Comparing Modular and Integrated Autonomous Bus/Vehicle Systems:

Design Inspired by the Human Brain

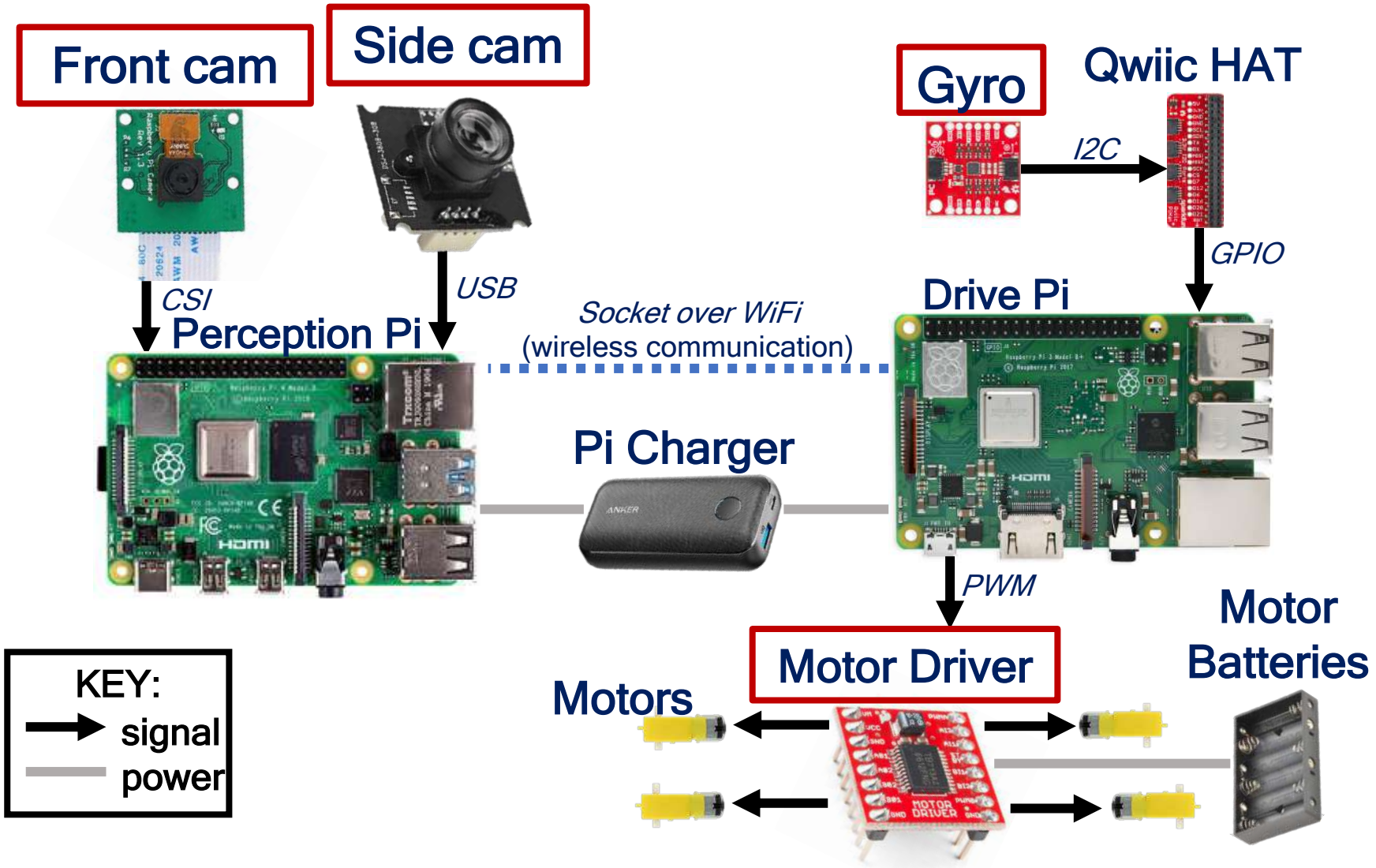
Motivation:
Mobility limited & unsafe for minors

- PPS short 650 seats for 1st day of school due to COVID[3]

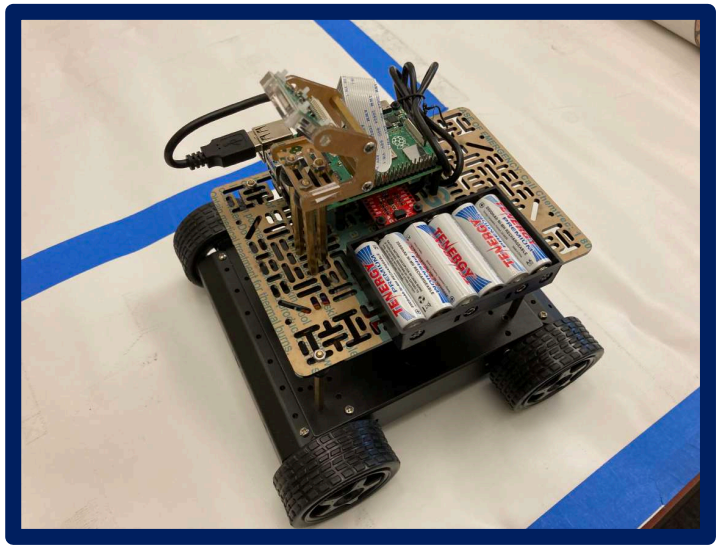
- 71% of non-family abductions on way to or from school[12]

Solution: Design & test autonomous vehicle

Built Vehicle



bought from Amazon, Pololu, Sparkfun, Arrow

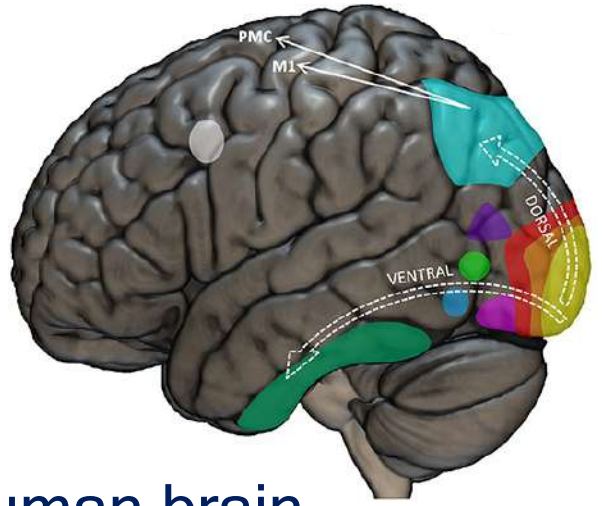


Design Decision:
Integrated v. Modular

Integrated
single, general component

Tesla's integrated hardware & software

Modular
multiple, separate, specialized components



Modular human brain

EBA recognizes bodies

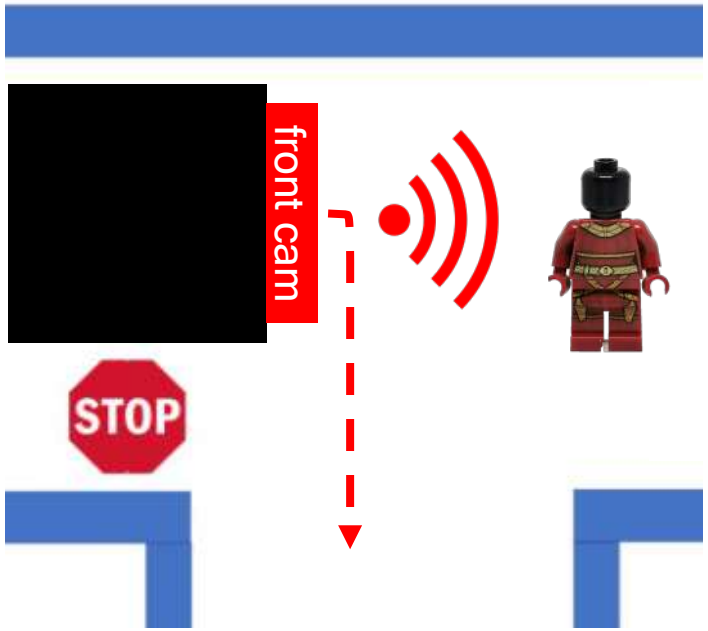
FFA recognizes faces

Which is the safest design?

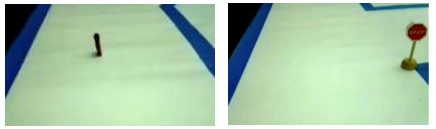
Meunier, David, et al. "Hierarchical Modularity in Human Brain Functional Networks." *Frontiers*, Frontiers, 1 Jan. 1AD, https://www.frontiersin.org/articles/10.3389/neuro.11.037.2009/full.

