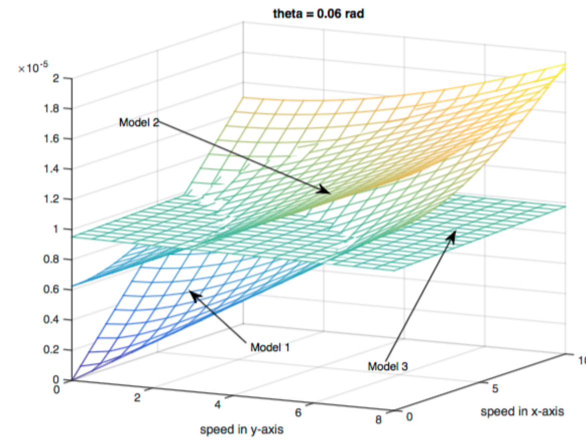
What about lots of obstacles?

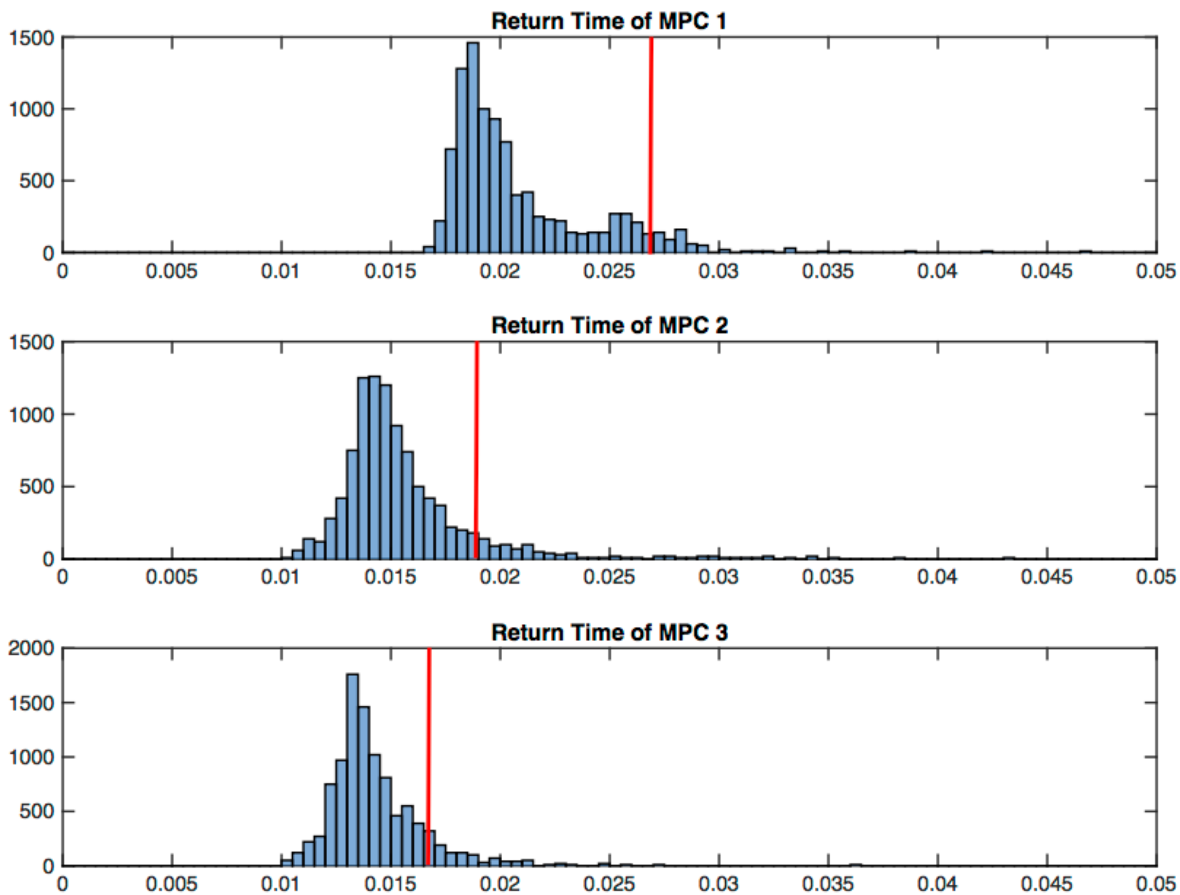


Simulation Result



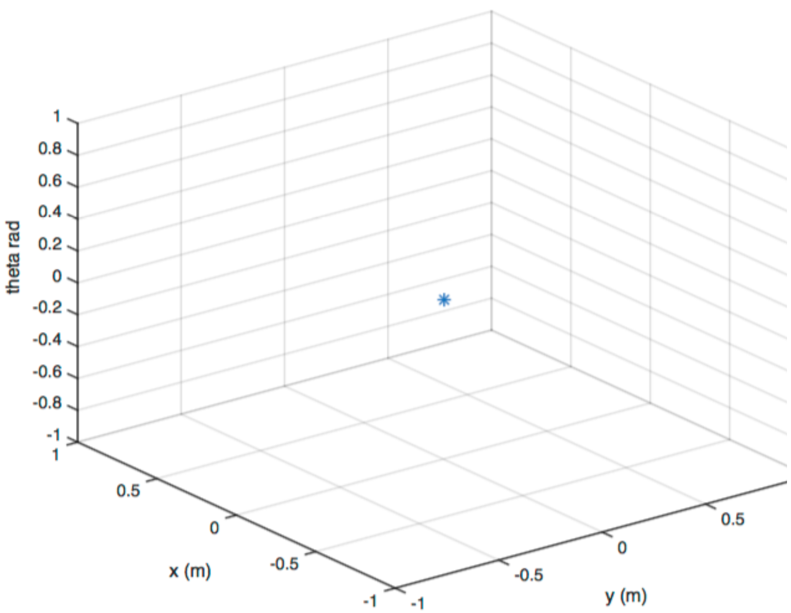

θ
r
y
x
u_2
u_1

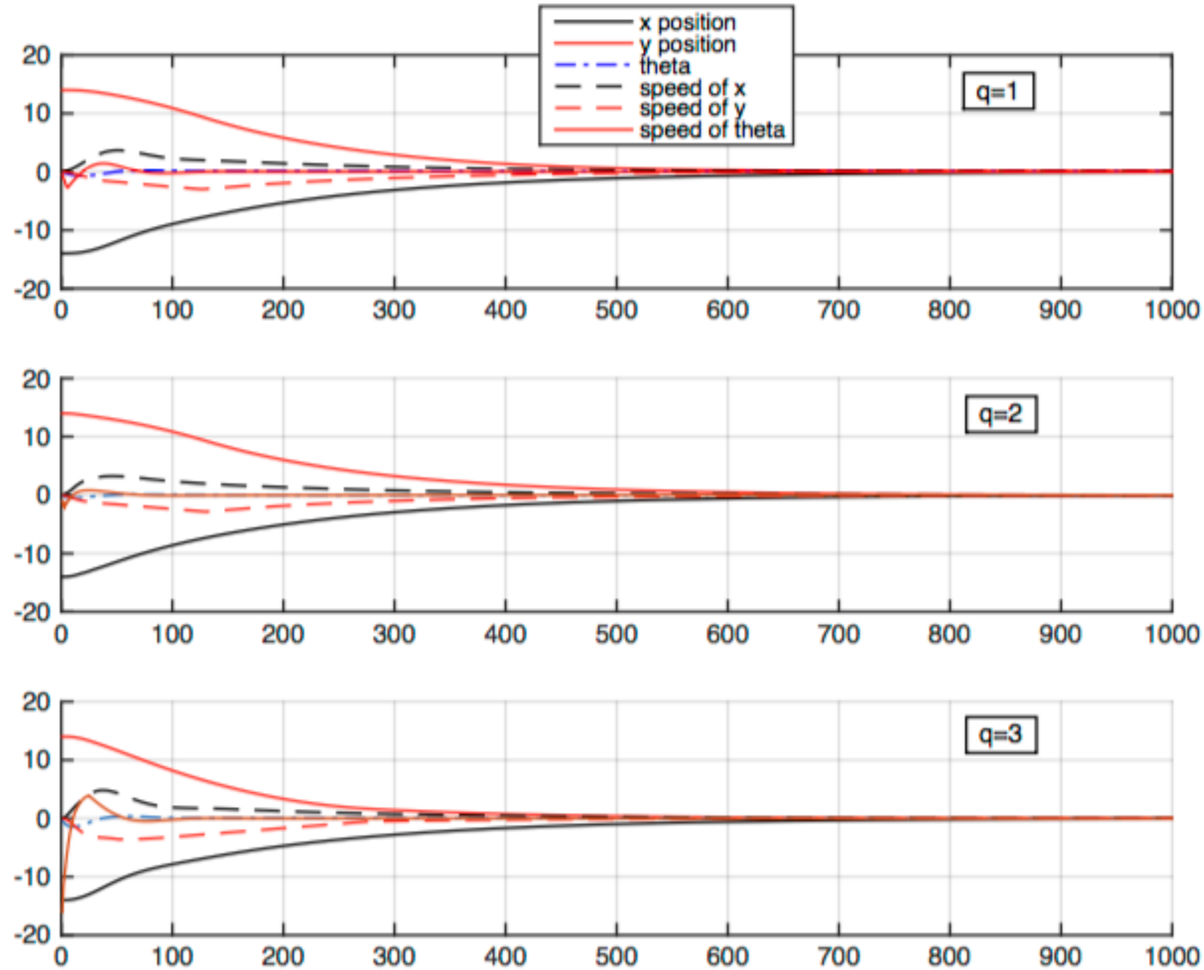

theta = 0.06 rad
$\times 10^{-5}$
Model 2
Model 1
Model 3
speed in y-axis
speed in x-axis


Return Time of MPC 1
Return Time of MPC 2
Return Time of MPC 3

Each model converges

$$
\begin{aligned}
R^{\mathrm{MPC}} &= \max\left(\max_q\left(\frac{b^q}{a^q}\right)^{\frac{1}{\sigma}}, \max_q\left(\frac{b^q}{a^q}\frac{b^{\bar{q}}}{a^{\bar{q}}}\gamma\right)^{\frac{1}{\sigma}}\right)\underline{\mathrm{R}}^{q+} \\
&= \max_q\left(\left(\frac{350}{250}\right)^{\frac{1}{2}}, \left(\frac{350}{250}\frac{350}{250}0.95\right)^{\frac{1}{2}}\right)0 \\
&= 0
\end{aligned}
$$

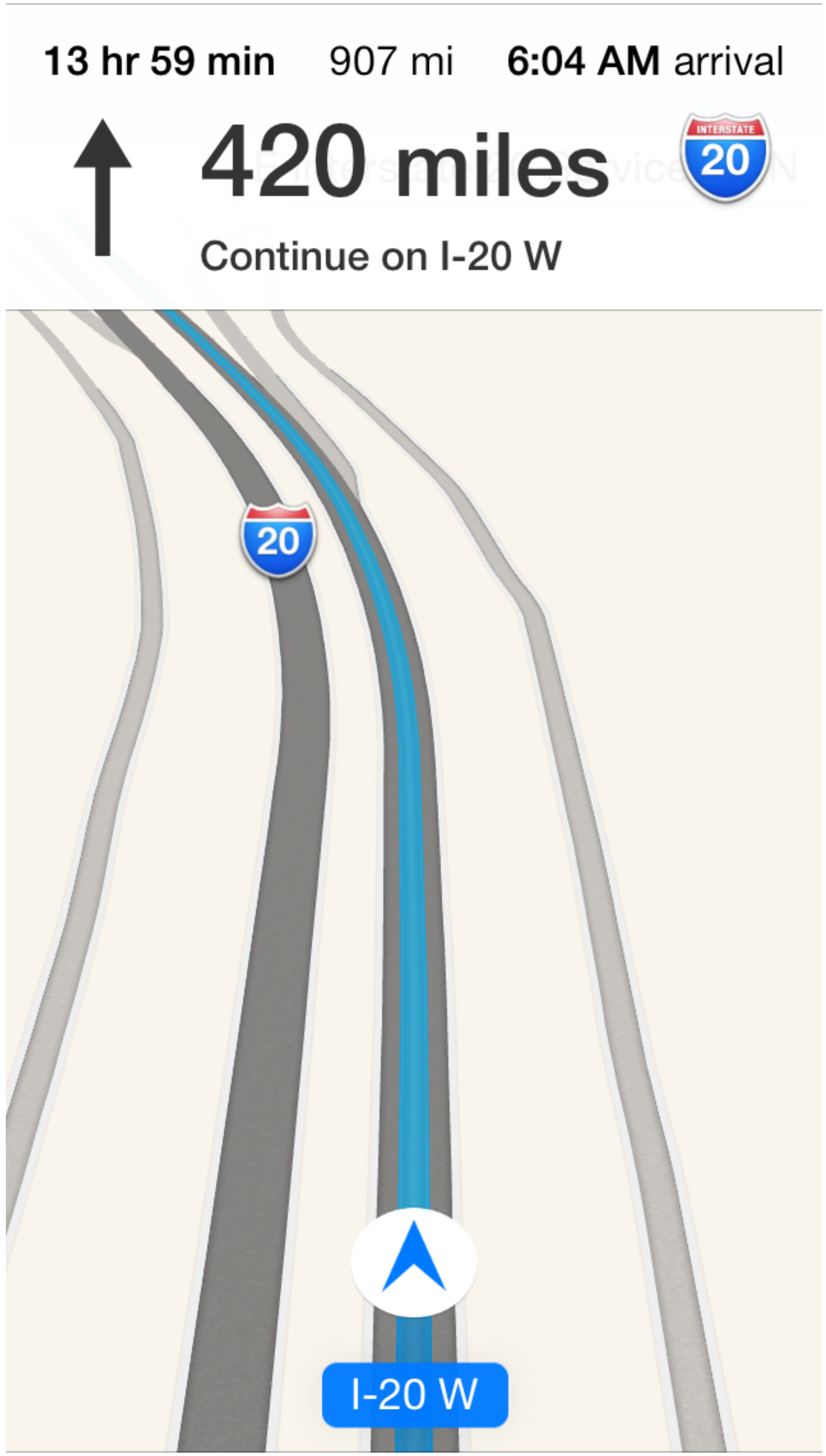




Numerical results of the superlevel sets of all three models suggest that each of these three MPCs can bound the aircraft to the origin, or at least a small ball containing the origin with a radius smaller than the discrete spatial steps.

