# Dynamics and Control of a Steer-By-Wire Bicycle

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PME - Mechatronic System Design

27-11-2012

# Presentation Overview

[1] Steer-by-Wire? On Bicycles?

[2] Bicycle Modeling

[3] System Modeling and Simulation

[4] Steer-by-Wire Implementation

[5] Experimental Tests

[6] Conclusions and Recommendations

# Presentation Overview

# [1] Steer-by-Wire? On Bicycles?

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- By-Wire technology covers terms like Drive-by-Wire, Fly-by-Wire and Steer-by-Wire.

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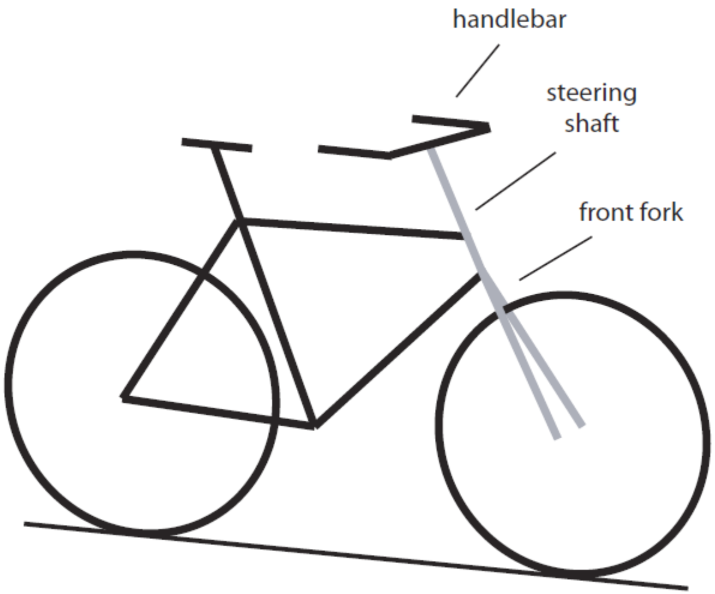


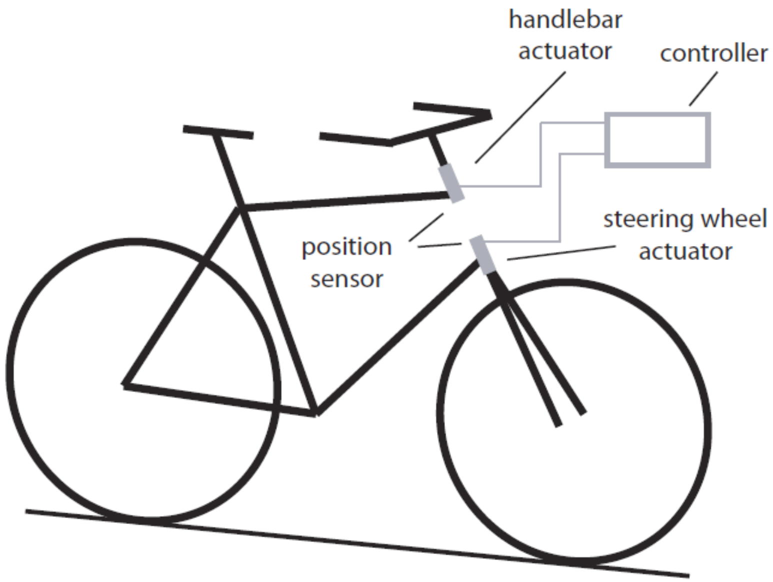

# [1] Steer-by-Wire? On Bicycles?

- By-Wire technology offers advantages in terms of Design Freedom and additional Features.
- Highly unstable vehicles can benefit from additional control (single-track vehicles!).
- Lateral Stability Enhancement for application on bicycles.