Hardware Systems:
Integrated v. Modular

Integrated Hardware
single, general sensor



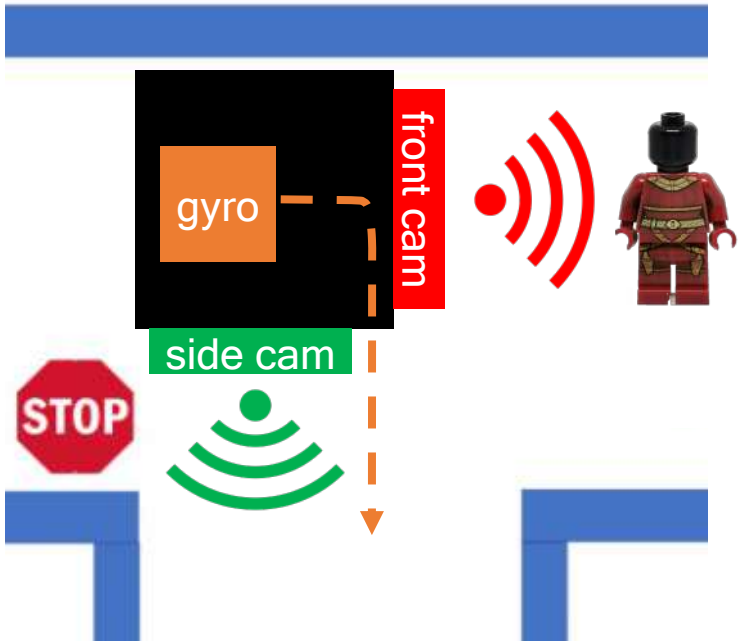
Intersection (Front Camera)

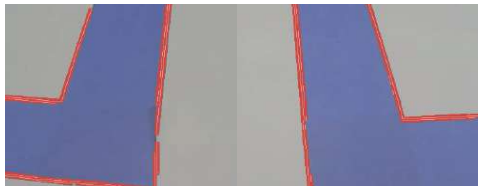


People & Stop Sign
(Front Camera)

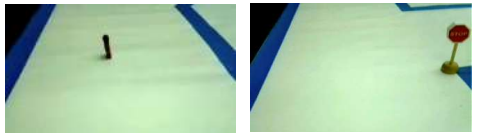
Front cam: sense *lanes*, *signs*, *people*, *intersections*

Modular Hardware
multiple, separate, specialized sensors





Intersection (Side Camera)

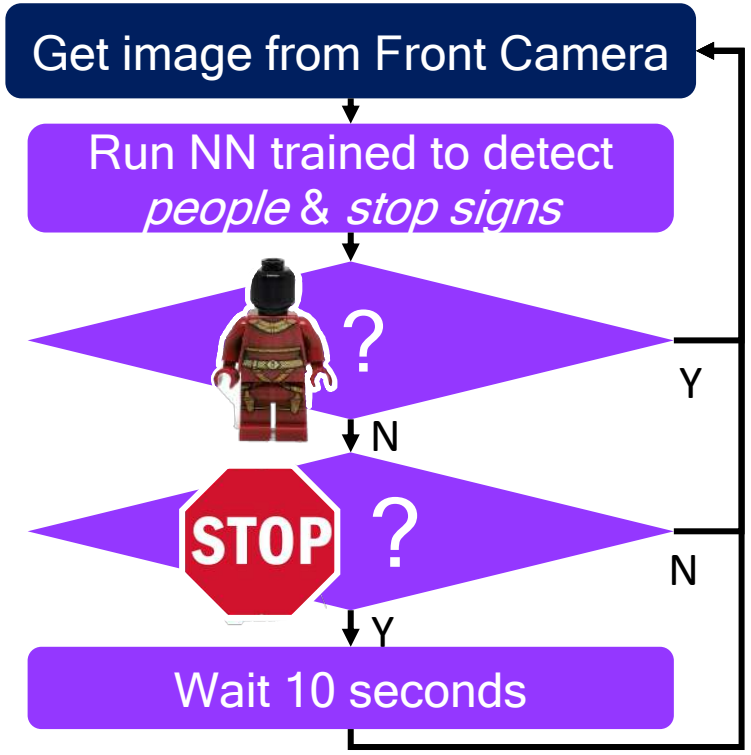


People & Stop Sign
(Front Camera)

Front cam: sense *lanes*, *signs*, *people*
Side cam: sense *intersections*
Gyro: turn into *intersections*

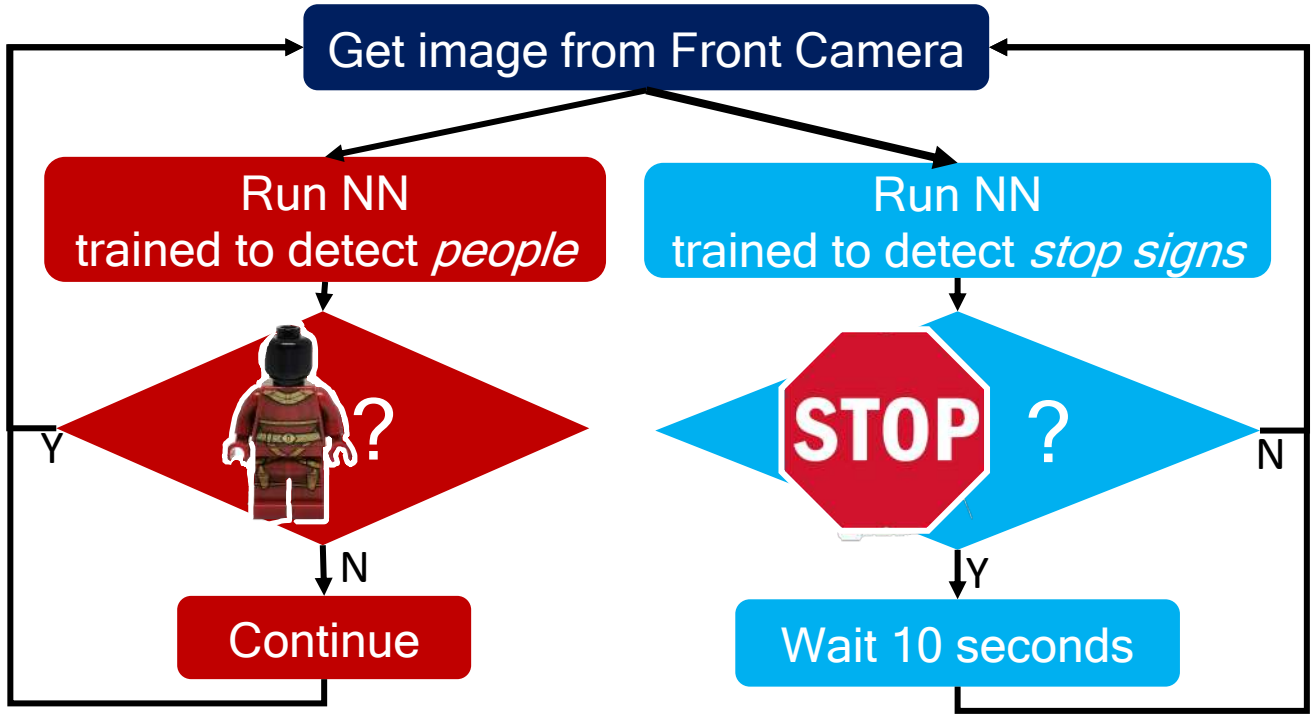
Software Systems:
Integrated v. Modular

Integrated Software
single, general neural network (NN)



1 general NN detects both people & stop signs

Modular Software
multiple, separate, specialized neural networks (NN)

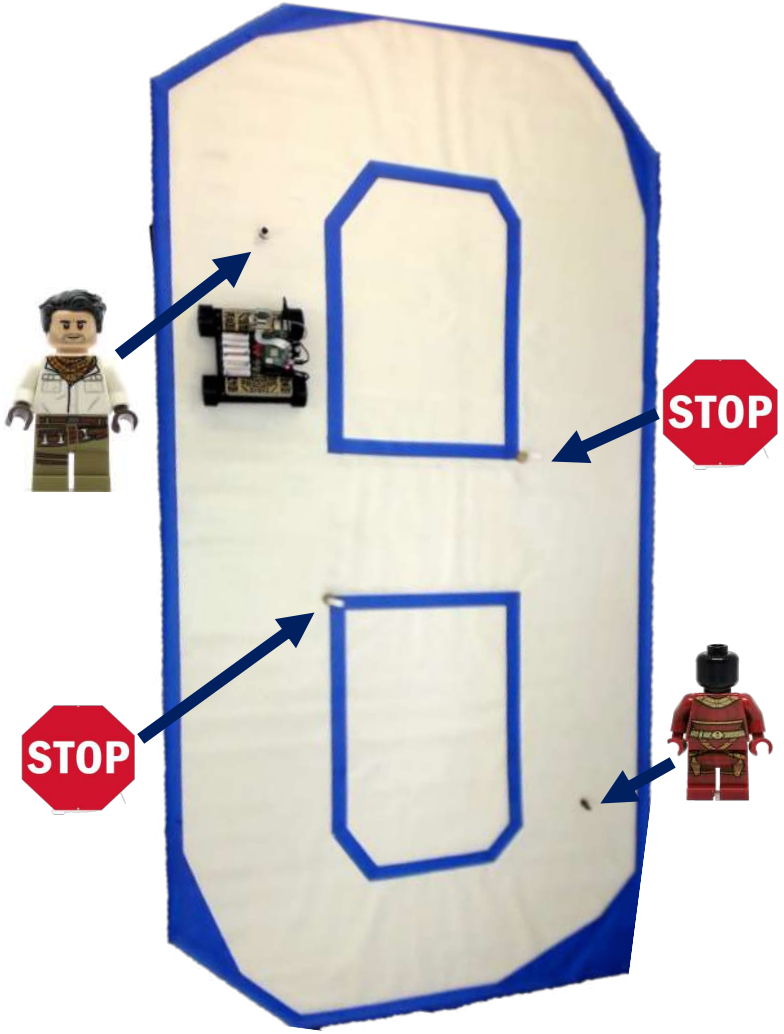


1 specialized NN detects people
1 specialized NN detects stop signs

Results: 4 Prototypes

fully modular

	Modular Hardware	Integrated Hardware
Modular Software	MHMS	IHMS
Integrated Software	MHIS	IHIS