Cheaper sensors may not be able to do it all.

But maybe they can do a lot of the tasks we don't like to do.

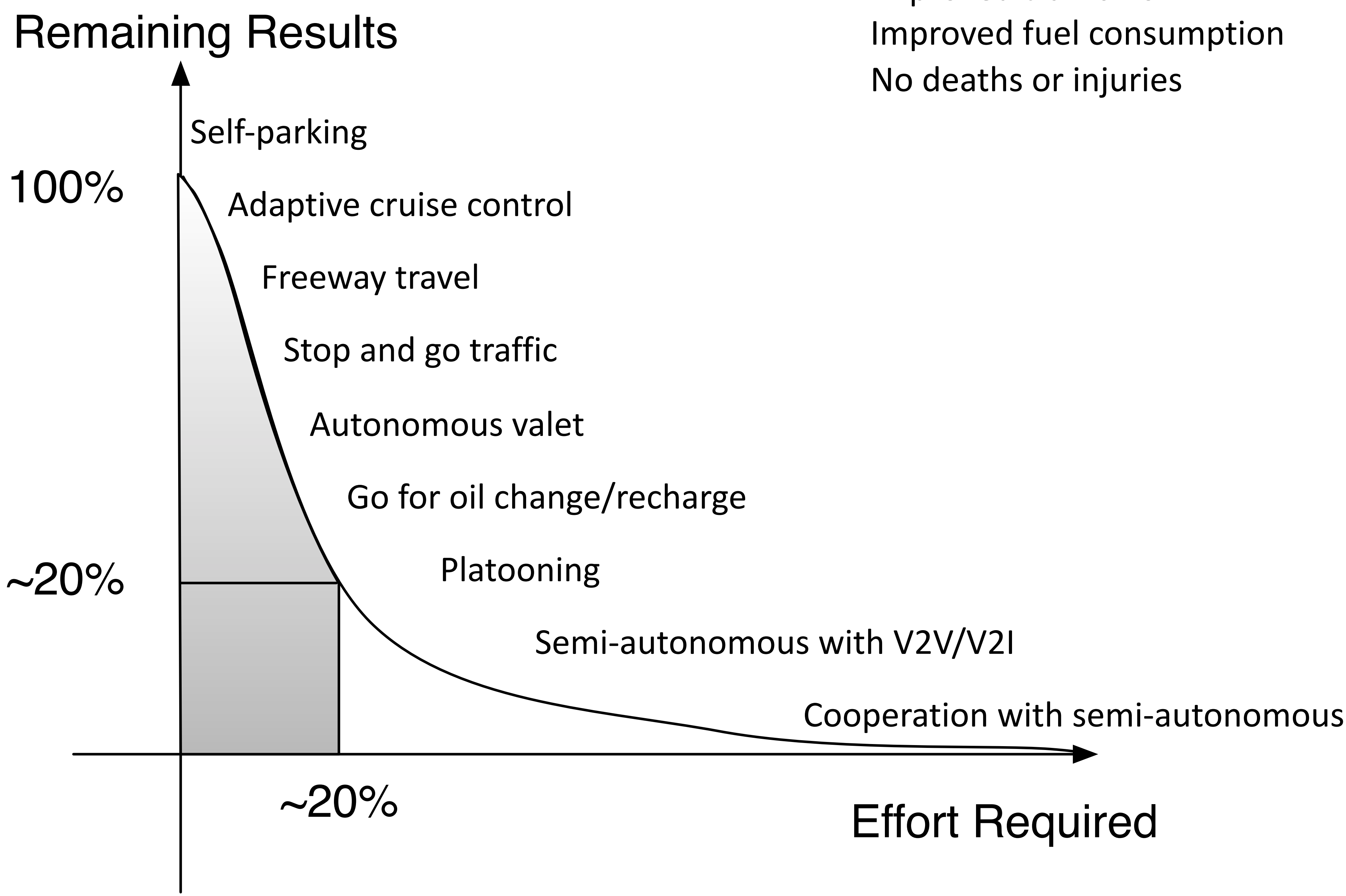

13 hr 59 min
907 mi
6:04 AM arrival
420 miles
INTERSTATE
20
Continue on I-20 W
20
I-20 W


THE UNIVERSITY OF ARIZONA
REDACTED


Combi

Emergent properties

Improved traffic flow
Improved fuel consumption
No deaths or injuries



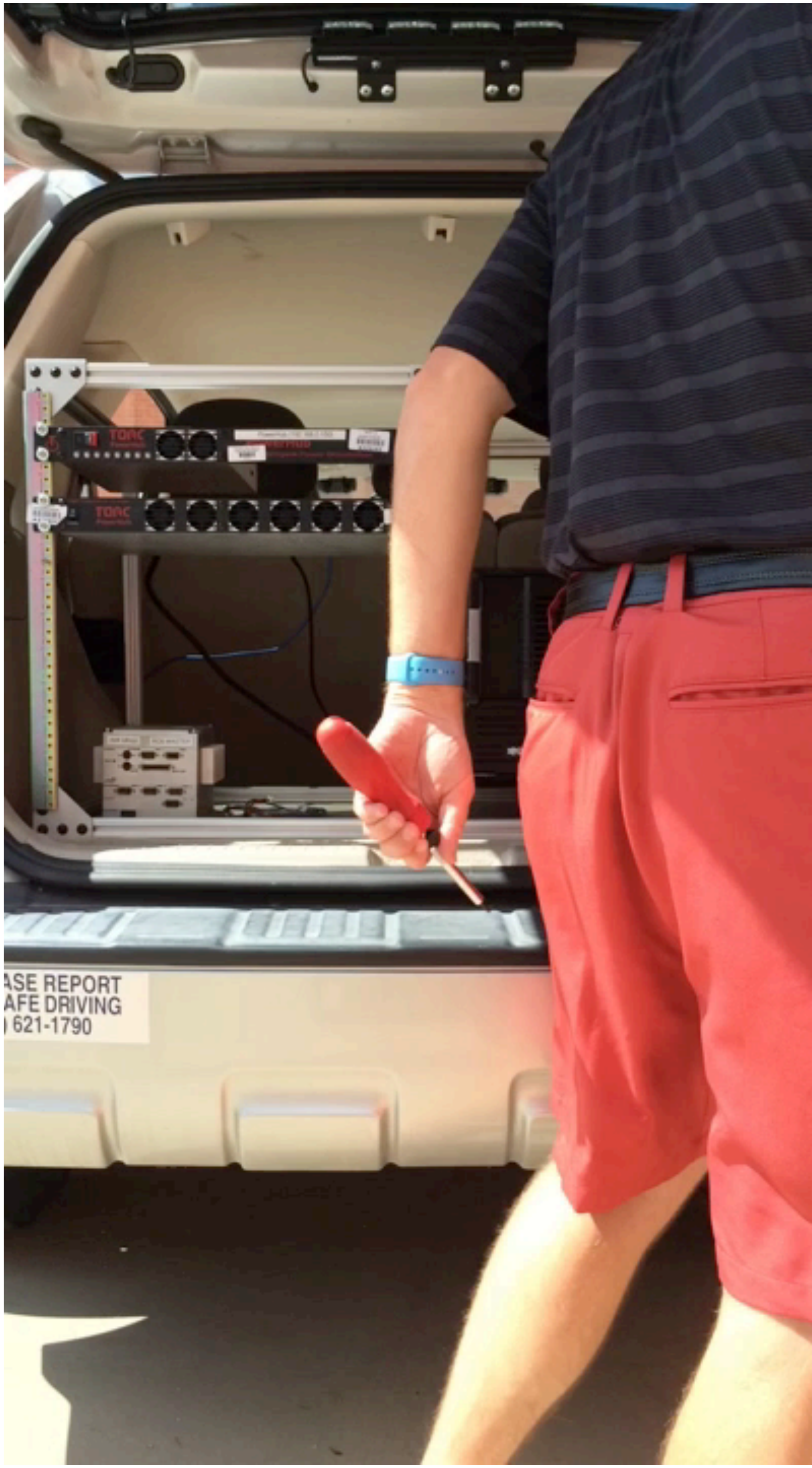
** Listed concepts change in effort depending on available sensors/cost

Testbed for Research!

Our Testbed: Full-sized Ford Escape

Down to the wires and back again

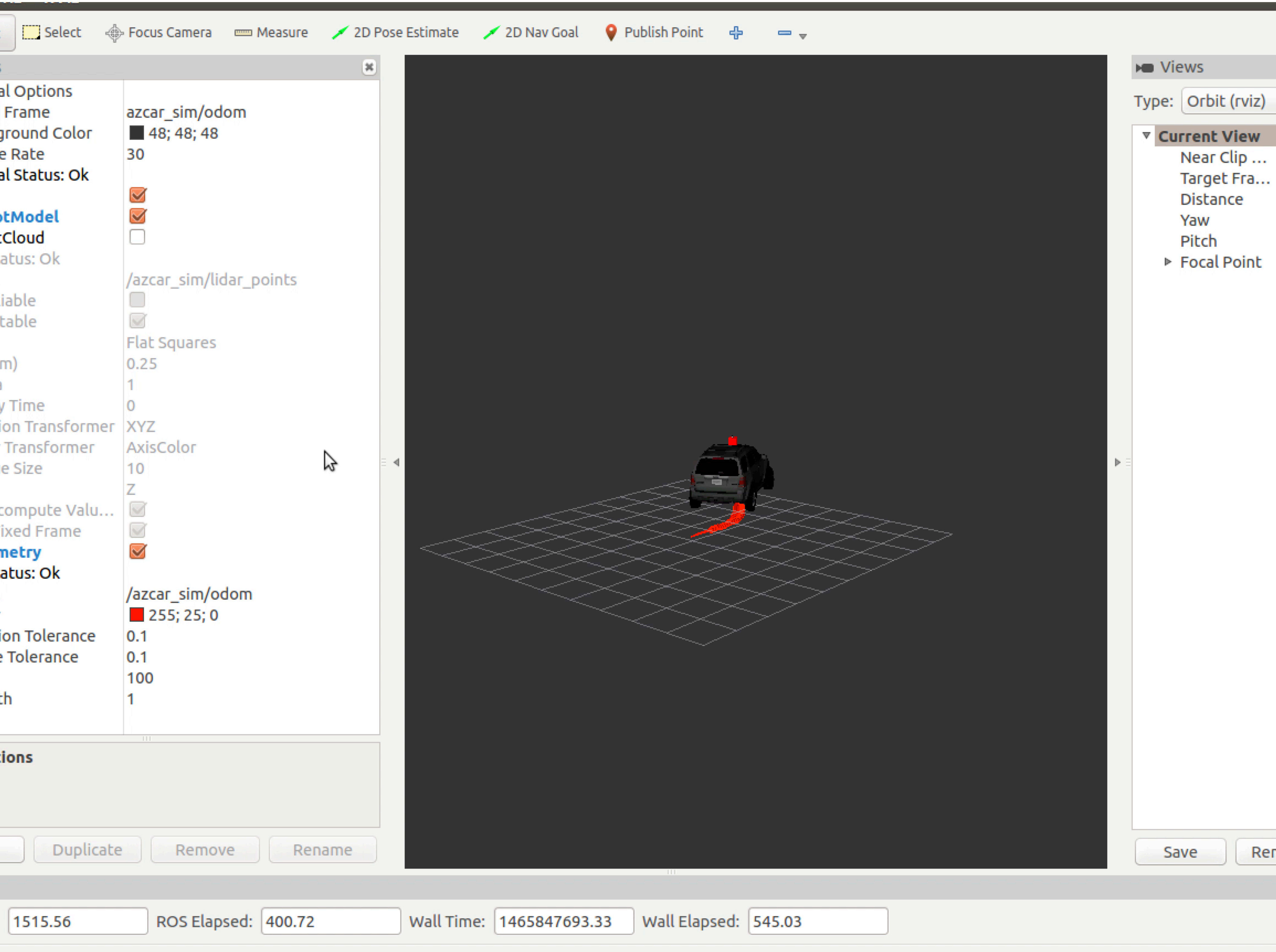
- 2008 Ford Escape Hybrid
- Equipped with **pause/stop**: modes for safety, **emergency-stop**: normally open held closed, **dead-man's switch**: executes e-stop when no message received in time frame
- 2 MILSPEC machines with dedicated handling for ROS whitepages, GPS/INS
- Logging of all potentially useful data to TB++ HDD arrays that rotate out old logs if not claimed
- Dedicated interaction to Velodyne sensor
- 12-18 V DC power supply with 8 output ports (all at same V_0)



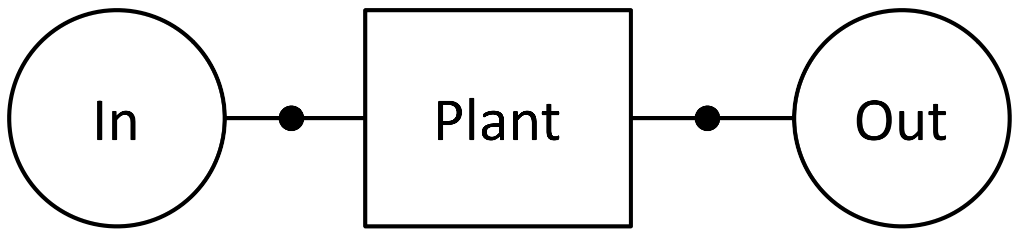
Featuring various hardware additions...