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# [2] Bicycle Modeling

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- First recognized bicycle model by F. Whipple [1899][1]

- Benchmark Bicycle model by J.P. Meijaard et al. [2007][2]

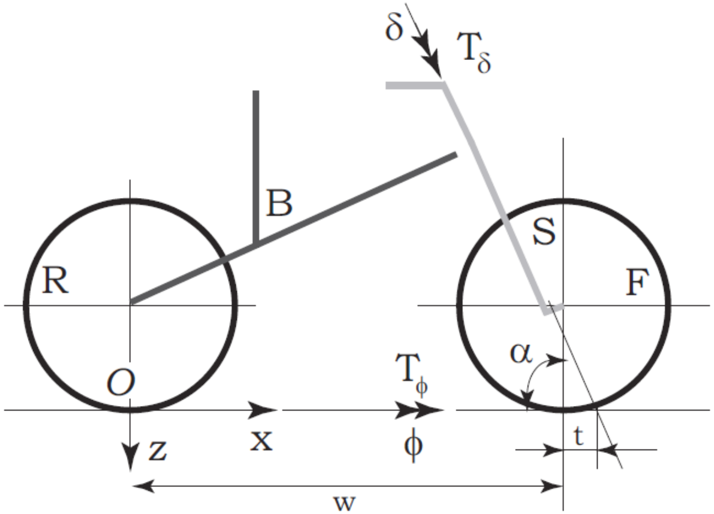
1 [Whipple, F.J.W.; The stability of the motion of a bicycle, 1899]
2 [Meijaard, J.P. and Papadopoulos, J.M. and Ruina, A. and Schwab, A.L.; Linearized dynamics equations for the balance and steer of a bicycle: a benchmark and review, 2007]

# [2] Bicycle Modeling

- Benchmark Bicycle model:

$$\mathbf{M}\ddot{q} + [v\mathbf{C1}]\dot{q} + [\mathbf{K0} + v^2\mathbf{K2}]\mathbf{q} = \begin{bmatrix} T_\phi \\ T_\delta \end{bmatrix}$$

$$\mathbf{q} = [\phi, \delta]^T$$



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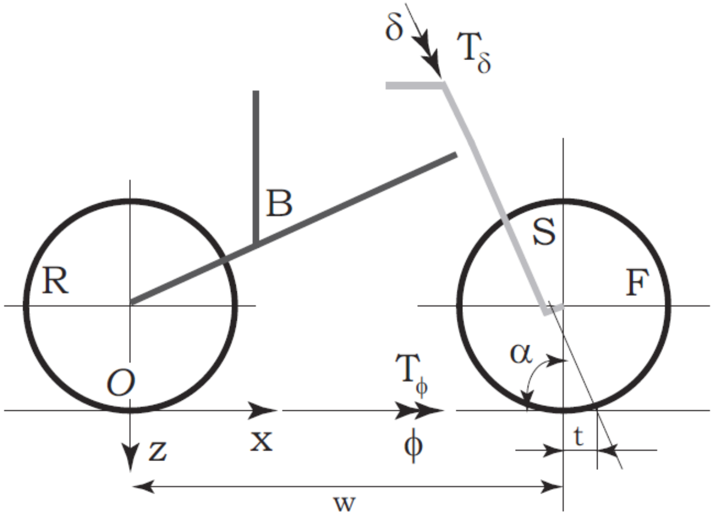
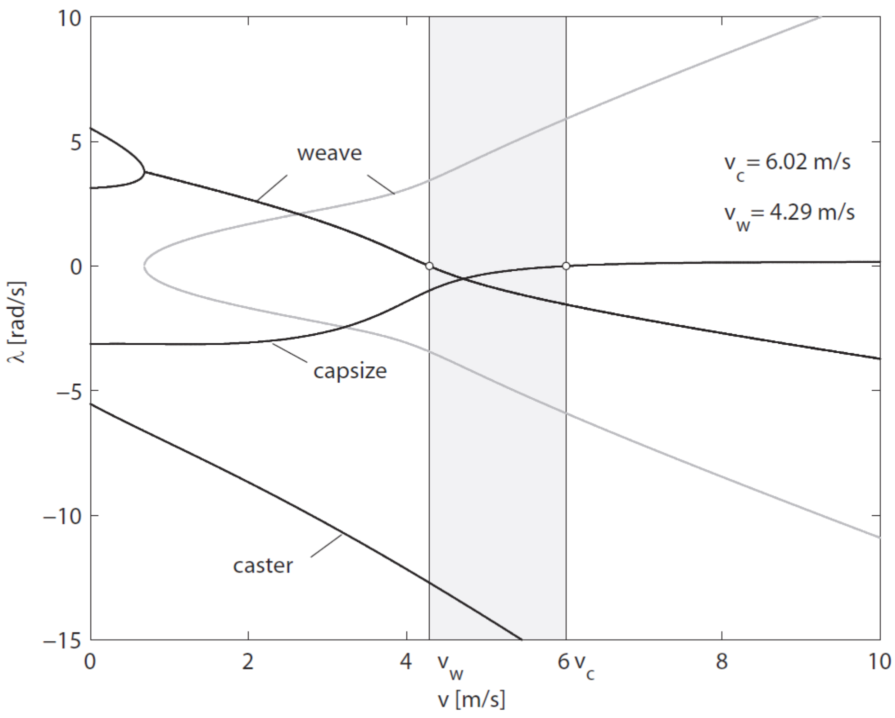
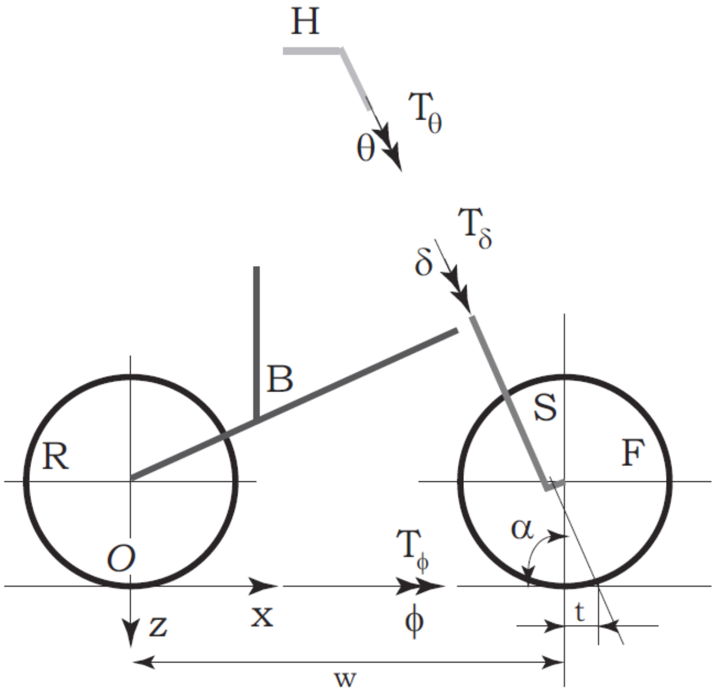