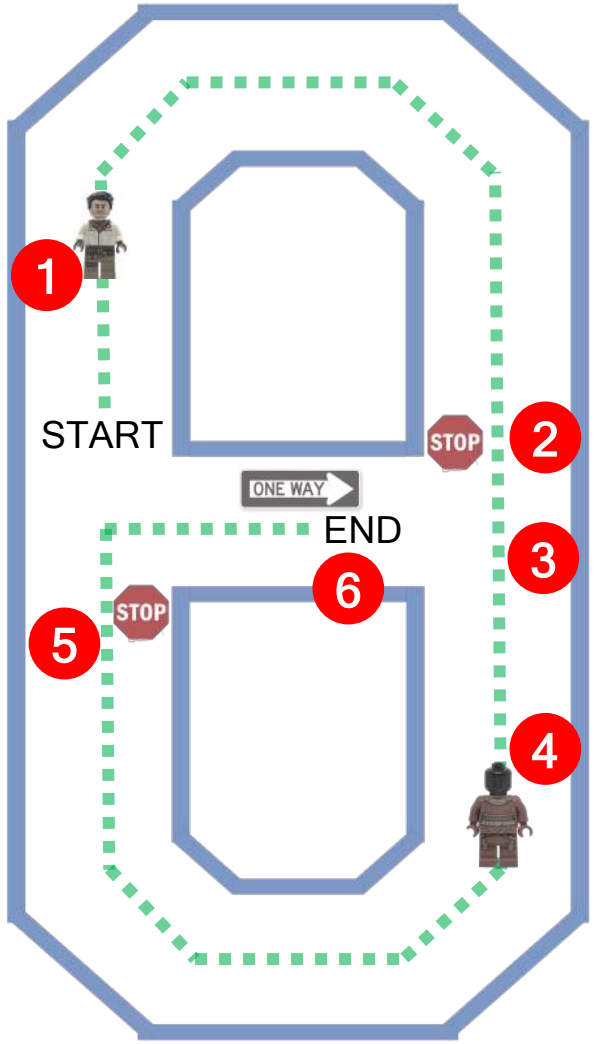
Street Map

Prototypes tested on street map 20 times each & errors made were recorded

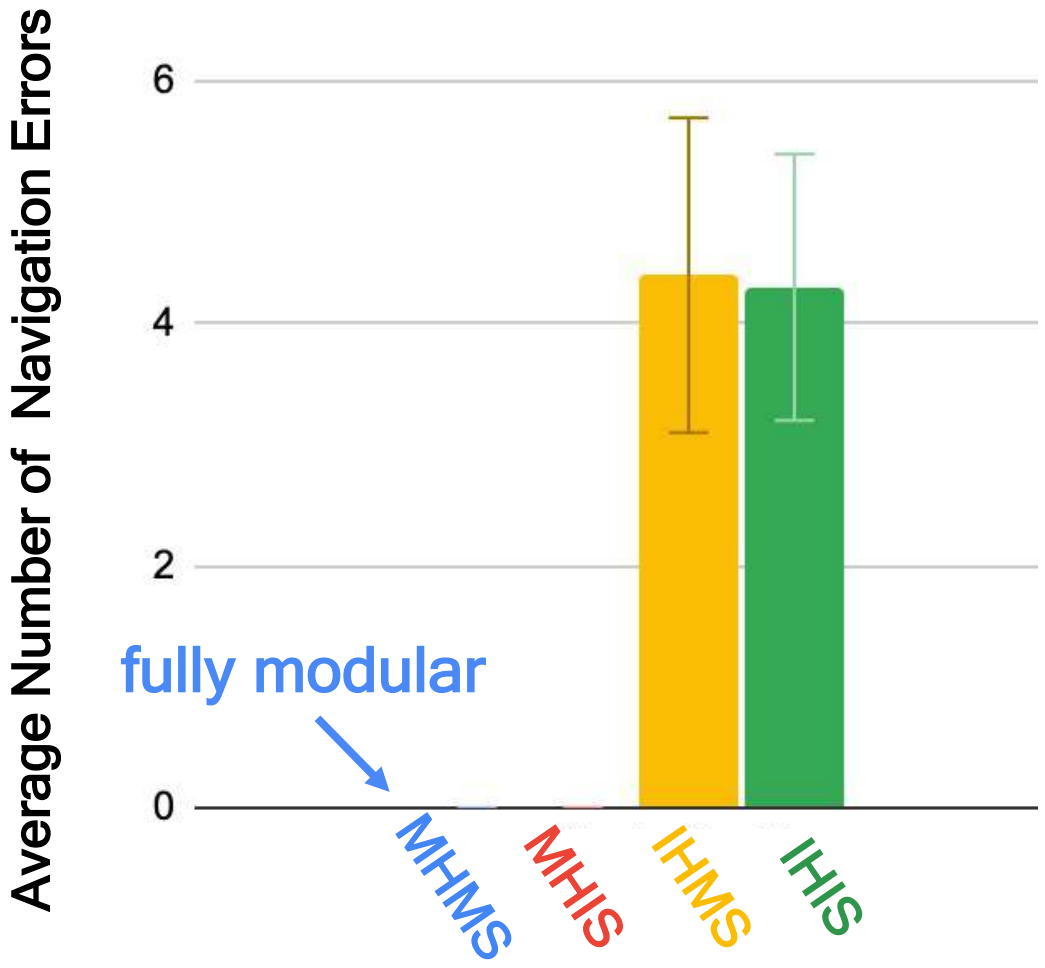
All Possible Navigation Errors Identified

1. Failure to reach 1st person
2. Failure to reach 1st stop sign
3. Failure to pass 1st intersection
4. Failure to reach 2nd person
5. Failure to reach 2nd stop sign
6. Failure to turn into 2nd intersection

1 point penalty per Navigation Error



Results: Navigation Errors Observed



- Each prototype run on street map 20 times

Modular Hardware (MH):

- average errors: 0
- standard deviation of errors: 0

Integrated Hardware (IH):

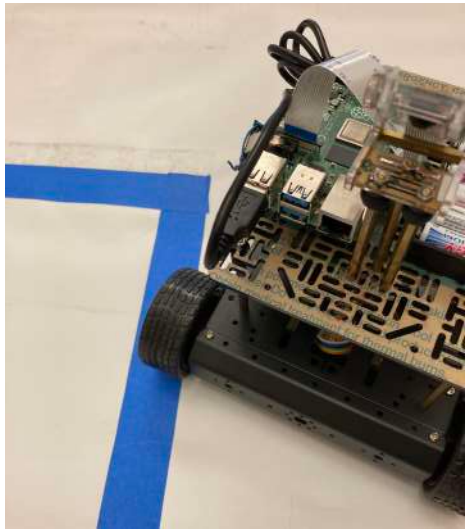
- average errors: 4.35
- standard deviation of errors: 1.17

P-value = 3.12×10^{-37}, $\alpha = 0.05$

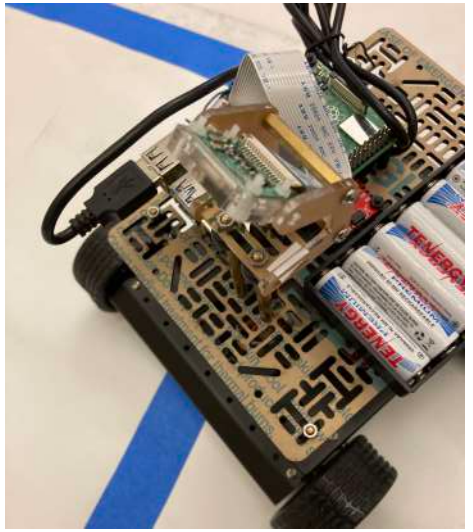
Modular hardware had 0 errors, significantly outperforming integrated hardware