Velodyne 64e
3D lidar (~$80,000)
STATE OF ARIZONA FOR OFFICIAL USE ONLY
HYBRID
ByWire XGV


NoVaTel GPS/
IMU (~$25,000)
STATE OF ARIZONA FOR OFFICIAL USE ONLY
ByWire XGV
five star ford.com
Scottsdale
ESCAPE

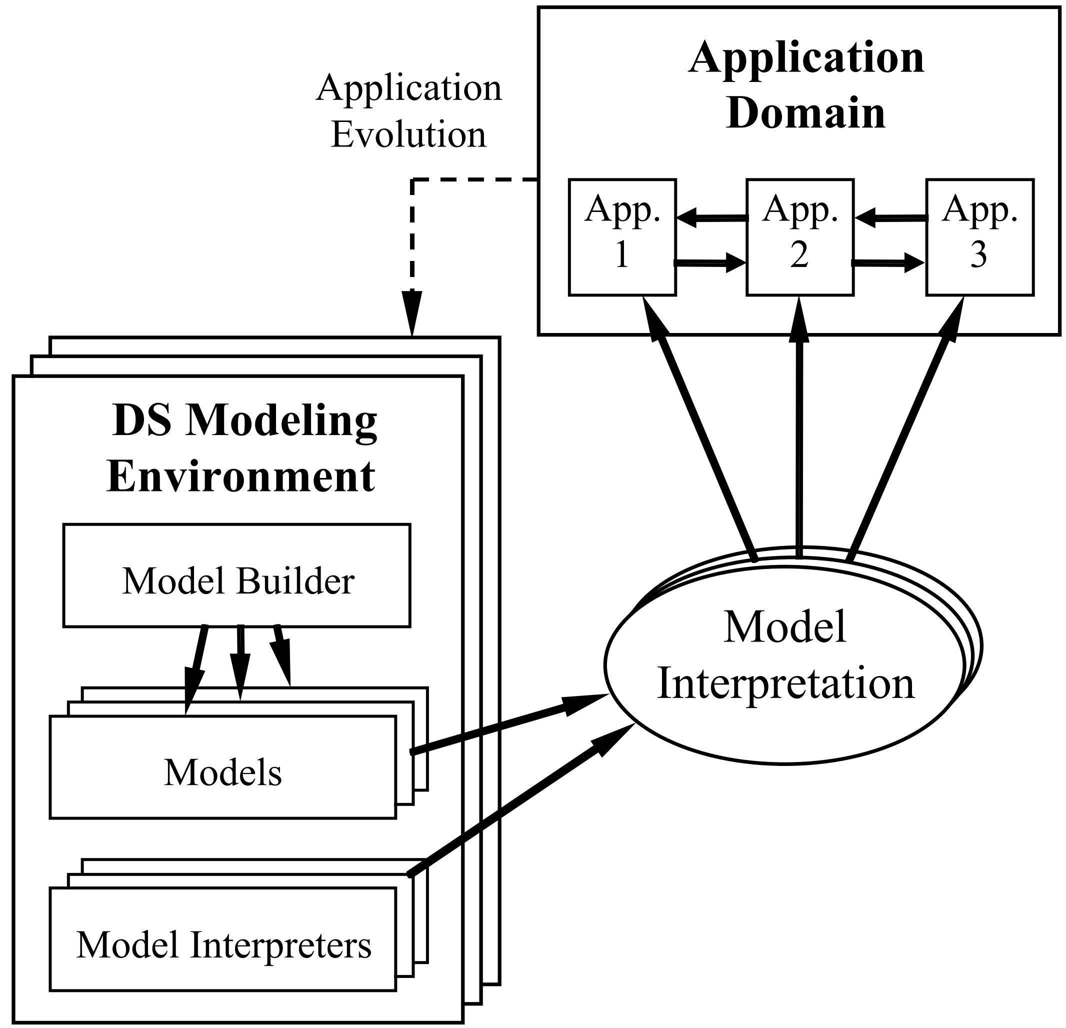

Select
Focus Camera
Measure
2D Pose Estimate
2D Nav Goal
Publish Point
al Options
Frame
azcar_sim/odom
ground Color
48; 48; 48
e Rate
30
al Status: Ok
otModel
:Cloud
atus: Ok
/azcar_sim/lidar_points
iable
table
Flat Squares
m)
0.25
1
y Time
0
ion Transformer
XYZ
Transformer
AxisColor
e Size
10
Z
compute Valu...
ixed Frame
metry
atus: Ok
/azcar_sim/odom
255; 25; 0
ion Tolerance
0.1
e Tolerance
0.1
100
th
1
ions
Duplicate
Remove
Rename
Views
Type:
Orbit (rviz)
Current View
Near Clip ...
Target Fra...
Distance
Yaw
Pitch
Focal Point
Save
Rer
1515.56
ROS Elapsed:
400.72
Wall Time:
1465847693.33
Wall Elapsed:
545.03

With interfaces, we can model.



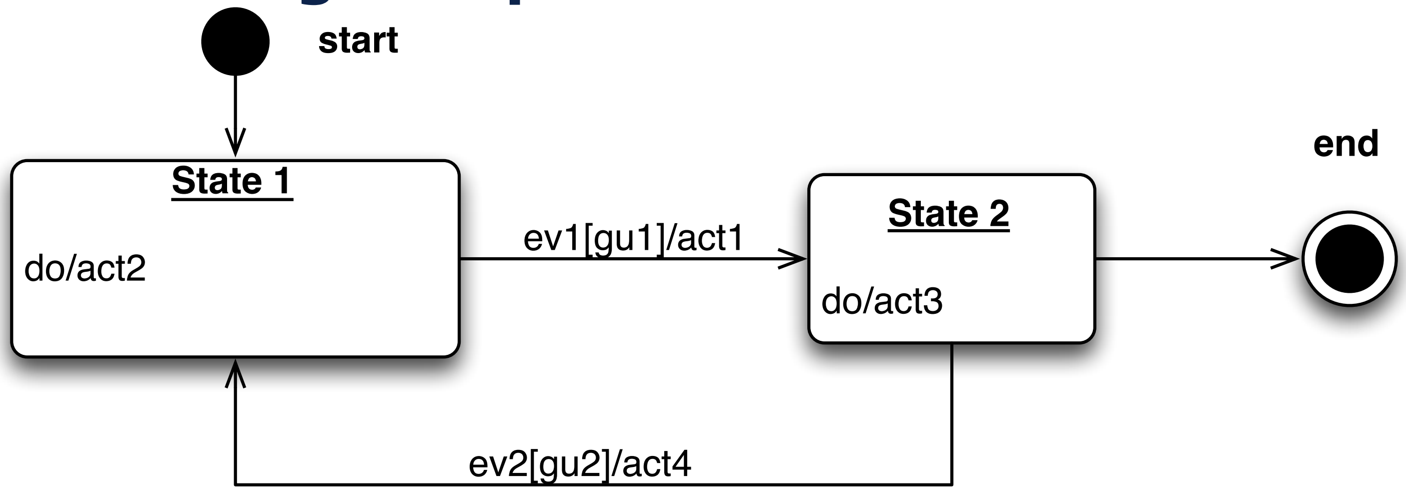
Domain-Specific Modeling

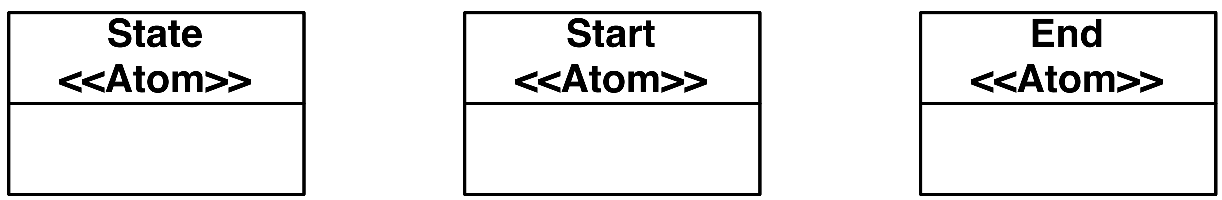
- Create model of the system
- Perform
  - Analysis
  - Architecture exploration
  - Simulation
- Generate
  - Configuration
  - Code
  - Executables
- From the same models!



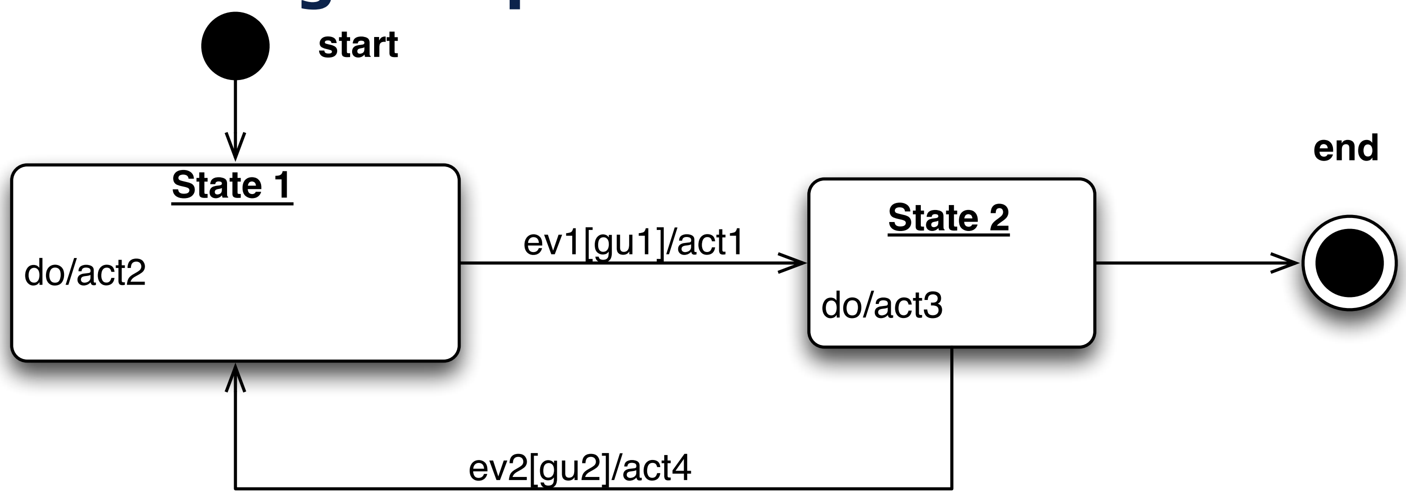
Example Domains & Environments:
- VLSI Layout (e.g., Altera)
- Engg Drawing (e.g., AutoCAD)
- Physical Modeling (e.g., SolidWorks)
- Signal Processing (e.g., LabVIEW)
- Controls (e.g., Simulink)