# [2] Bicycle Modeling

- Steer-by-Wire Bicycle model:
- Additional handlebar body (H)




$$\bar{M}\ddot{q} + \bar{C}\dot{q} + \bar{K}\mathbf{q} = \begin{bmatrix} T_\theta \\ T_\phi \\ T_\delta \end{bmatrix} \qquad \mathbf{q} = [\theta, \phi, \delta]^T$$

$$\bar{\mathbf{M}} = \begin{bmatrix} I_\theta & 0 \\ 0 & \mathbf{M} \end{bmatrix}$$

$$\bar{\mathbf{C}} = \begin{bmatrix} 0 & 0 \\ 0 & v\mathbf{C1} \end{bmatrix}$$

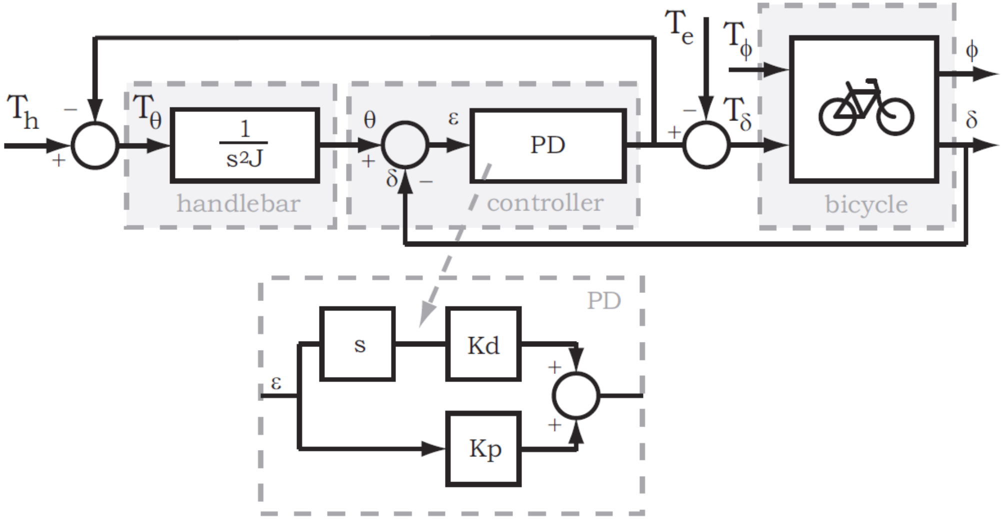
$$\bar{\mathbf{K}} = \begin{bmatrix} 0 & 0 \\ 0 & \mathbf{K0} + v^2\mathbf{K2} \end{bmatrix}$$