All Possible Safety Errors Identified

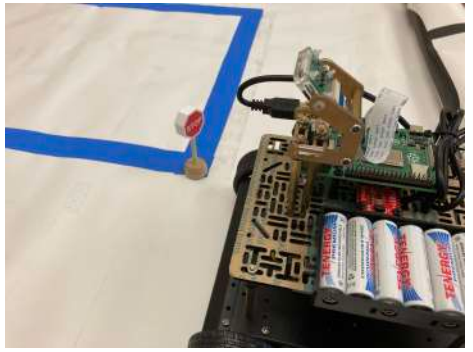
1. Wheel touches a lane line
2. Wheel crosses a lane line
3. Failure to stop at a stop sign
4. Failure to stop for people crossing
5. Stopping due to falsely detected stop signs
6. Stopping due to falsely detected people



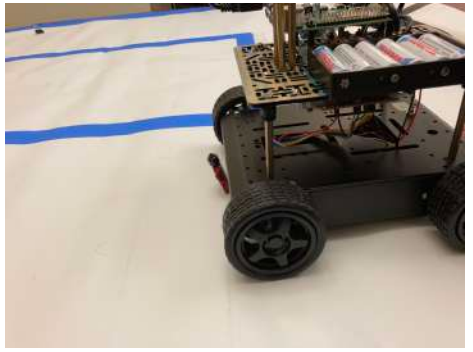
wheel touches lane



wheel crosses lane



robot at a stop sign



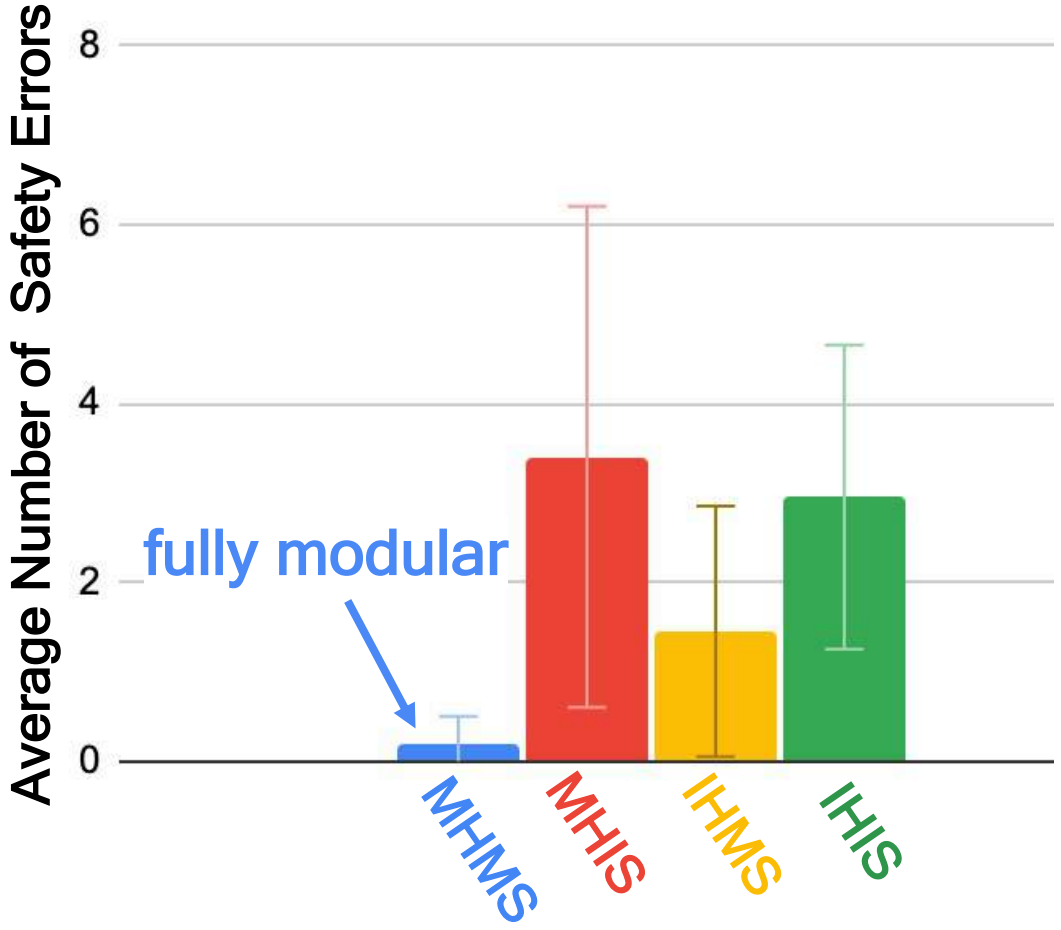
robot failing to stop for people

0.5 points penalty per Safety Error #1

3 points penalty per Safety Errors #2-6

(based on PA Department of Transportation's Point System)

Results: Safety Errors Observed



- Each prototype run on street map 20 times

Modular Software (MS):

- average errors: 0.83
- standard deviation of errors: 1.17

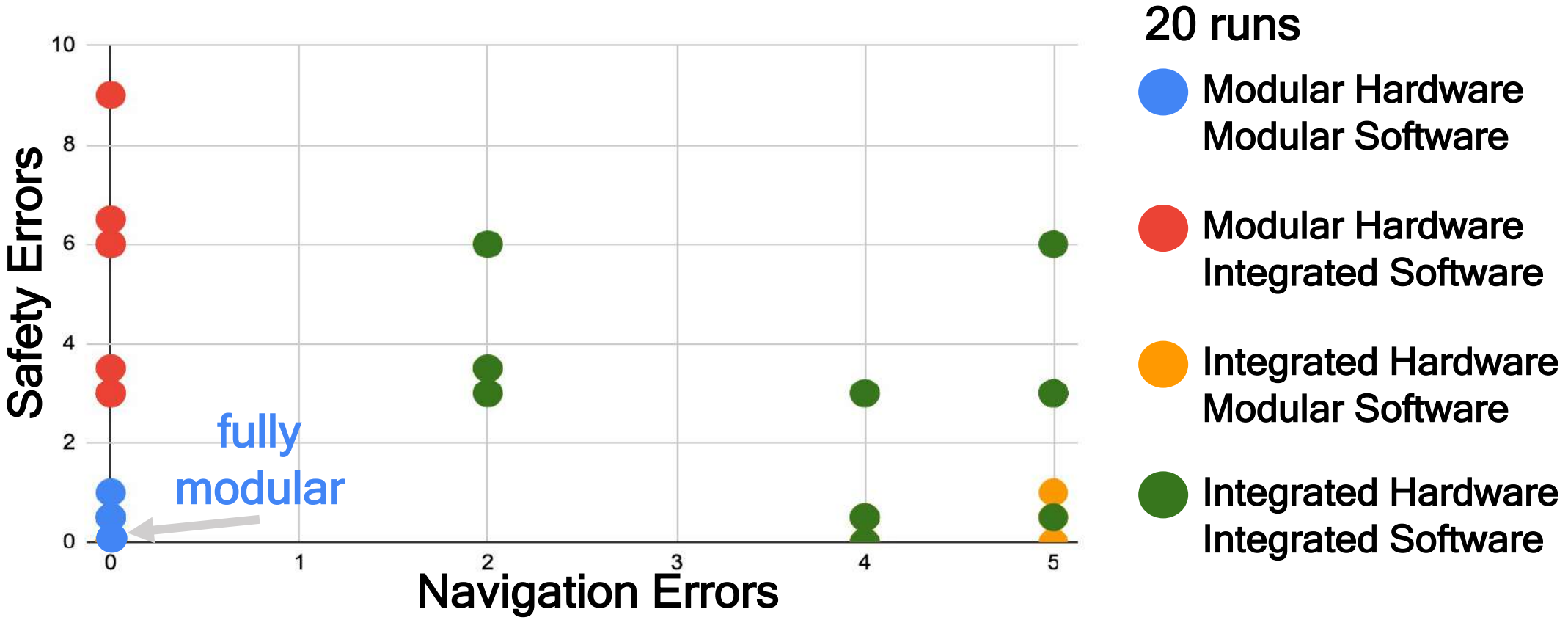
Integrated Software (IS):