Thought Experiment: State Models





Thought Experiment: State Models



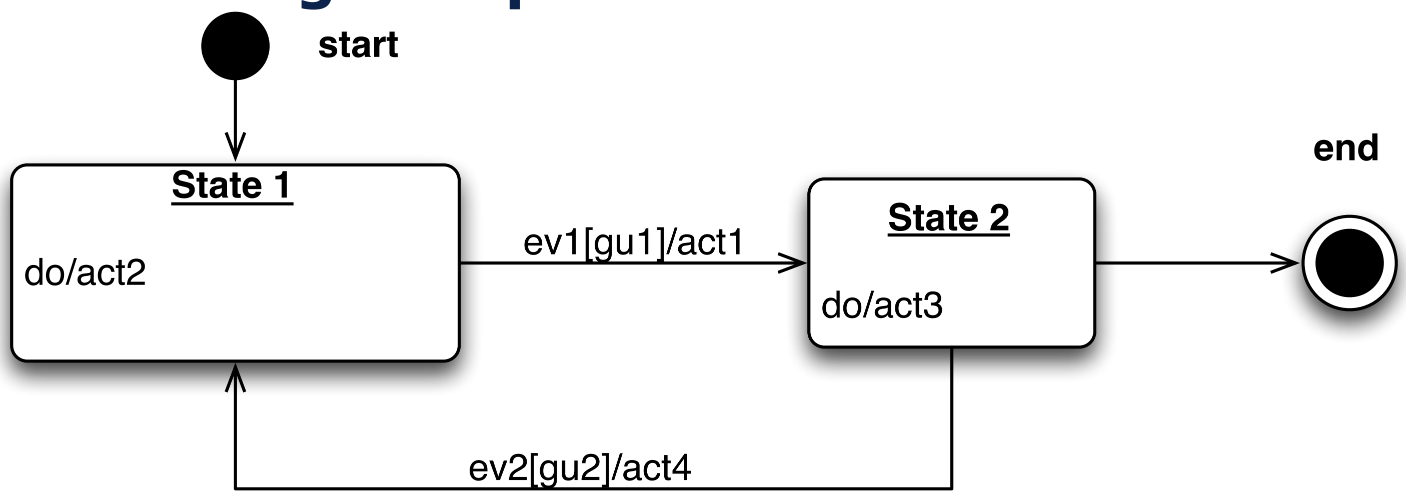
State <<Atom>>
String: doActivity

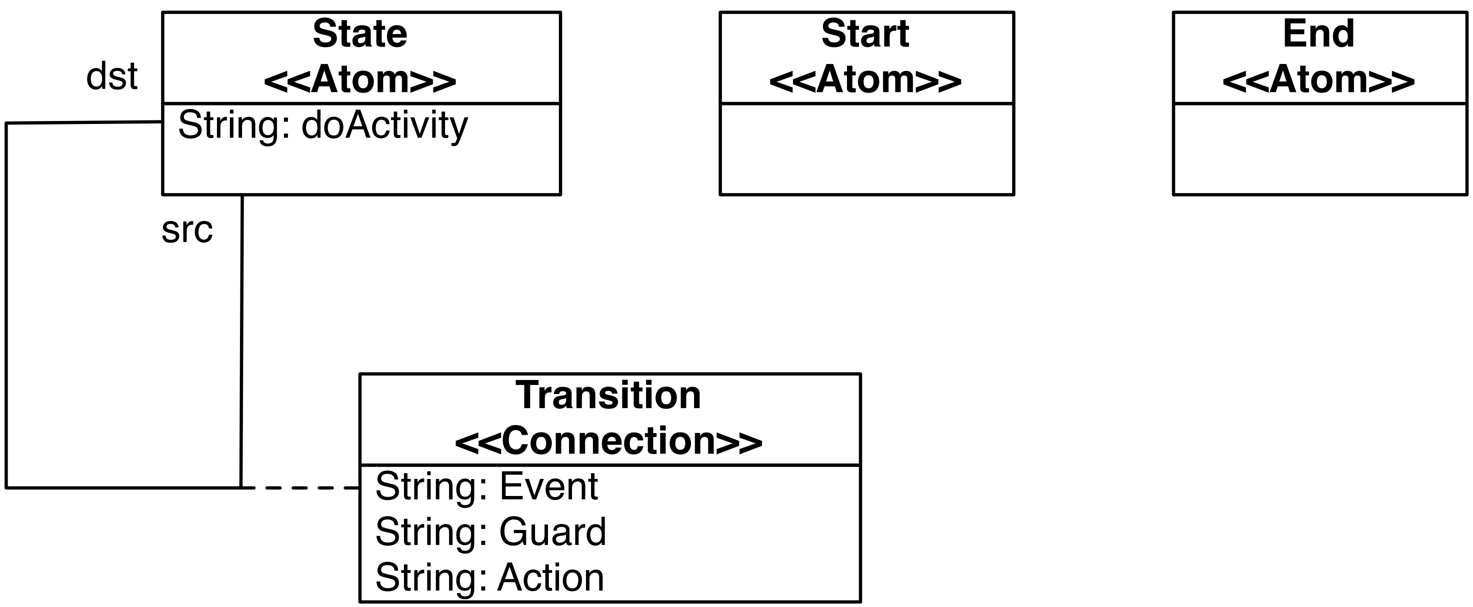
Start <<Atom>>

End <<Atom>>

Transition <<Connection>>
String: Event String: Guard String: Action

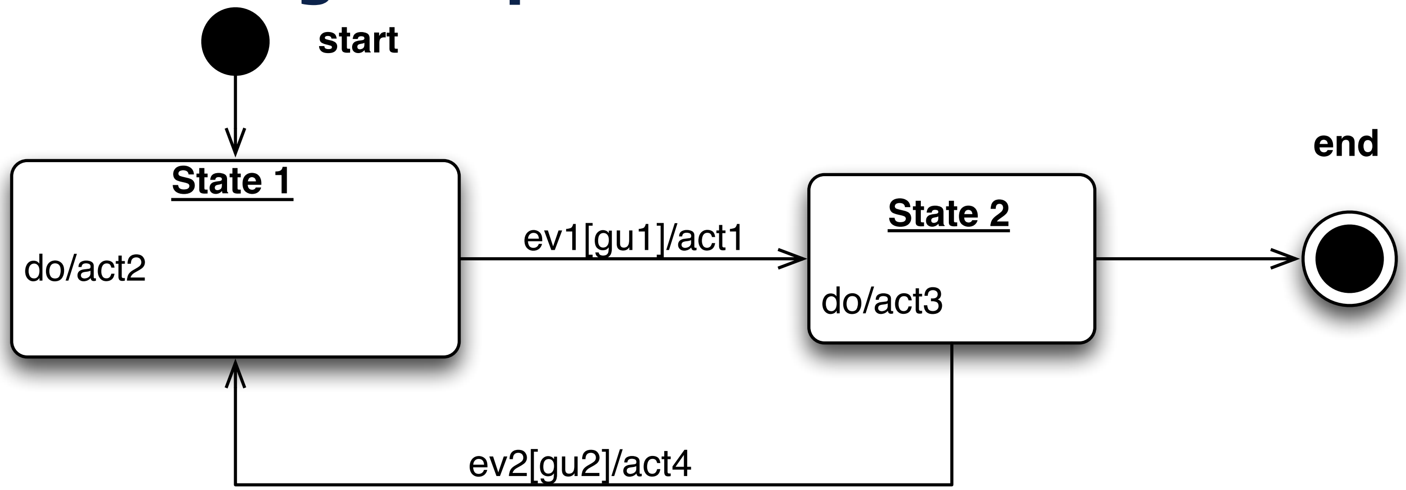
Thought Experiment: State Models

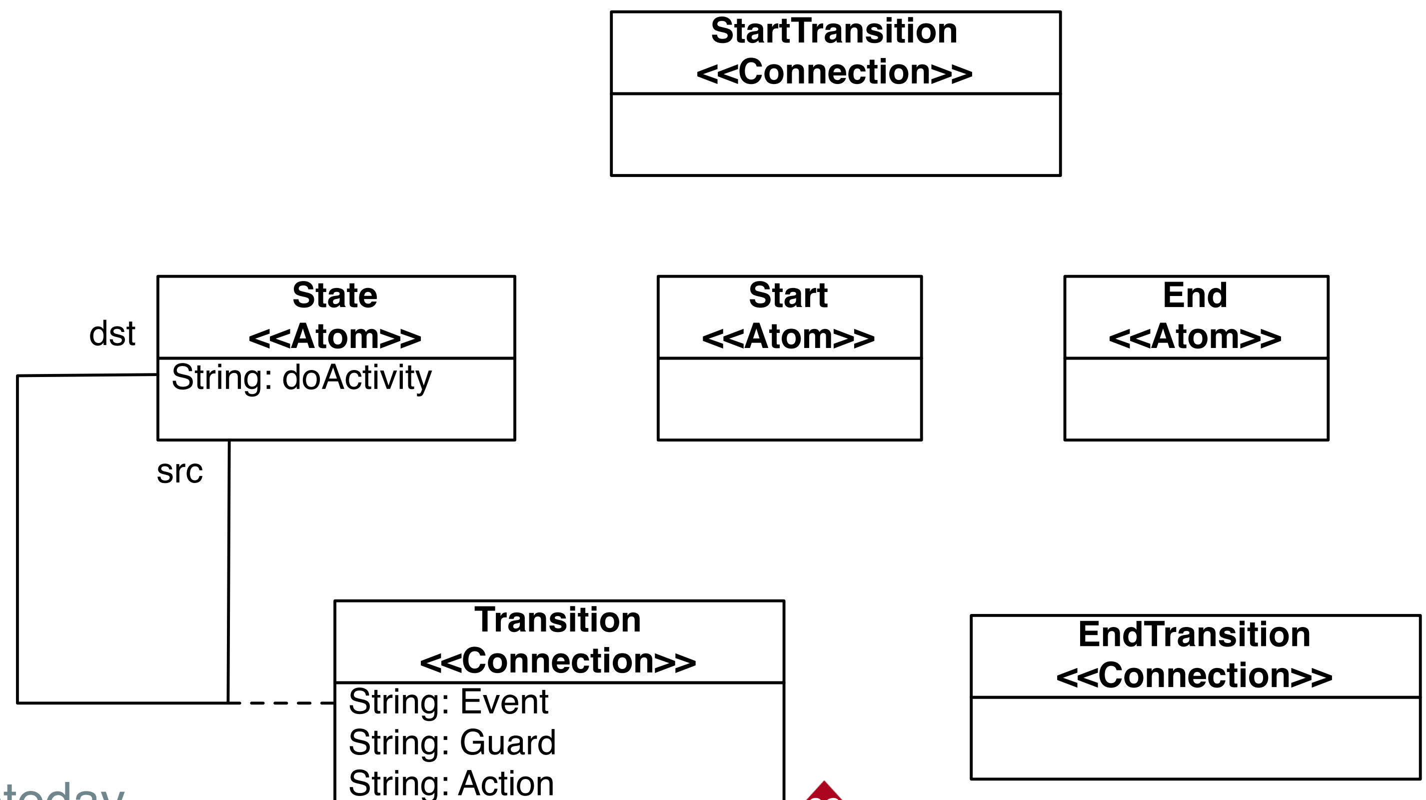




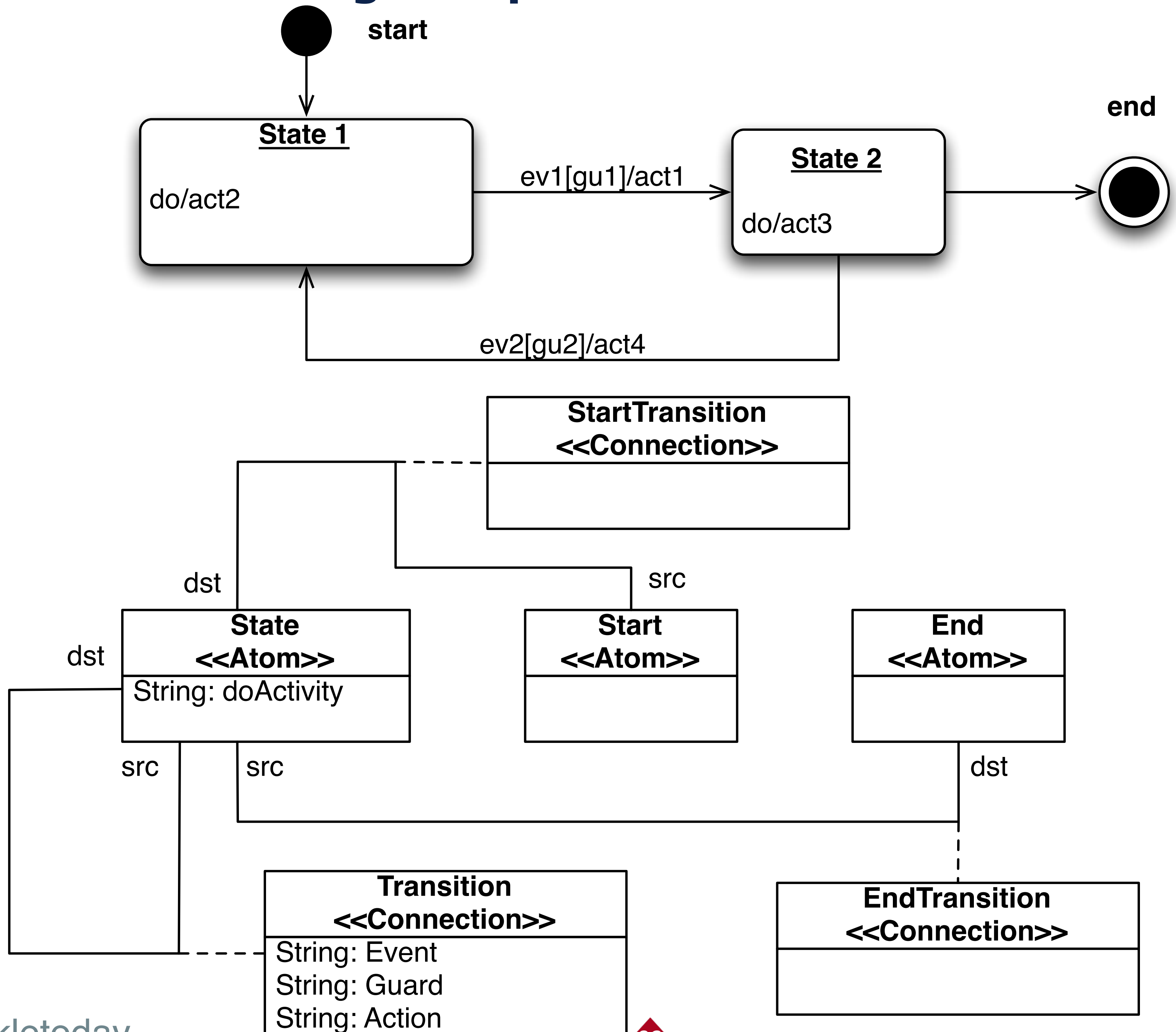
@sprinkletoday

Thought Experiment: State Models

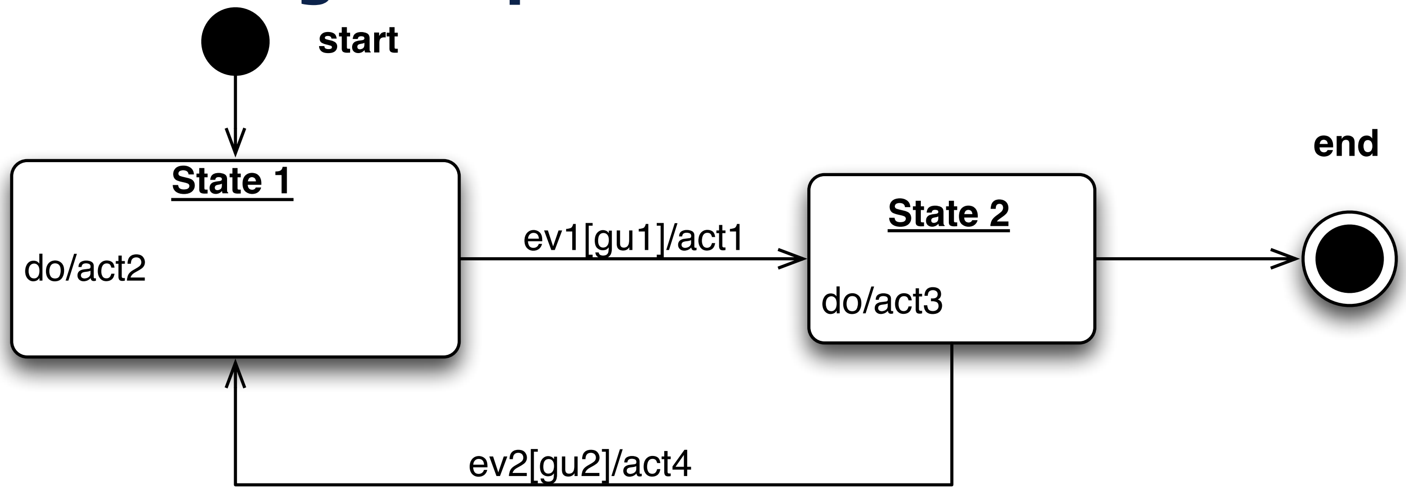


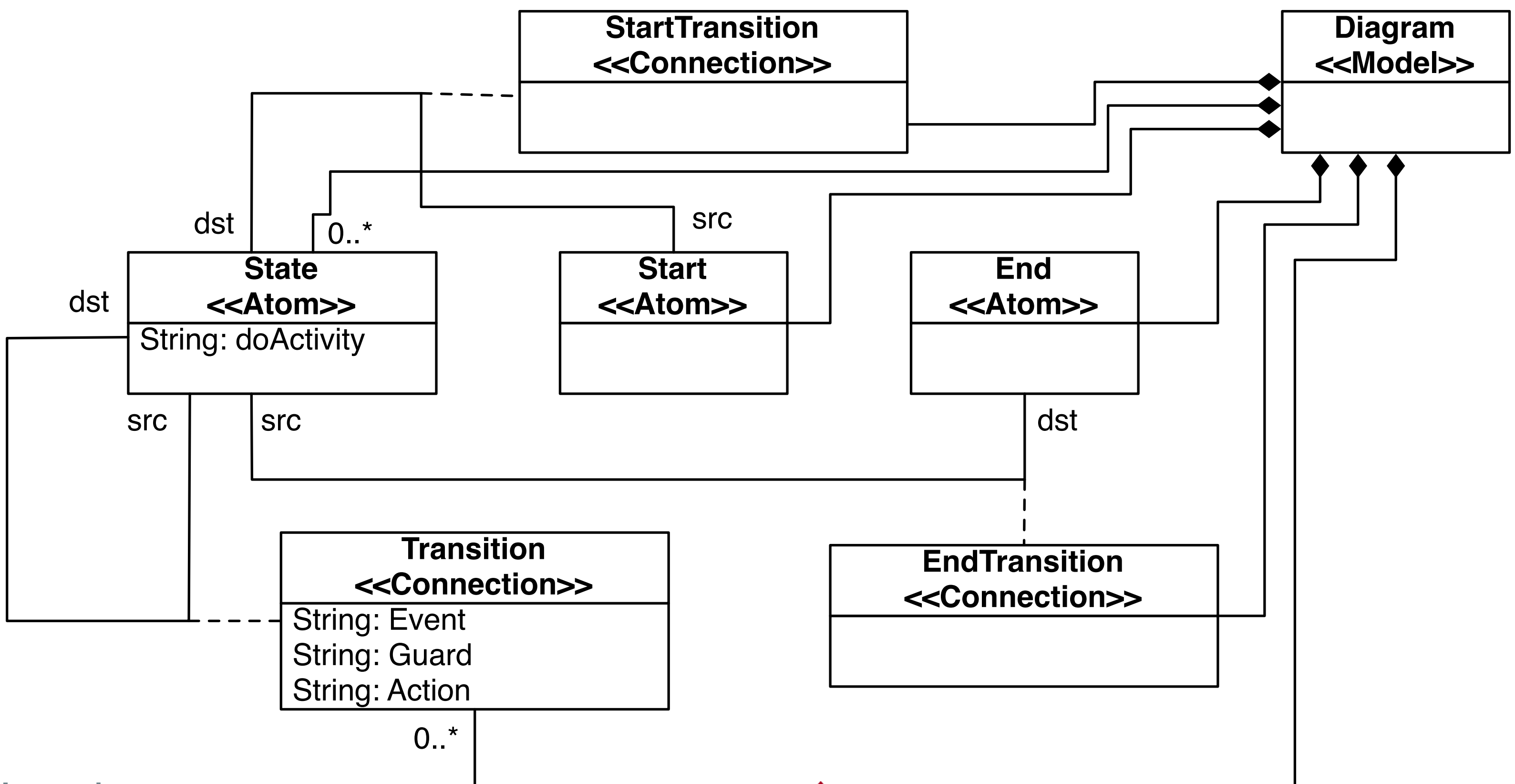


Thought Experiment: State Models

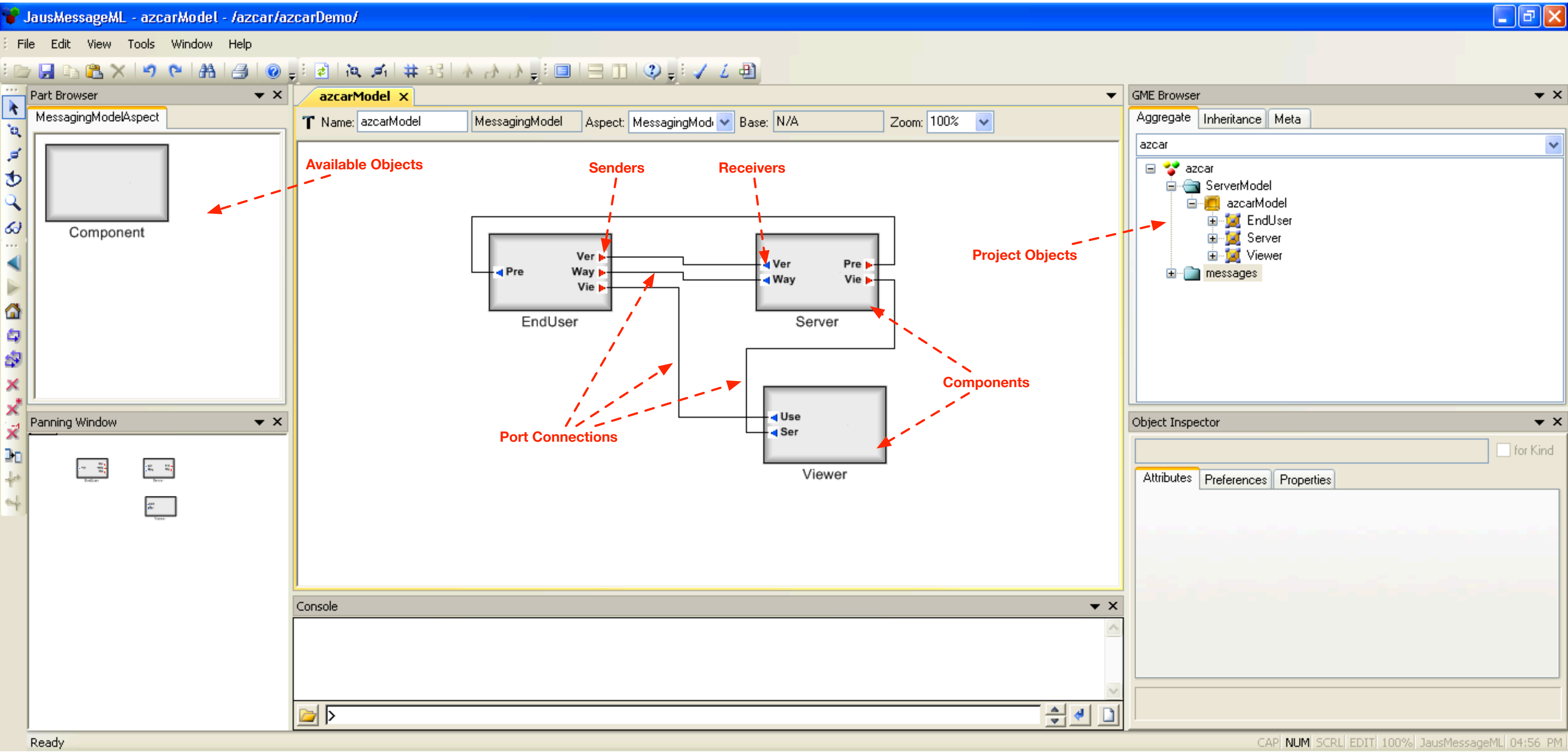


Thought Experiment: State Models



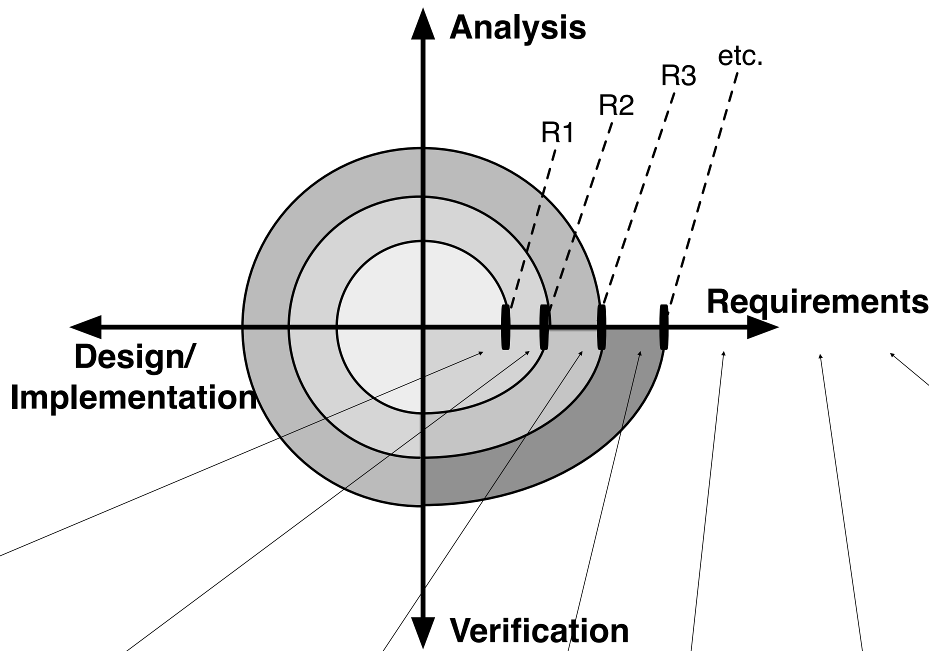


Example model of component interconnection



@sprinkletoday

Example Workflow



Simulate ideal data source values in MATLAB or Simulink

Replace noisy data with data from simulator (Gazebo) data

Replace ideal data with noisy data