# [2] Bicycle Modeling

- Steer-by-Wire Bicycle model:
- Handlebar- and steering assembly coupling by PD-control

$$\bar{f} = \begin{bmatrix} T_h - T_{PD} \\ 0 \\ T_{PD} \end{bmatrix}$$

$$T_{PD} = K_p(\theta - \delta) + K_d(\dot{\theta} - \dot{\delta})$$



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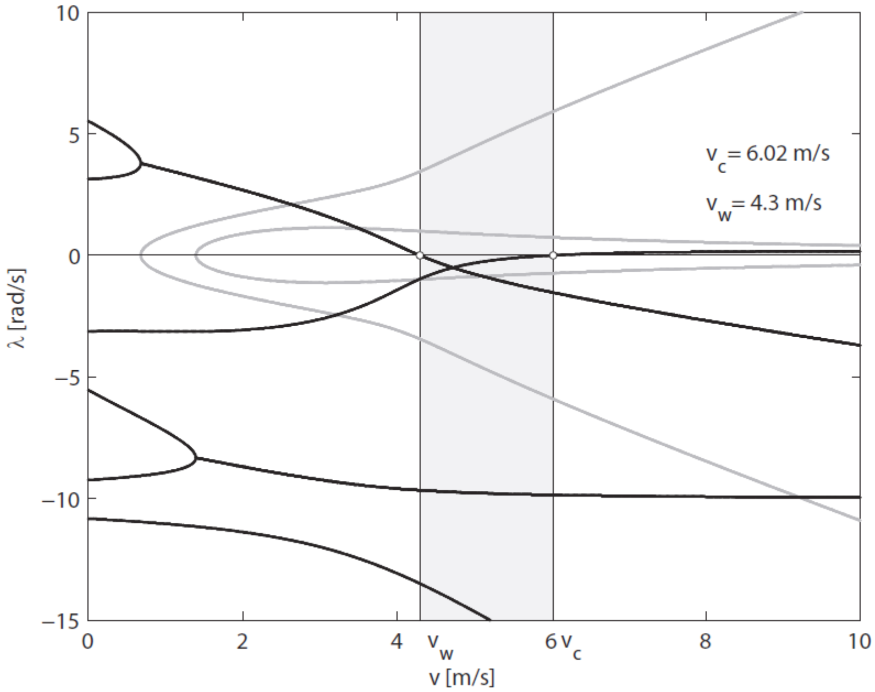