- average errors: 3.17
- standard deviation of errors: 2.29

P-value = 1.48×10^{-7}, $\alpha = 0.05$

Modular software significantly outperformed integrated software

Results: Safety v. Navigation Errors



P-value = 3.79×10^{-7}, $\alpha = 0.05$ → results are significant

Fully modular prototype outperformed other prototypes consistently

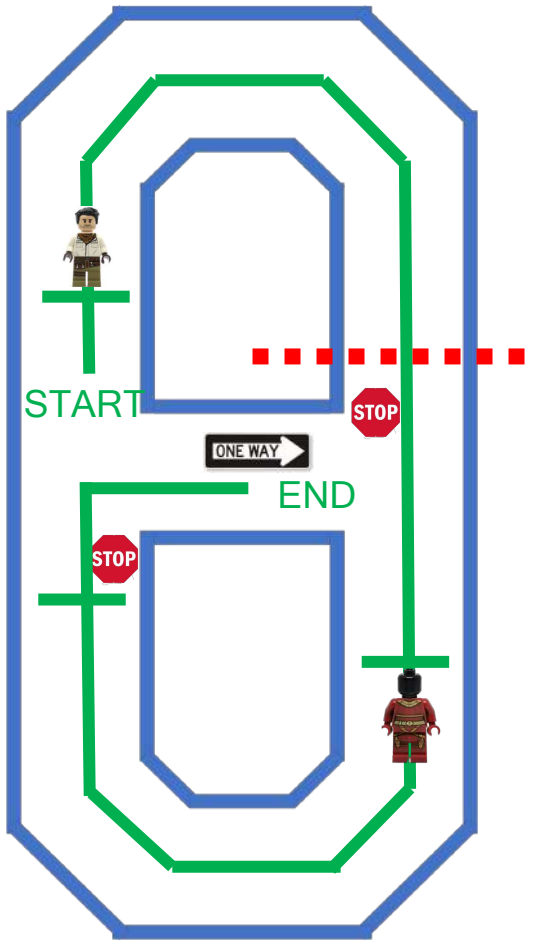
Results: Median Cases

Fully Modular made 0 errors

KEY:

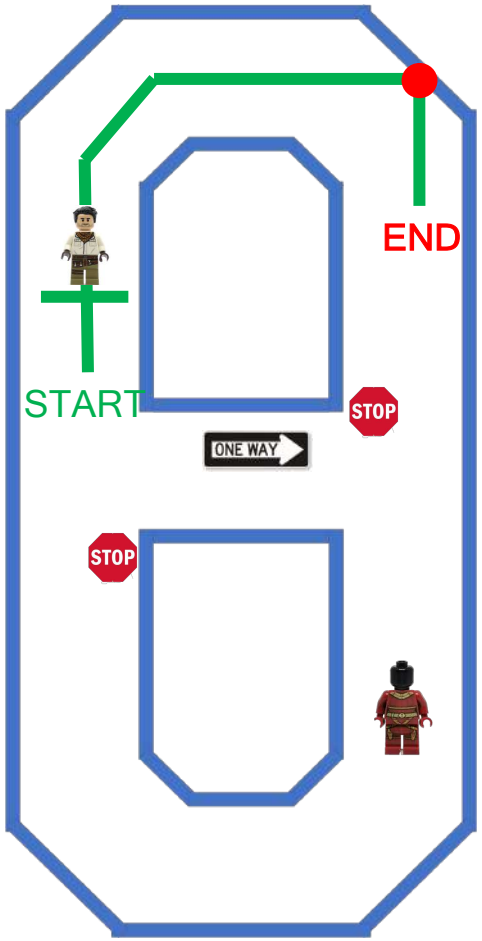
END wrong dest. | END correct dest. | touched lane | crossed lane | stopped well | missed stop

Modular Hardware
Integrated Software

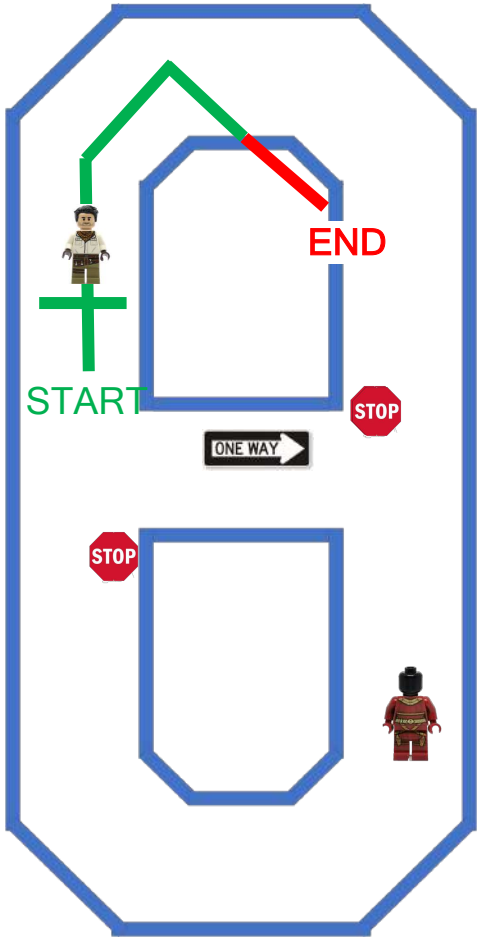


missed stop sign

Integrated Hardware
Modular Software

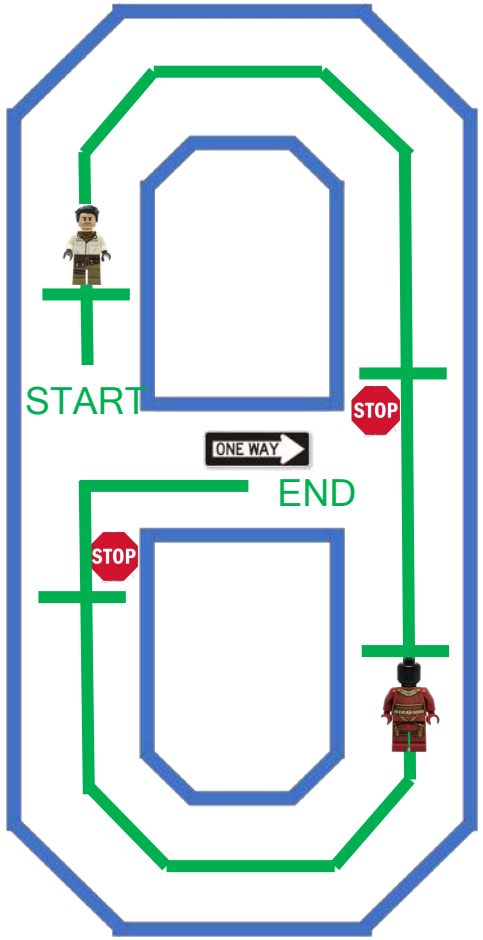


Integrated Hardware
Integrated Software



front cam falsely detects intersection

Modular Hardware
Modular Software

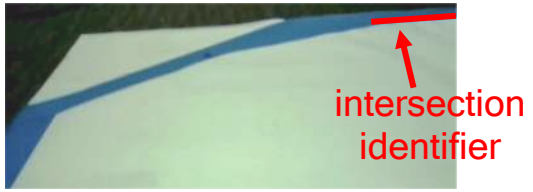


0 errors

Analysis of Hardware Results

Integrated Hardware
Front Camera Only

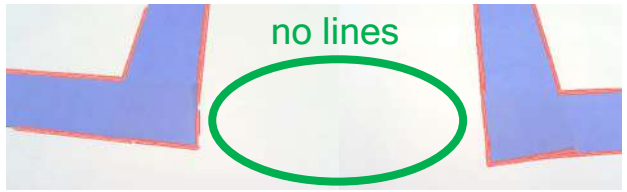
True Intersection



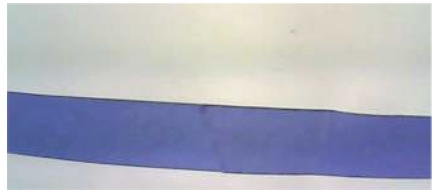
Falsely Detected Intersection

- Non-specialized front camera
  - No unique intersection identifiers
    - False intersection detection in curved lanes

Modular Hardware
Front Camera, Side Camera, Gyro



True Intersection



True Negative (not an intersection)

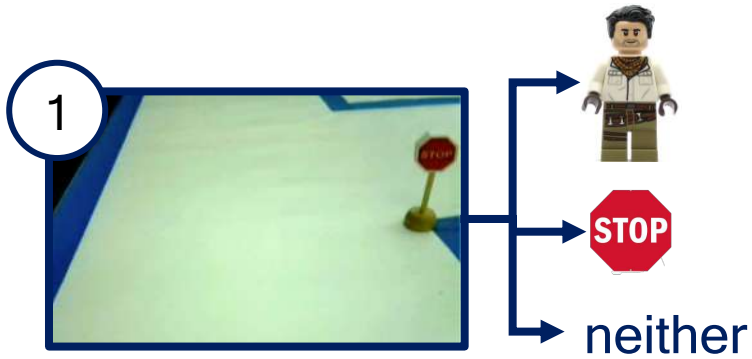
- Specialized side camera
  - Unique intersection identifier (no lines)
    - Accurate, reliable intersection detection