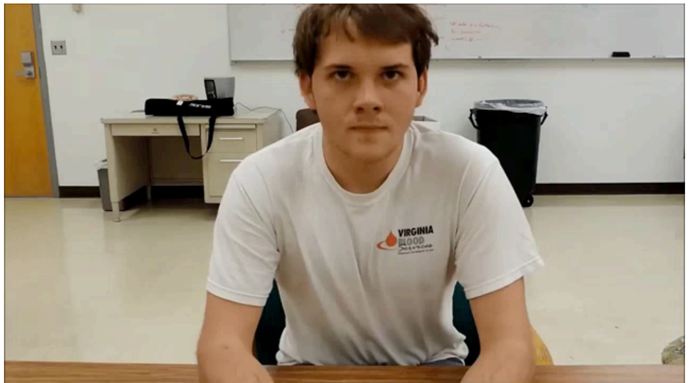
Rewrite data sources to acquire data directly from ROS

Run node directly in the loop from Simulink/ MATLAB

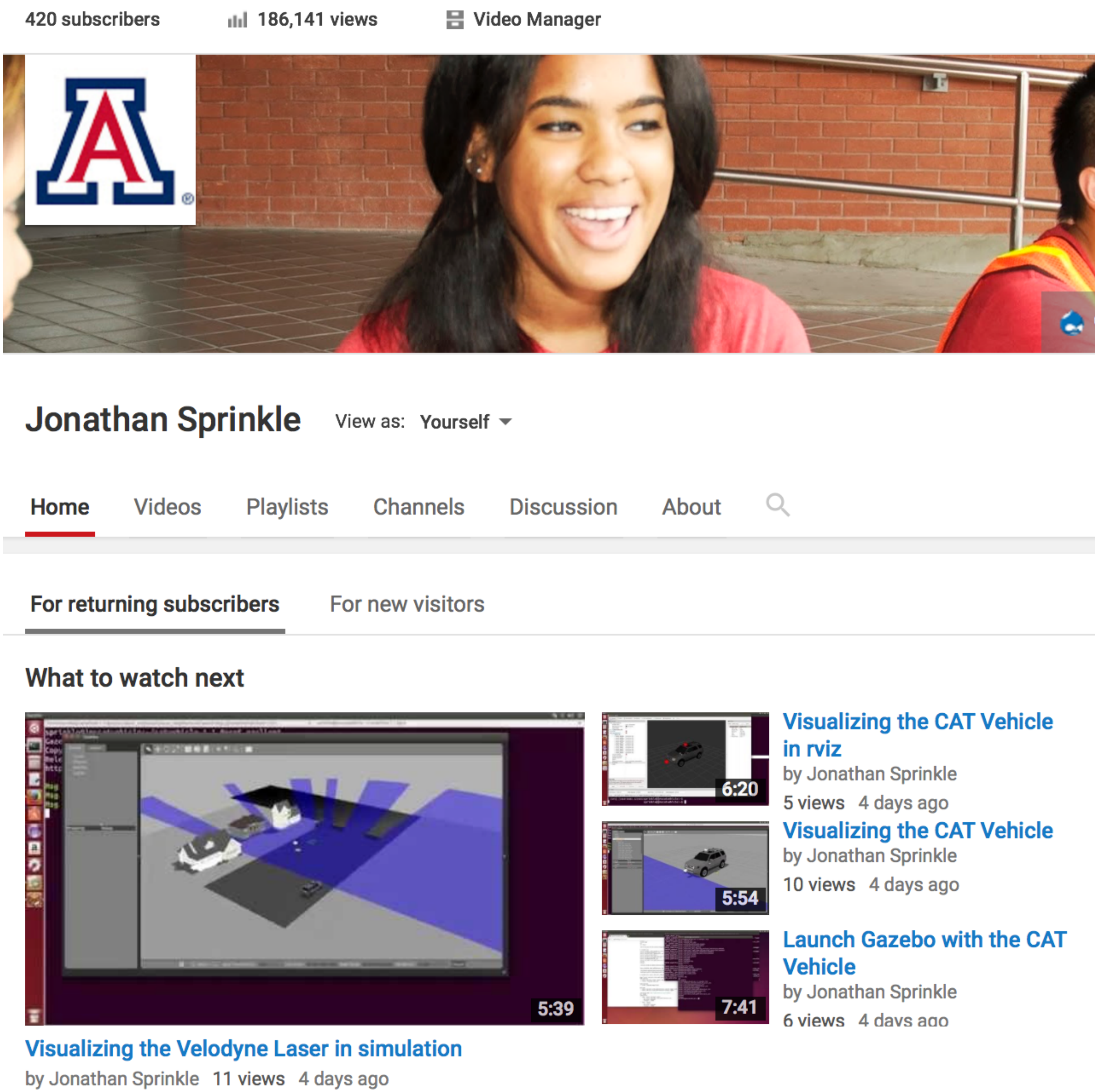
Generate code from Simulink/MATLAB and run generated code on simulator

Run generated code on actual vehicle

With models, we extend the user base



CAT Vehicle
2014


420 subscribers
186,141 views
Video Manager
Jonathan Sprinkle
View as: Yourself
Home
Videos
Playlists
Channels
Discussion
About
For returning subscribers
For new visitors
What to watch next
5:39
Visualizing the Velodyne Laser in simulation
by Jonathan Sprinkle 11 views 4 days ago
6:20
Visualizing the CAT Vehicle in rviz
by Jonathan Sprinkle
5 views 4 days ago
5:54
Visualizing the CAT Vehicle
by Jonathan Sprinkle
10 views 4 days ago
7:41
Launch Gazebo with the CAT Vehicle
by Jonathan Sprinkle
6 views 4 days ago

Car Following with ROS and a cell phone camera. Done in 10 weeks with no prior experience.