# Presentation Overview

# [3] System Modeling and Simulation

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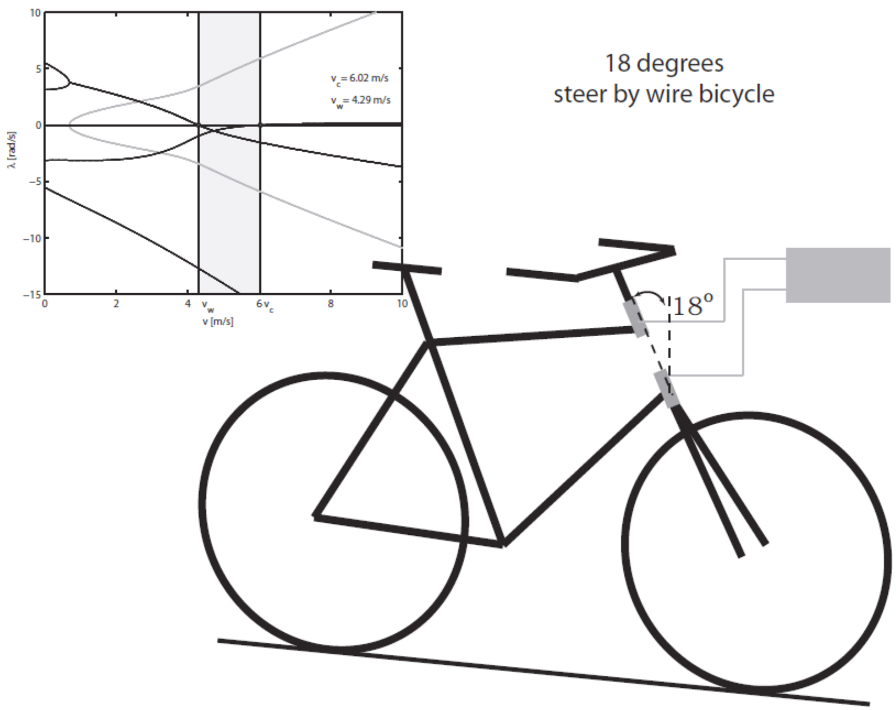
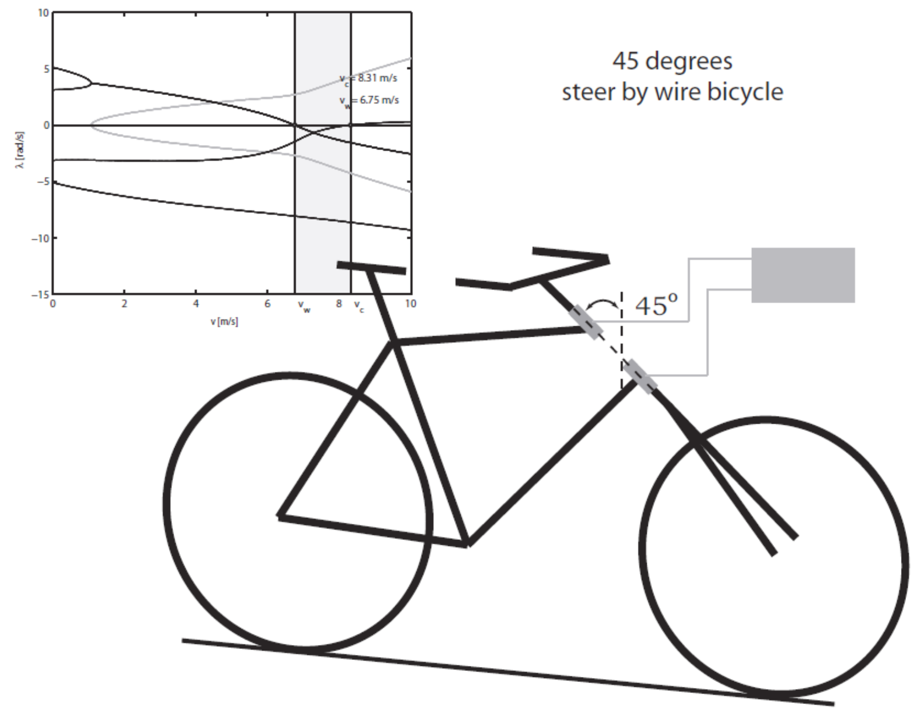
- The Steer-by-Wire Bicycle model is used to implement additional control strategies:
  1) Identity Transformation
  2) Low Speed Stabilization Control

# [3] System Modeling and Simulation

- Identity Transformation (pole placement technique)