Analysis of Software Results

Integrated Software

Single Neural Network

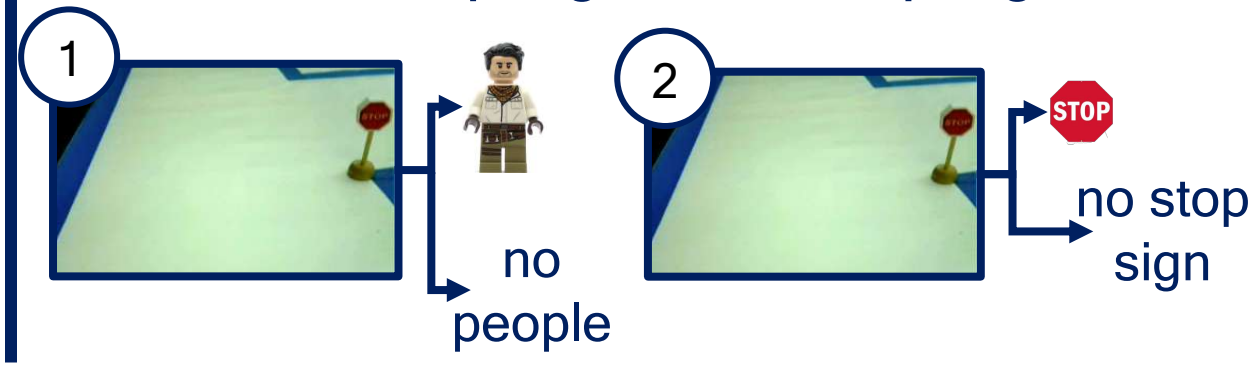
- more errors & higher σ → overfitting
  - need more training images
- complex, one-step decision:
  1. people or stop sign or neither?



Modular Software

2 Specialized Neural Networks

- less errors & lower σ
  - # training images sufficient
- simple, two-step decision:
  1. people or no people?
  2. stop sign or no stop sign?



Complex tasks need modular designs, like the human brain

Conclusions

Autonomous Cars today support this conclusion

- SAE says Tesla (1 video system & 1 NN) needs supervision
- SAE says Waymo (3 types of sensors & multiple NNs) doesn't need supervision

Costs of Modular: longer runtime, more computing resources, more money

Limitations: only stop sign & people tested, static environment, lack of distracting objects (eg. trees)

Future Work: more human-inspired designs

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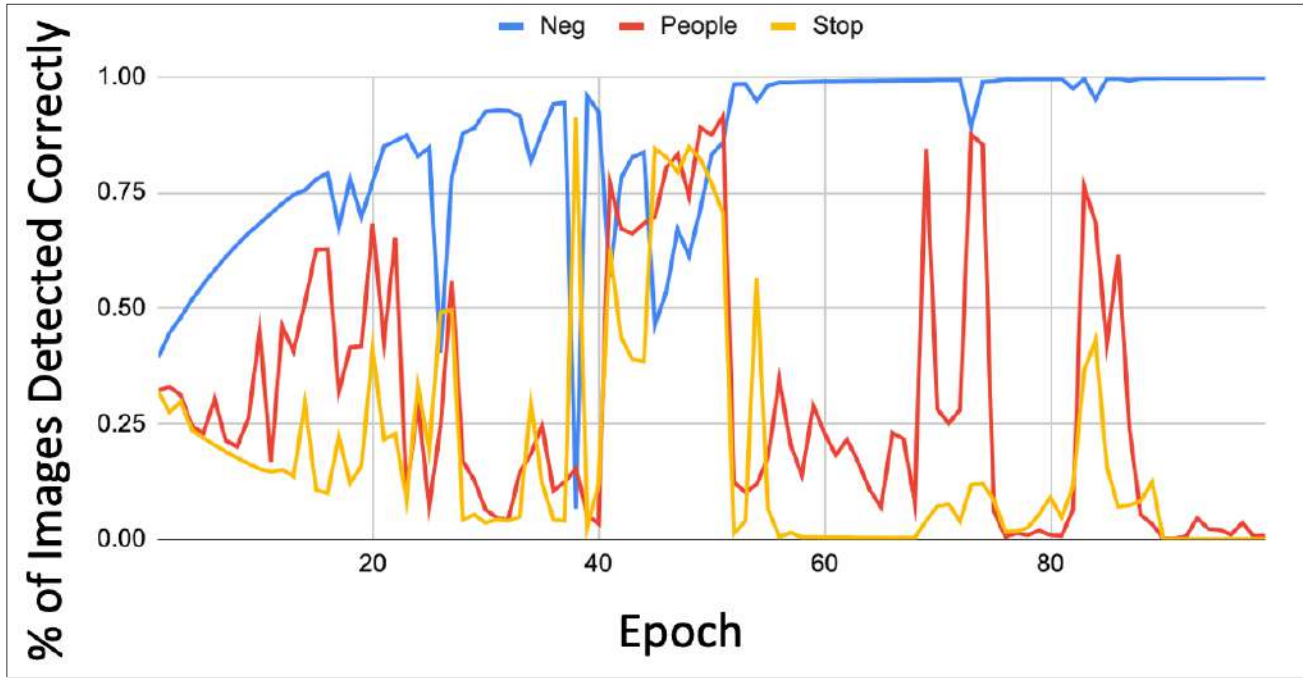
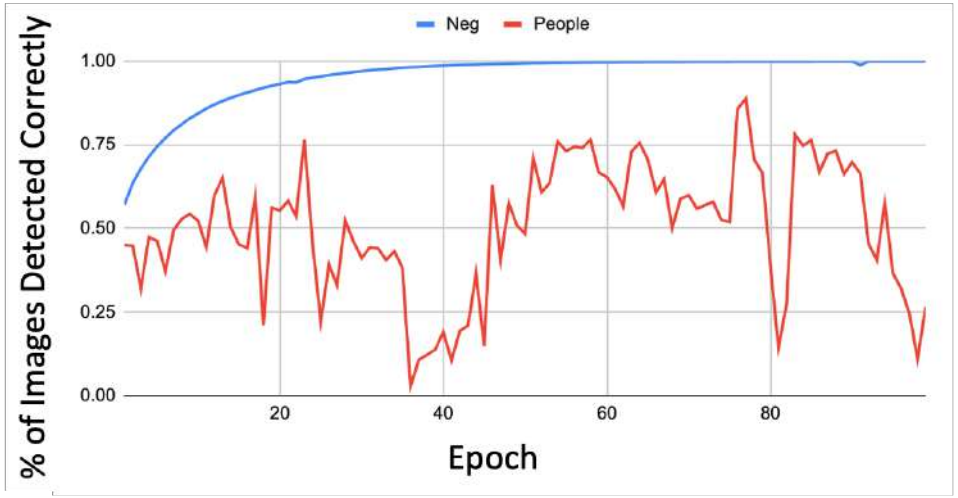
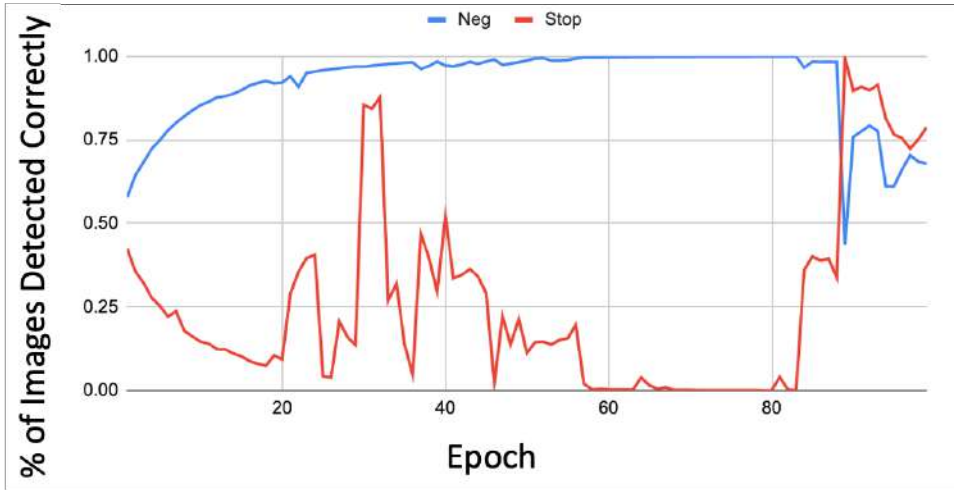
Training the Neural Networks

Integrated Software
(Single Neural Network)



Modular Hardware
(2 Specialized Neural Networks)





Confusion Matrixes

Integrated Software
(Single Neural Network)

EPOCH 49

(percentages calculated using 100 images of each class)

predicted \ actual	negative	people	stop sign
negative	71.3%	3.2%	25.5%
people	8.8%	89.0%	2.2%
stop sign	14.3%	3.4%	82.3%

Modular Hardware
(2 Specialized Neural Networks)