CAT Vehicle 2015

https://youtu.be/83rPuR159eM

https://youtu.be/Yufd6y0ML0s

Liz Olson

Adam Johnson

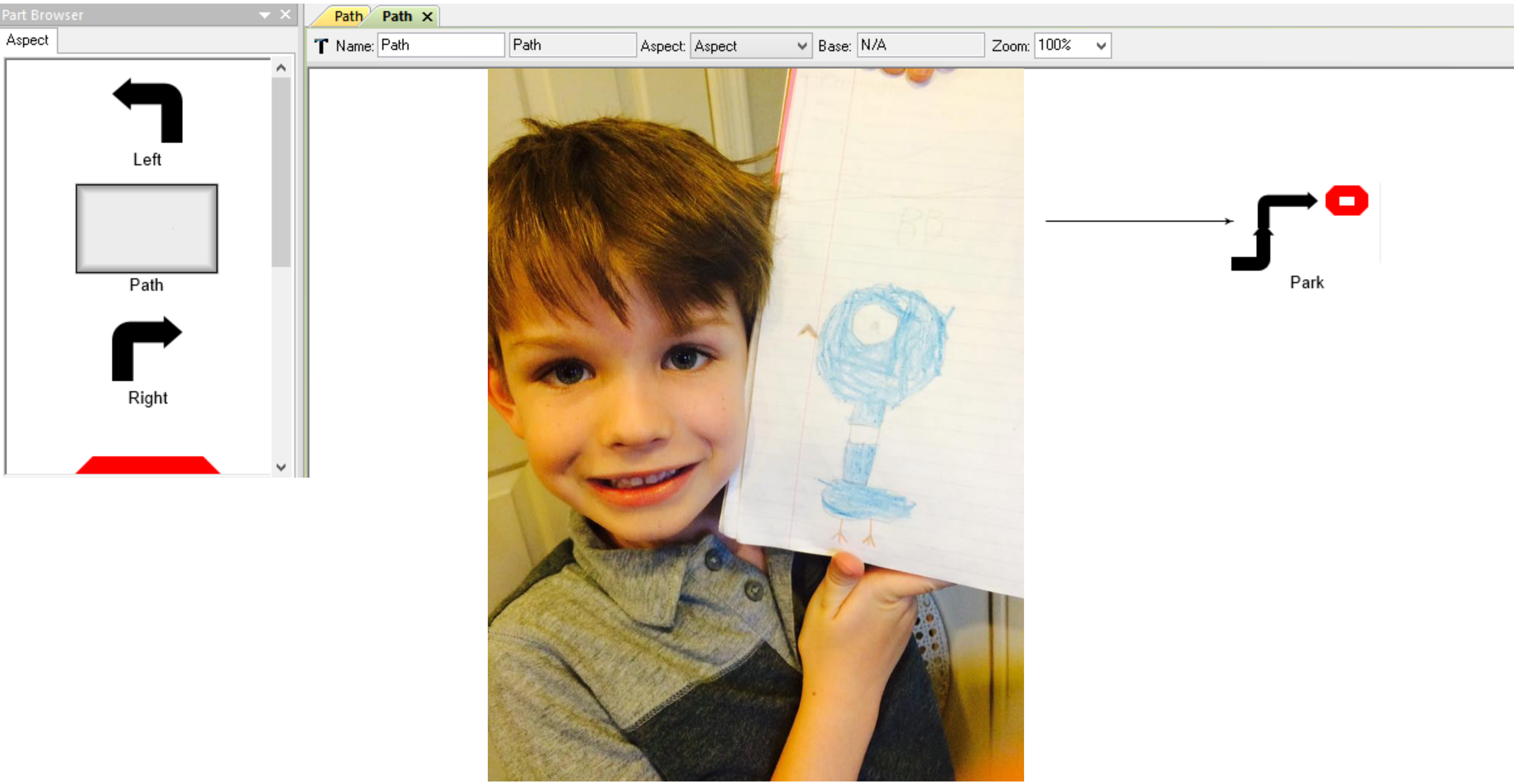
Switched MPC control, implemented in less than 10 weeks with no prior experience.

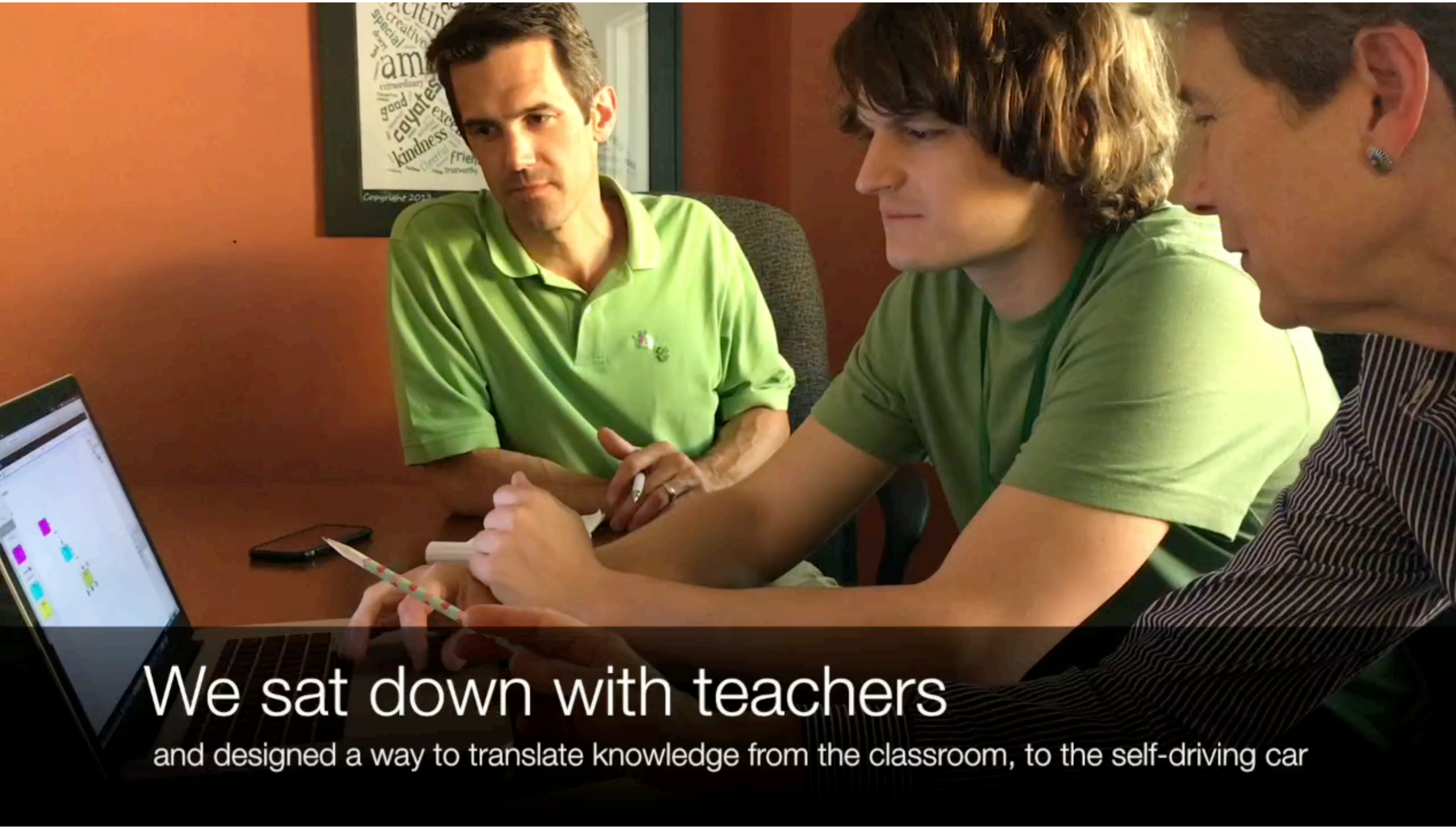
CAT Vehicle 2015

https://youtu.be/581VedR7NOA
https://youtu.be/UC7ncHjx2jg

Yesenia Velasco
Charles Jawny

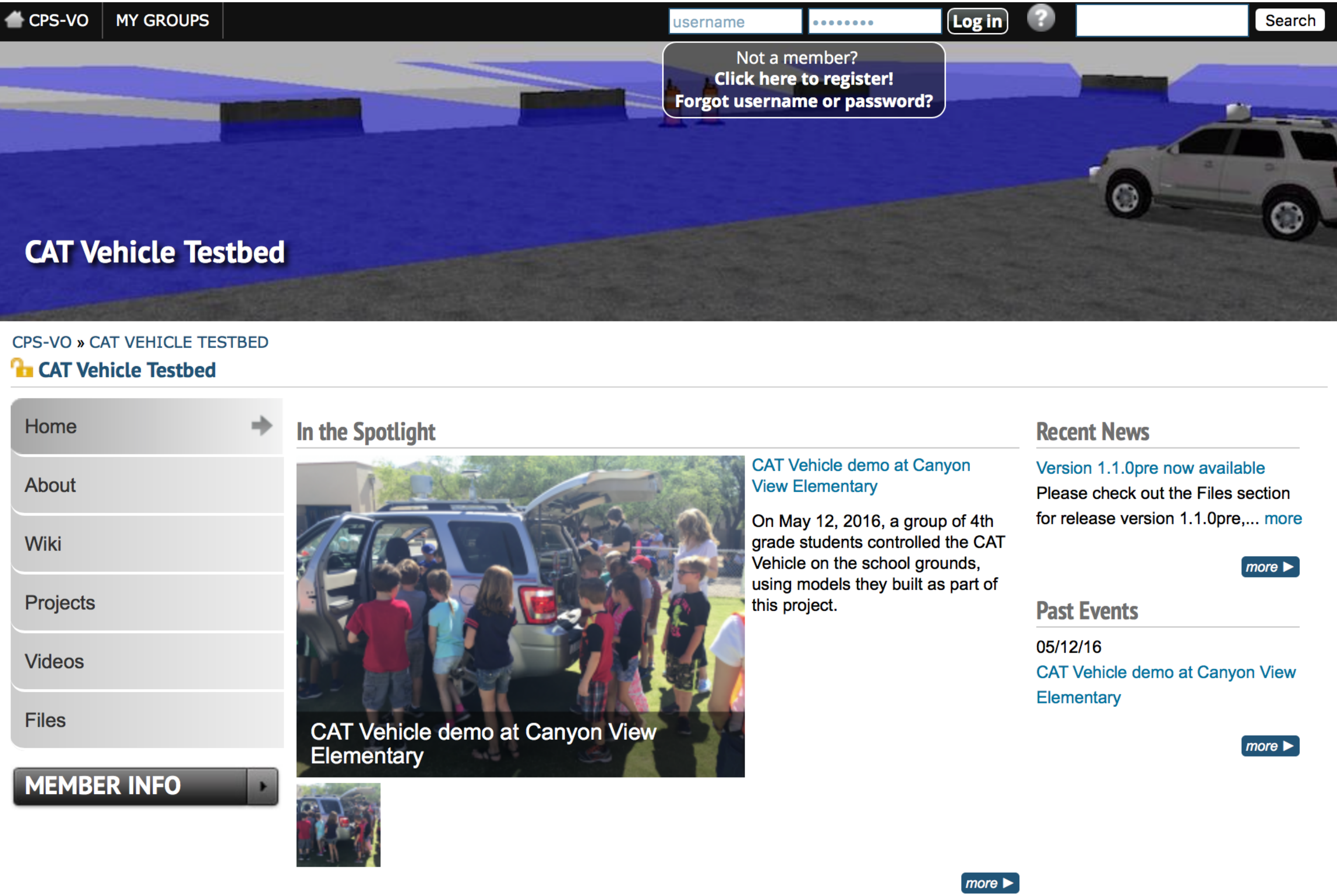

worker's teen
PAGE A11
FOR THE BIG PLA
Arizona Daily
tucson.com
Hands off the wheel, please
Kennon McKeever, 20, a junior at the University of Arizona, uses Meta GME, a computer
and Autonomous Test, or CAT, vehicle where to drive. A dozen visiting and Tucson colle
ipate in the National Science Foundation's Research Experiences for Undergraduates
and developed apps to remotely operate the CAT vehicle in a parking lot Tuesday. Se
tucson.com online.