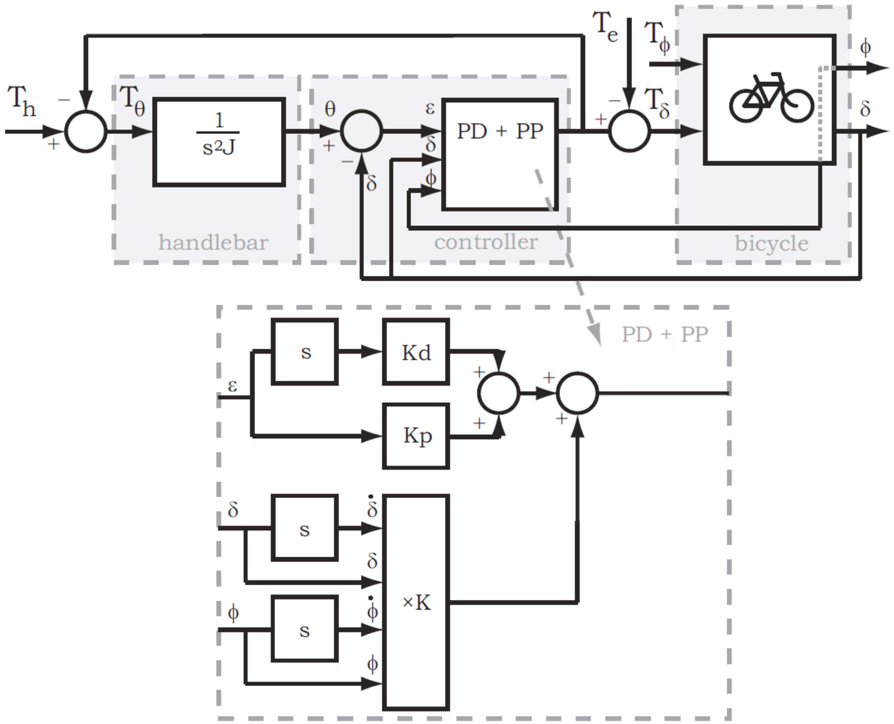


# [3] System Modeling and Simulation

- Identity Transformation (pole placement technique)