PEOPLE EPOCH 77

(percentages calculated using 100 images of each class)

predicted \ actual	negative	people
negative	99.8%	0.2%
people	11.3%	88.7%

STOP SIGN EPOCH 32

(percentages calculated using 100 images of each class)

predicted1 \ actual	negative	stop sign
negative	97.4%	2.6%
stop sign	12.2%	87.8%

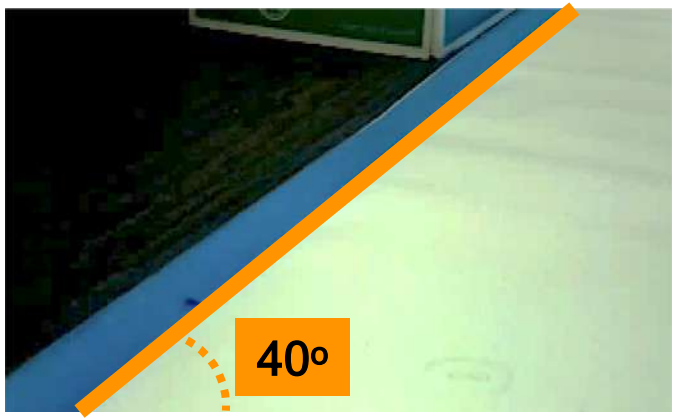
Stay Inside Lane

Perception Pi

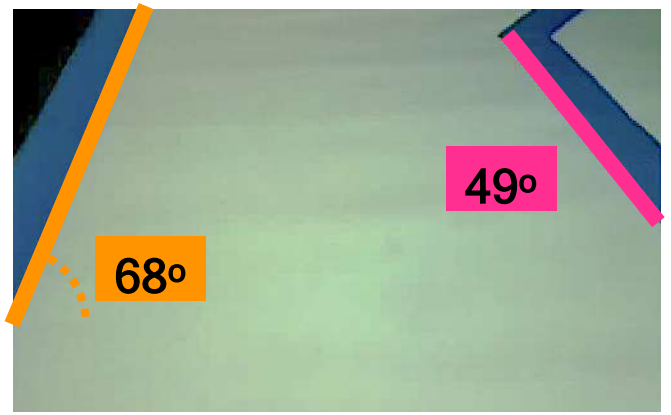
- Get image from Front Camera
- Find all lines (Canny & Hough)
- Select left & right lane edges
- Find lane edge angles
- Determine robot move (straight, turn left, turn right)
- Send robot move msg to Drive Pi

Drive Pi

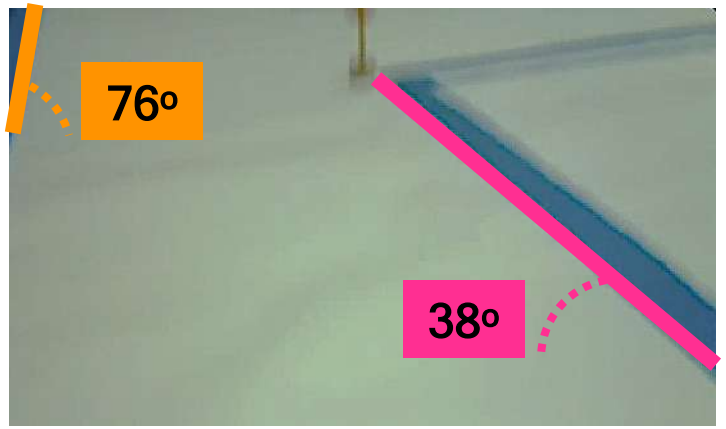
- Listen for robot move msg
- Move robot



Left lane angle less than min threshold → "Turn Right"



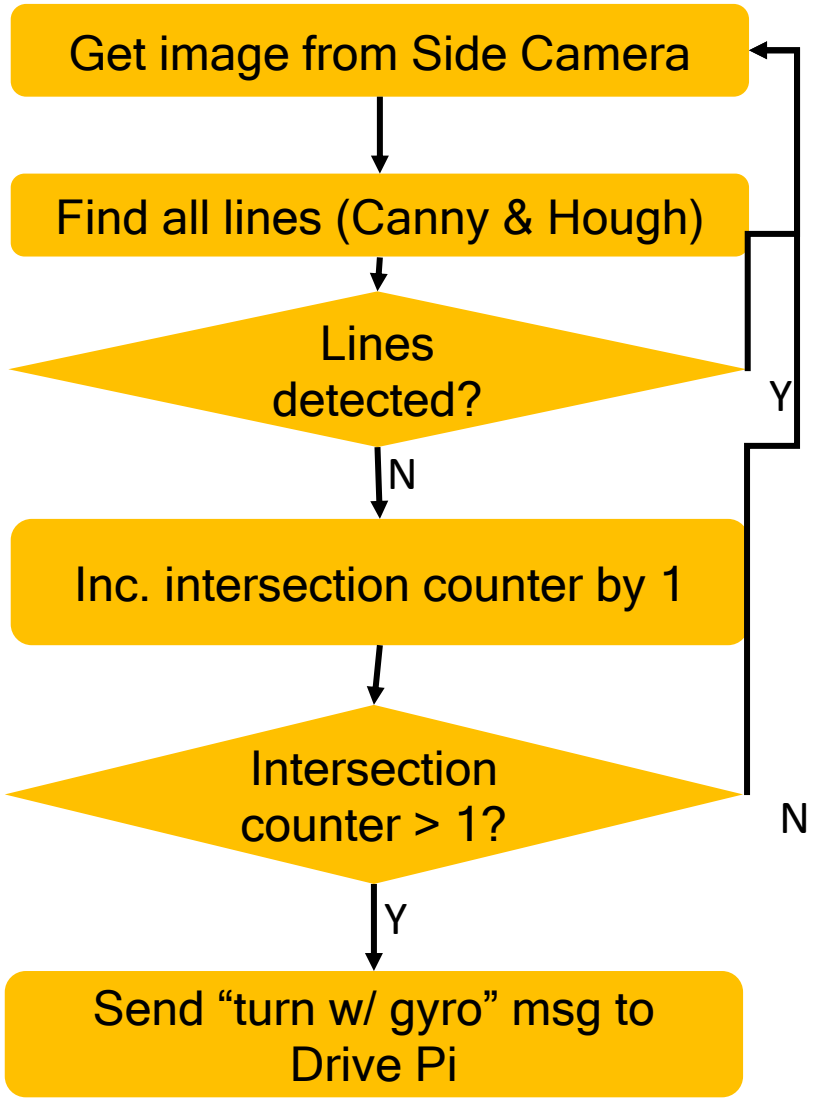
Left & right lane angles over min thresholds → "Straight"



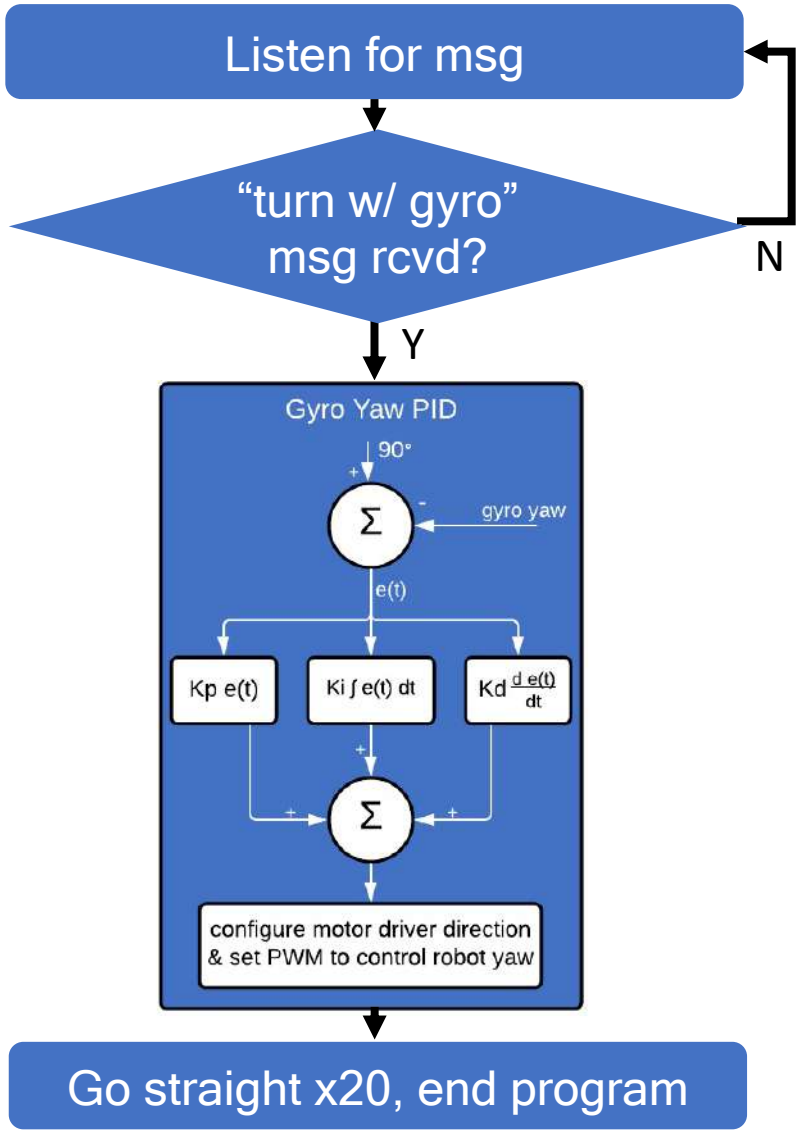
Right lane angle less than min threshold → "Turn Left"