Part Browser
Aspect
Left
Path
Right
Path
Path
Name: Path
Path
Aspect: Aspect
Base: N/A
Zoom: 100%
Park

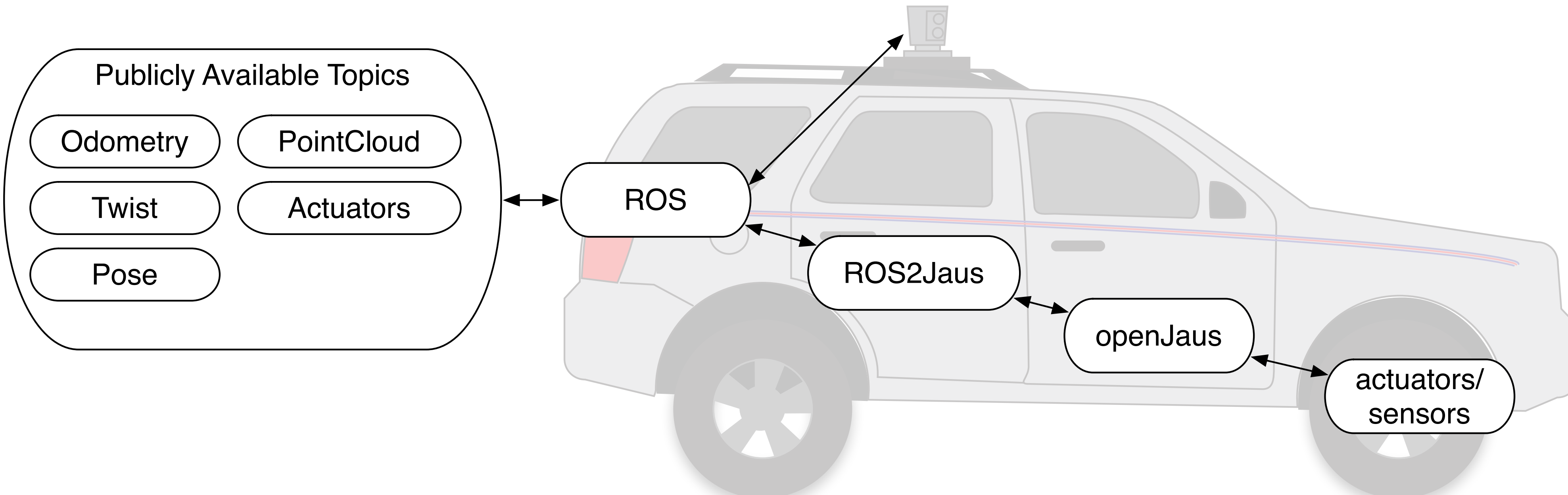

We sat down with teachers
and designed a way to translate knowledge from the classroom, to the self-driving car


ByWire XGV

Announcing the CAT Vehicle Testbed



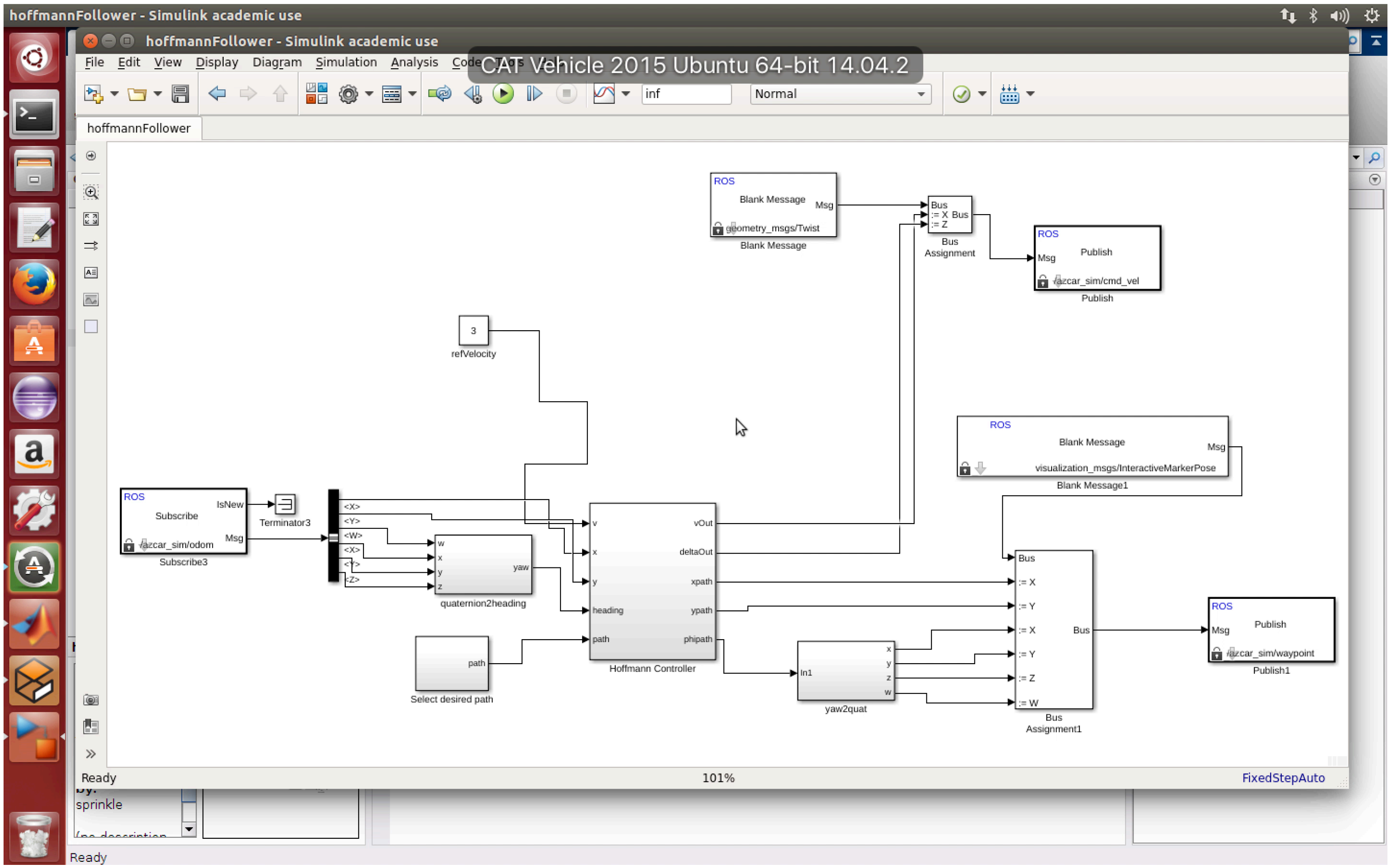
Software Interface Layers

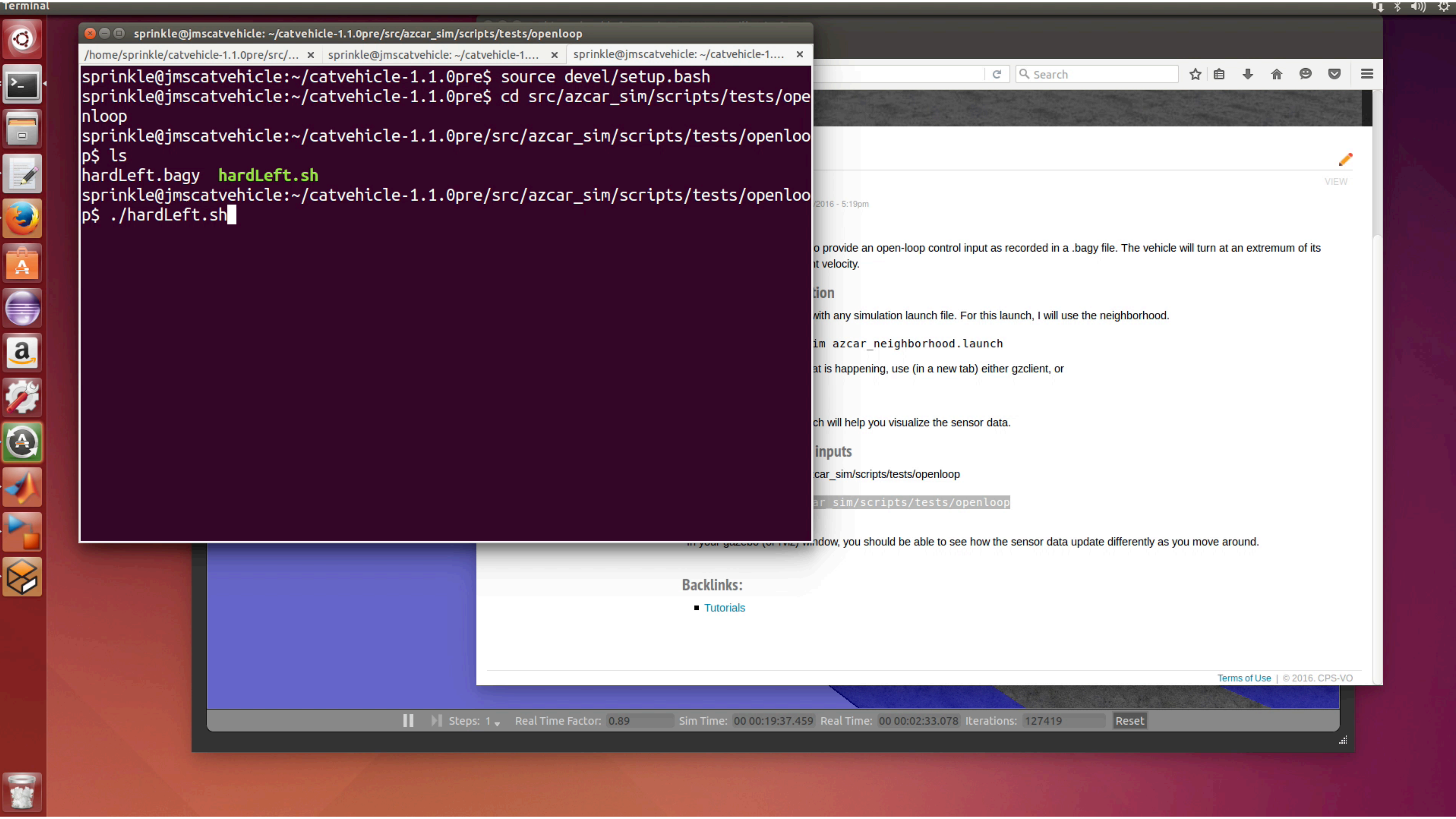


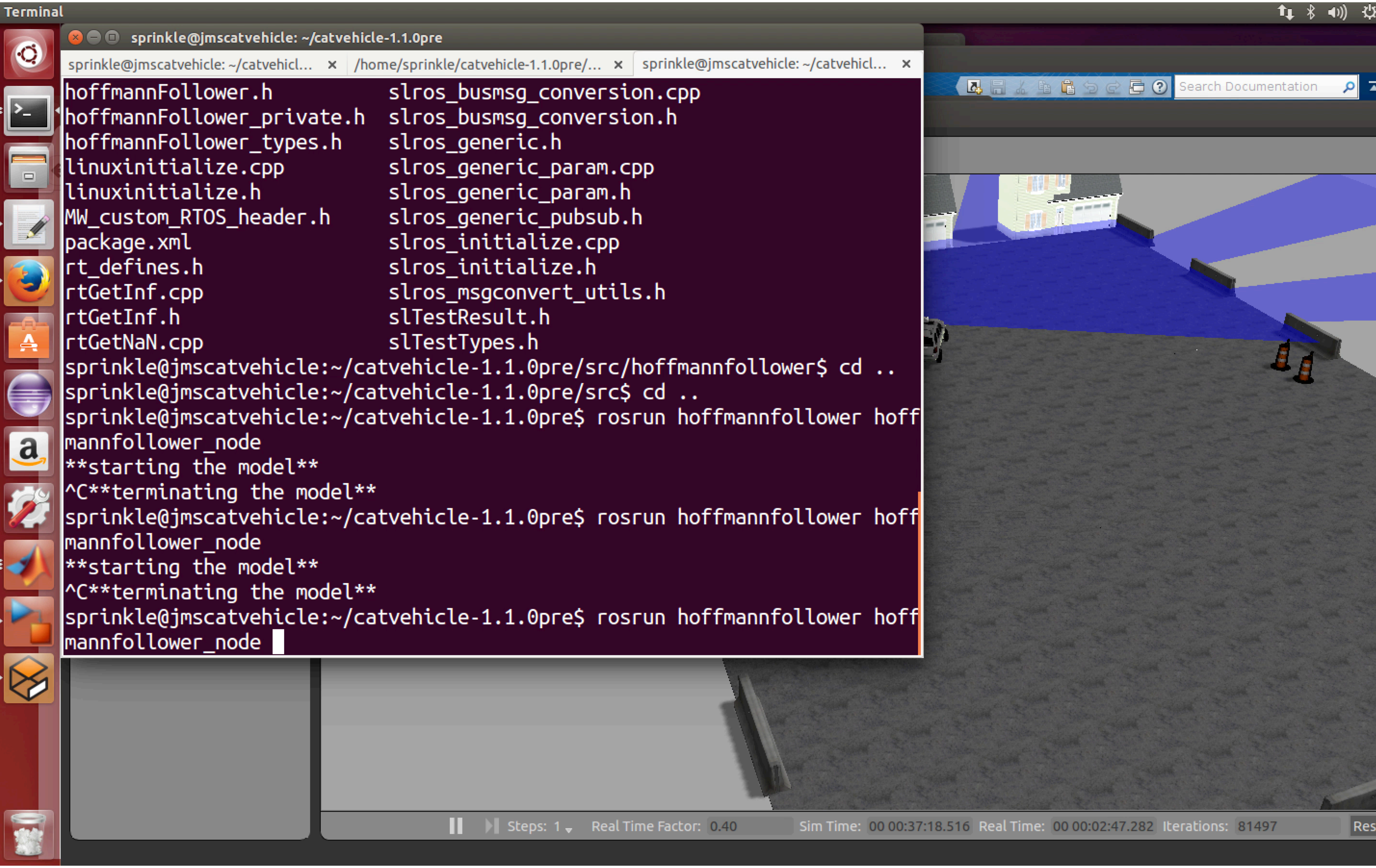
- ROS access to system
- Gazebo simulator with
  - Ackermann steering
  - Lidar (Velodyne and SICK)
  - Realistic (but not "correct") masses and dynamics
- Published topics for odometry, path, laser scans, velocity, steering angles
- Example Simulink Robotics System Toolbox models distributed with the source
- Control inputs through velocity and steering angle (cmd_vel)

http://cps-vo.org/group/CATVehicleTestbed

CatVehicle Testbed
(BSD license)