$$T_{PP} = \mathbf{K}\left[\dot{\phi}, \dot{\delta}, \phi, \delta\right]^T$$



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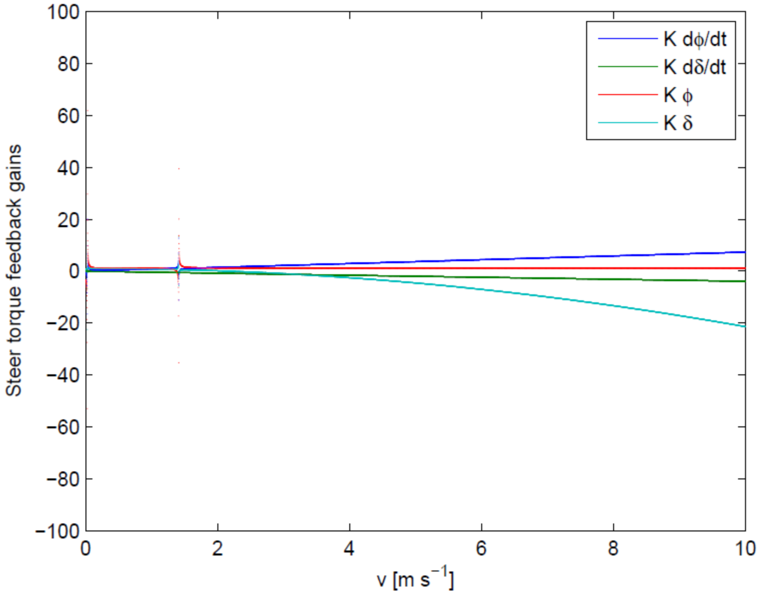
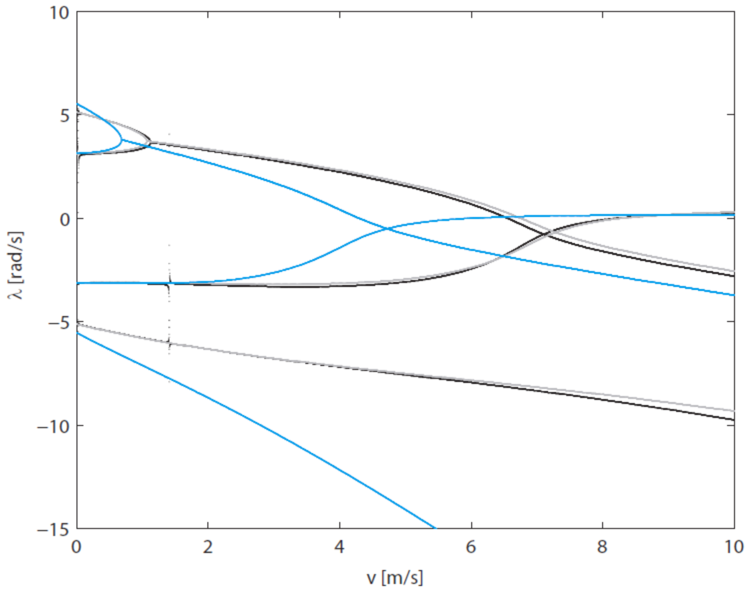
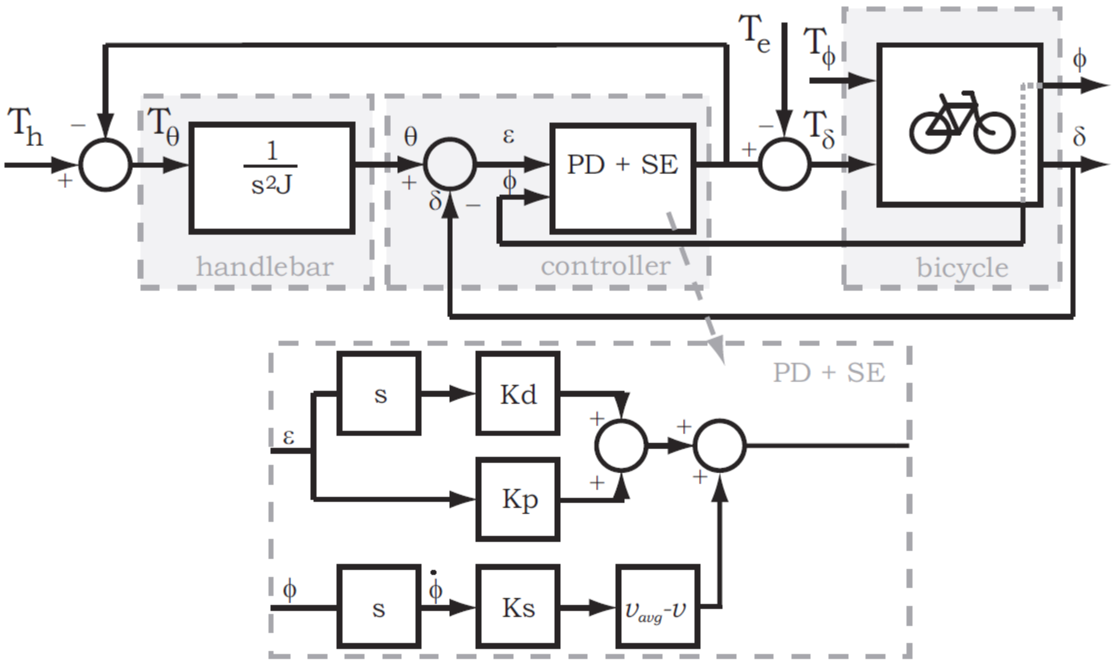


# [3] System Modeling and Simulation

- Low Speed Stabilization Control (Intuitive Control) [1]

$$T_{SE} = K_s(v_{avg} - v)\dot{\phi}$$




1 [Schwab, A.L. and Kooijman, J.D.G. and Meijaard, J.P.; Some recent developments in bicycle dynamics and control, 2008]