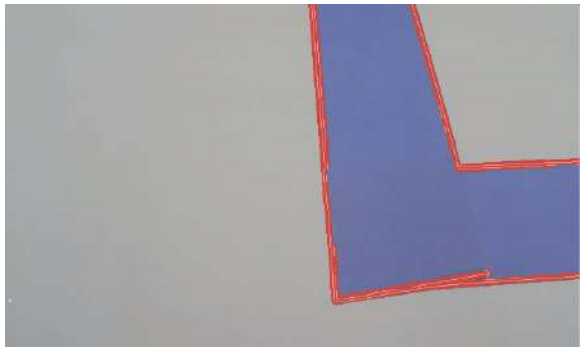
Intersection (Modular)

Perception Pi

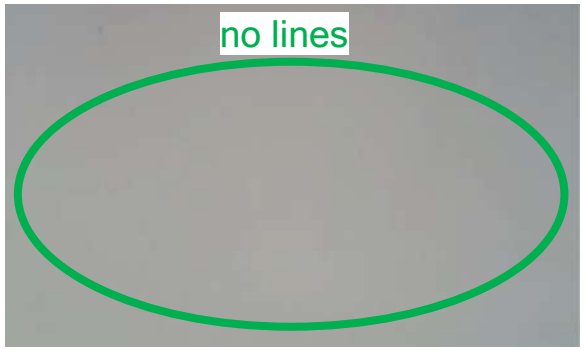


Drive Pi

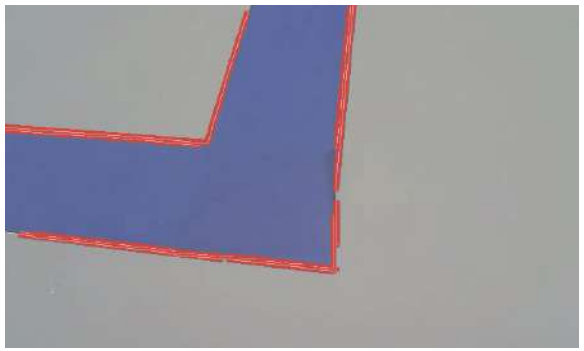




i (approaching intersection)

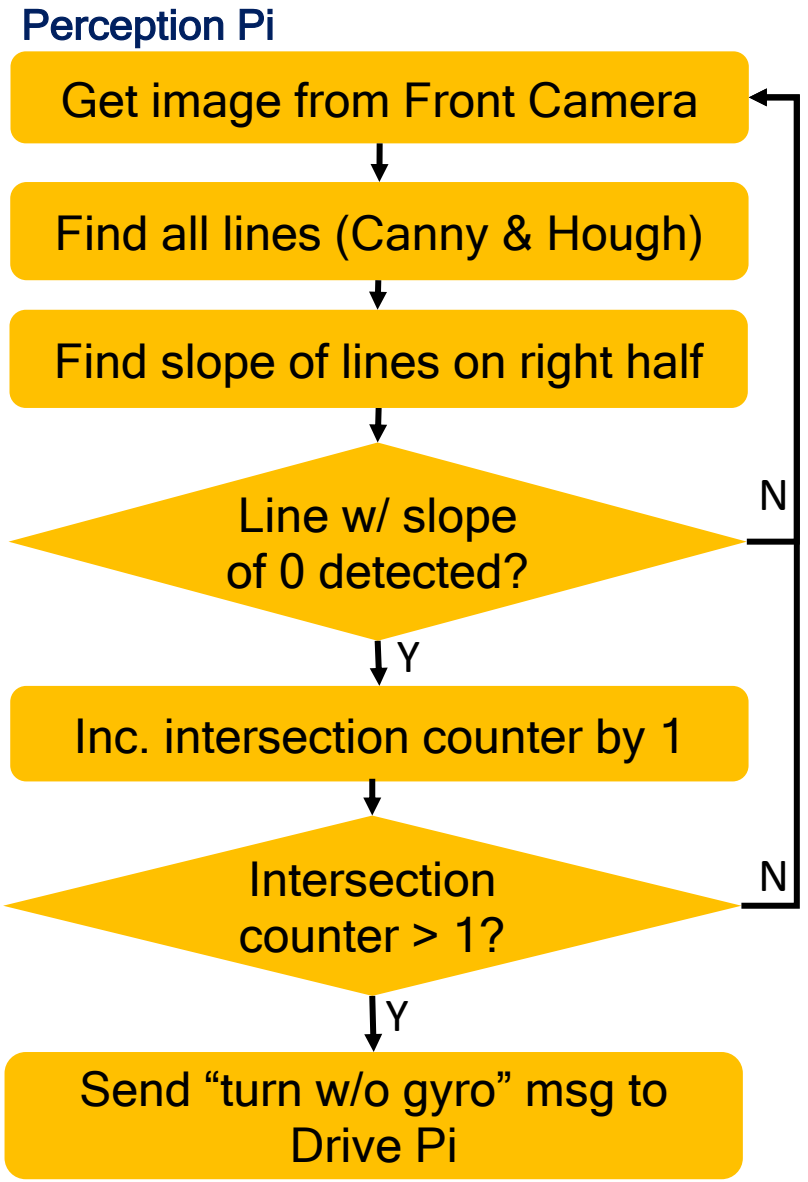


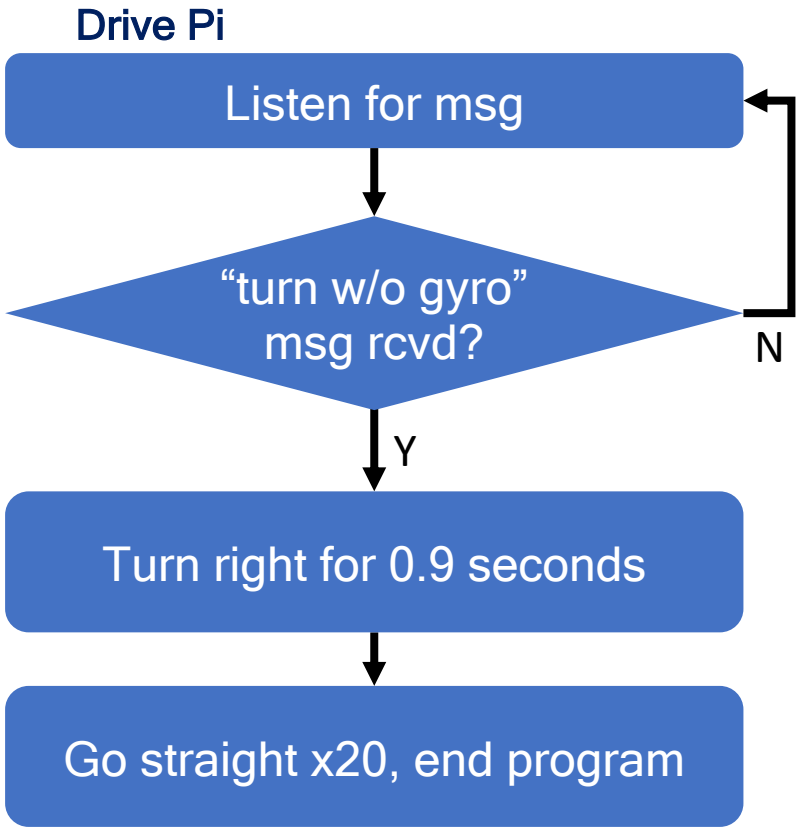
i + 1 (seeing intersection)



i + 2 (past intersection)

Intersection (Integrated)



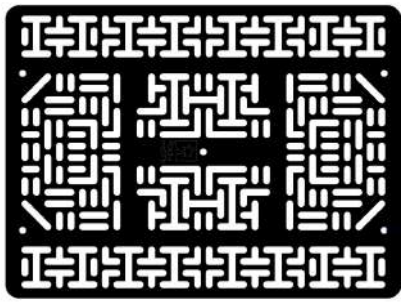


i (approaching intersection)

i + 1 (next to intersection)

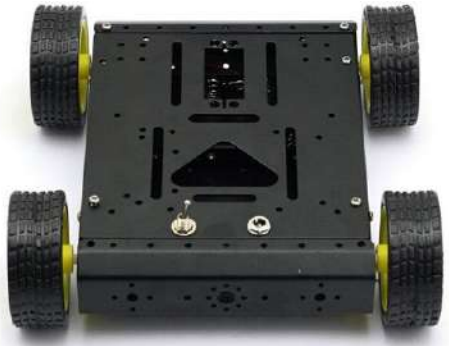
i + 2 (past intersection)

Assembled Vehicle



Pololu Expansion Plate

60mm brass standoffs



Sainsmart 4WD Robot Car Chassis