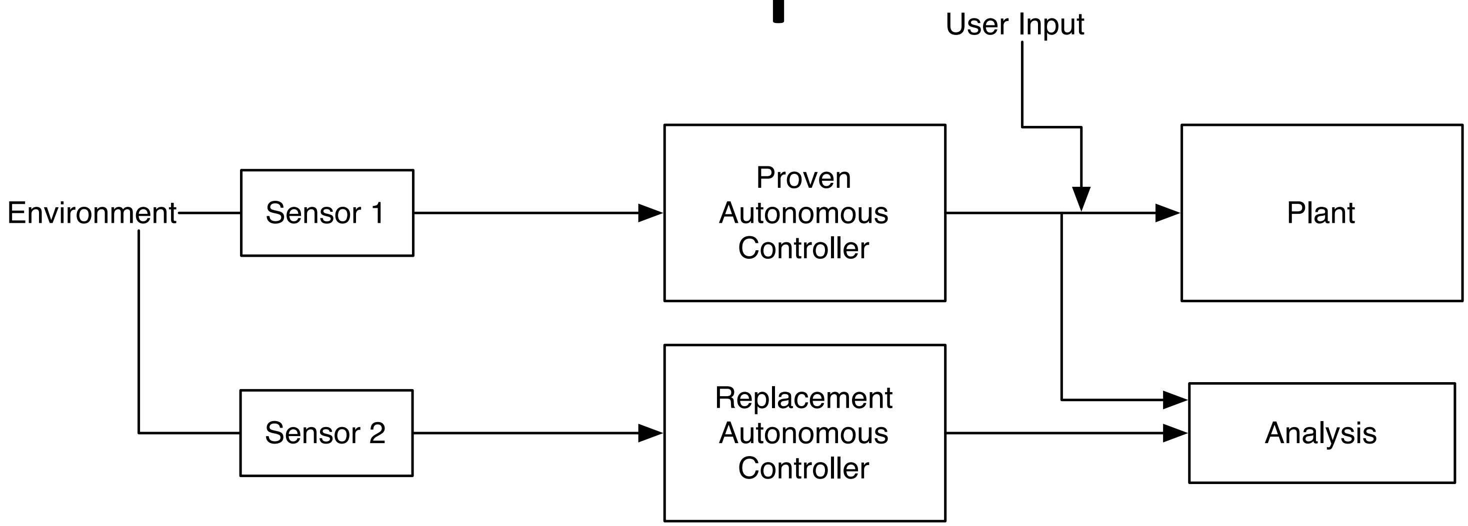

Terminal
sprinkle@jmscatvehicle: ~/catvehicle-1.1.0pre/src/azcar_sim/scripts/tests/openloop
/home/sprinkle/catvehicle-1.1.0pre/src/...
sprinkle@jmscatvehicle: ~/catvehicle-1....
sprinkle@jmscatvehicle: ~/catvehicle-1....
sprinkle@jmscatvehicle:~/catvehicle-1.1.0pre$ source devel/setup.bash
sprinkle@jmscatvehicle:~/catvehicle-1.1.0pre$ cd src/azcar_sim/scripts/tests/openloop
sprinkle@jmscatvehicle:~/catvehicle-1.1.0pre/src/azcar_sim/scripts/tests/openloop$ ls
hardLeft.bagy hardLeft.sh
sprinkle@jmscatvehicle:~/catvehicle-1.1.0pre/src/azcar_sim/scripts/tests/openloop$ ./hardLeft.sh
Search
VIEW
/2016 - 5:19pm
o provide an open-loop control input as recorded in a .bagy file. The vehicle will turn at an extremum of its
it velocity.
tion
with any simulation launch file. For this launch, I will use the neighborhood.
im azcar_neighborhood.launch
at is happening, use (in a new tab) either gzclient, or
ch will help you visualize the sensor data.
inputs
car_sim/scripts/tests/openloop
ar_sim/scripts/tests/openloop
ndow, you should be able to see how the sensor data update differently as you move around.
Backlinks:
Tutorials
Terms of Use | © 2016. CPS-VO
Steps: 1
Real Time Factor: 0.89
Sim Time: 00 00:19:37.459
Real Time: 00 00:02:33.078
Iterations: 127419
Reset


Terminal
sprinkle@jmscatvehicle: ~/catvehicle-1.1.0pre
sprinkle@jmscatvehicle: ~/catvehicl...
/home/sprinkle/catvehicle-1.1.0pre/...
sprinkle@jmscatvehicle: ~/catvehicl...
hoffmannFollower.h slros_busmsg_conversion.cpp
hoffmannFollower_private.h slros_busmsg_conversion.h
hoffmannFollower_types.h slros_generic.h
linuxinitialize.cpp slros_generic_param.cpp
linuxinitialize.h slros_generic_param.h
MW_custom_RTOS_header.h slros_generic_pubsub.h
package.xml slros_initialize.cpp
rt_defines.h slros_initialize.h
rtGetInf.cpp slros_msgconvert_utils.h
rtGetInf.h slTestResult.h
rtGetNaN.cpp slTestTypes.h
sprinkle@jmscatvehicle:~/catvehicle-1.1.0pre/src/hoffmannfollower$ cd ..
sprinkle@jmscatvehicle:~/catvehicle-1.1.0pre/src$ cd ..
sprinkle@jmscatvehicle:~/catvehicle-1.1.0pre$ rosrun hoffmannfollower hoffmannfollower_node
starting the model
^C**terminating the model**
sprinkle@jmscatvehicle:~/catvehicle-1.1.0pre$ rosrun hoffmannfollower hoffmannfollower_node
starting the model
^C**terminating the model**
sprinkle@jmscatvehicle:~/catvehicle-1.1.0pre$ rosrun hoffmannfollower hoffmannfollower_node
Search Documentation
Steps: 1
Real Time Factor: 0.40
Sim Time: 00 00:37:18.516
Real Time: 00 00:02:47.282
Iterations: 81497
Rese

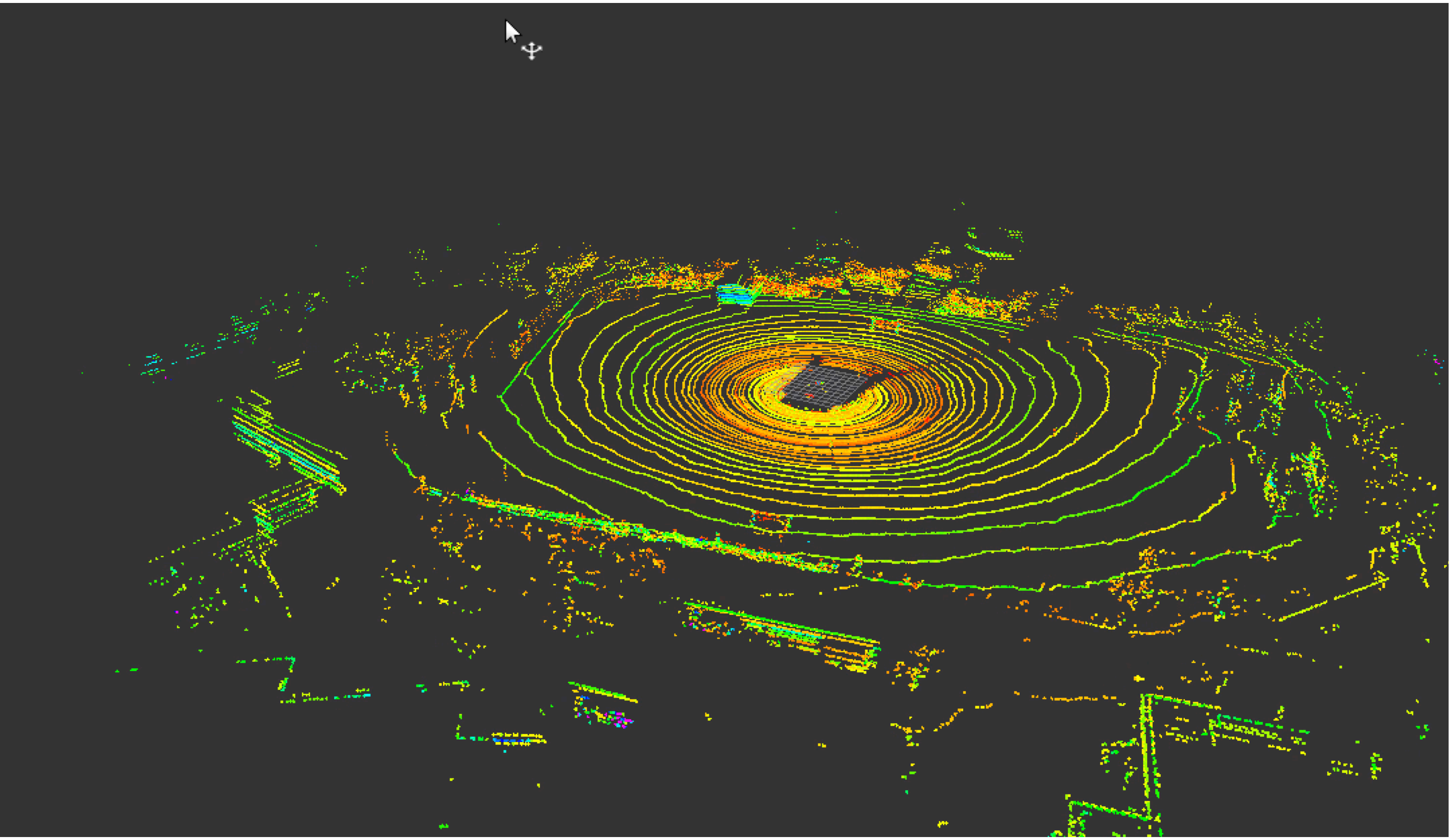
Well, what’s next?

Regression testing on *real data from real vehicles* is the new metric for displacing existing vehicle systems.

Architecture for replacement modules mimics pre-release tests.



The difference is *learning in the loop* which may occur with newer models for perception (and even control).



Data curation and archiving, to enable disruptive tech to have a chance.

Inspire the next generation. Give opportunities for them to realize how they are enabled to change the world for the better.

More reading

1. S. Whitsitt and J. Sprinkle. “A passenger comfort controller for an autonomous ground vehicle.” In *51st IEEE Conference on Decision and Control*, pages 3380–3385, 2012. http://dx.doi.org/10.1109/CDC.2012.6426049
2. S. Whitsitt and J. Sprinkle, “Modeling autonomous systems,” *AIAA Journal of Aerospace Information Systems*, vol. 10, no. 8, pp. 396–413, 2013. http://dx.doi.org/10.2514/1.I010039
3. K. Zhang, J. Sprinkle, and R. G. Sanfelice. “A hybrid model predictive controller for path planning and path following.” In *International Conference on Cyber-Physical Systems* (ICCPS), pp. 139-148. Seattle, WA, 2015. http://csl.arizona.edu/http//dx.doi.org/10.1145/2735960.2735966
4. K. Zhang, J. Sprinkle, and R. G. Sanfelice. “Computationally-Aware Control of Autonomous Vehicles: A Hybrid Model Predictive Control Approach.” *Autonomous Robots*. vol. 39, pp. 503-517, 2015. http://dx.doi.org/10.1007/s10514-015-9469-5
5. K. Zhang, Sprinkle, J., and Sanfelice, R. G., "Computationally-Aware Switching Criteria for Hybrid Model Predictive Control Of Cyber-Physical Systems", *IEEE Transactions on Automation Science and Engineering*, vol. 13, no. 2, pp. 479-490, April, 2016. http://dx.doi.org/10.1109/TASE.2016.2523341 .

Credit Due To…


Kun Zhang
PhD 2015


Matt Bunting
PhD 2017


CAT Vehicle 2013
RUSTY

CAT Vehicle 2014


CAT Vehicle 2015
STATE OF ARIZONA FOR OFFICIAL USE ONLY
HYBRID
ByWire
EXPERIENCE
VCU REC SPORTS

Thanks for the Support

"CAREER: Domain-Specific Modeling Techniques for Cyber-Physical Systems" NSF CNS-1253334

"REU Site: CatVehicle: Cognitive and Autonomous Test Vehicle" NSF IIS-1262960 (Co-PI: Tamal Bose)

Additional support for awards CNS-1253334 and IIS-1262960 provided by the Air Force Office of Scientific Research

"Control of Vehicular Traffic Flow via Low Density Autonomous Vehicles" NSF CNS-1446435 (joint with UIUC, Temple, Rutgers)

"Computationally Aware Cyber-Physical Systems" NSF CNS-1544395 (joint with R. Sanfelice, UC Santa Cruz)

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation or AFOSR.

More Awesome stuff

jmscslgroup

http://catvehicle.arizona.edu/

http://csl.arizona.edu