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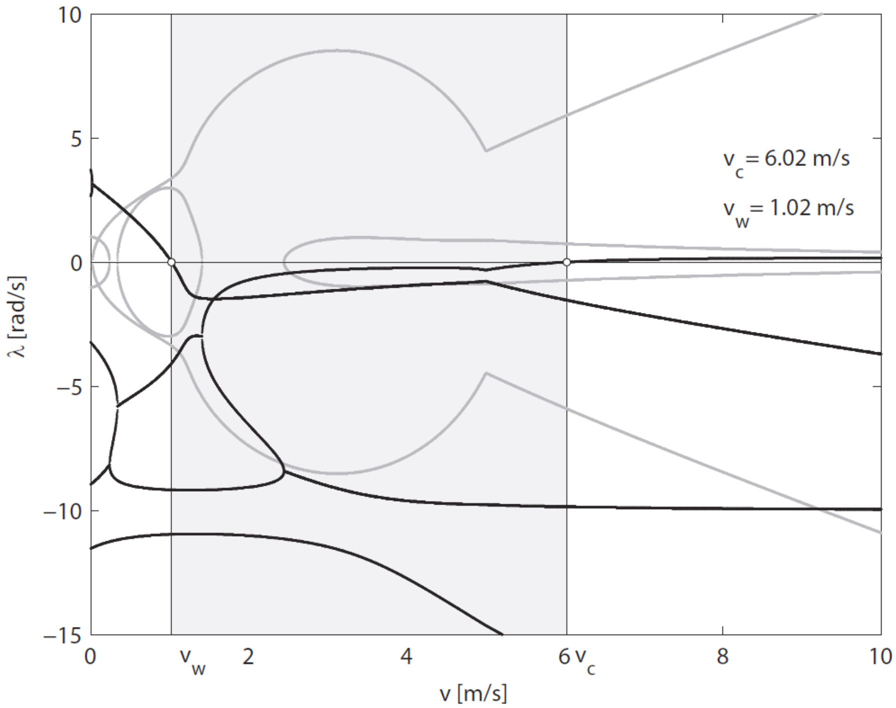
$$T_{SE} = K_s(v_{avg} - v)\dot{\phi}$$

$$K_s\!=\!10\,\mathrm{Ns^2/rad}$$

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# [4] Steer-by-Wire Implementation

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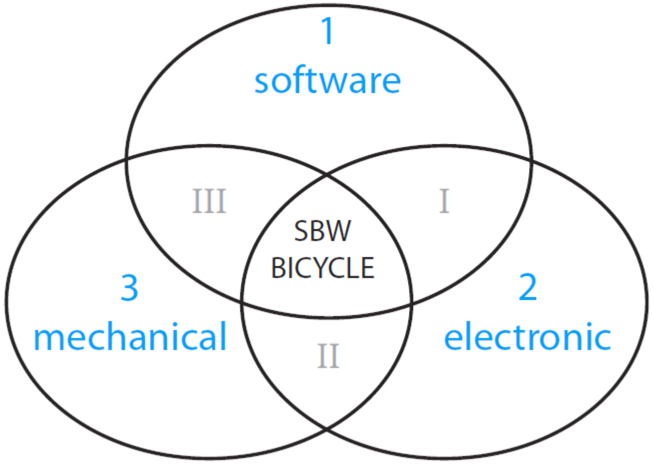
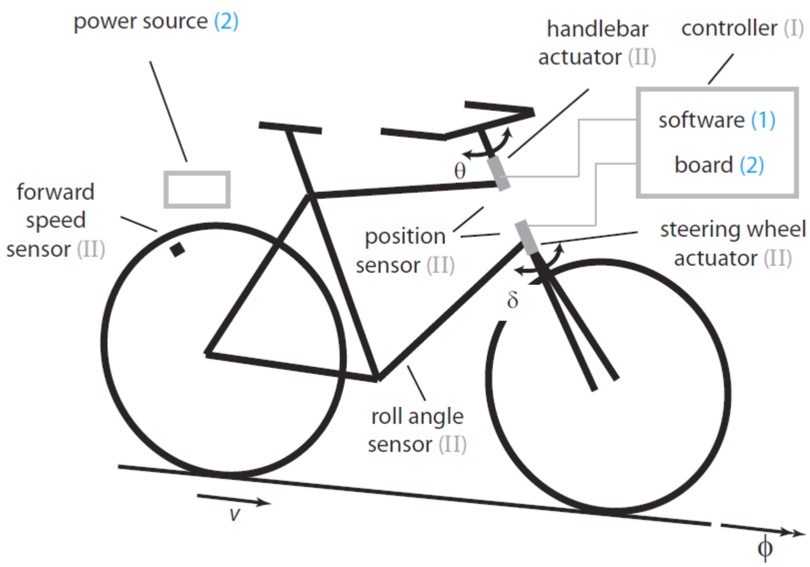
- Design approach:



# [4] Steer-by-Wire Implementation

- Development software selection

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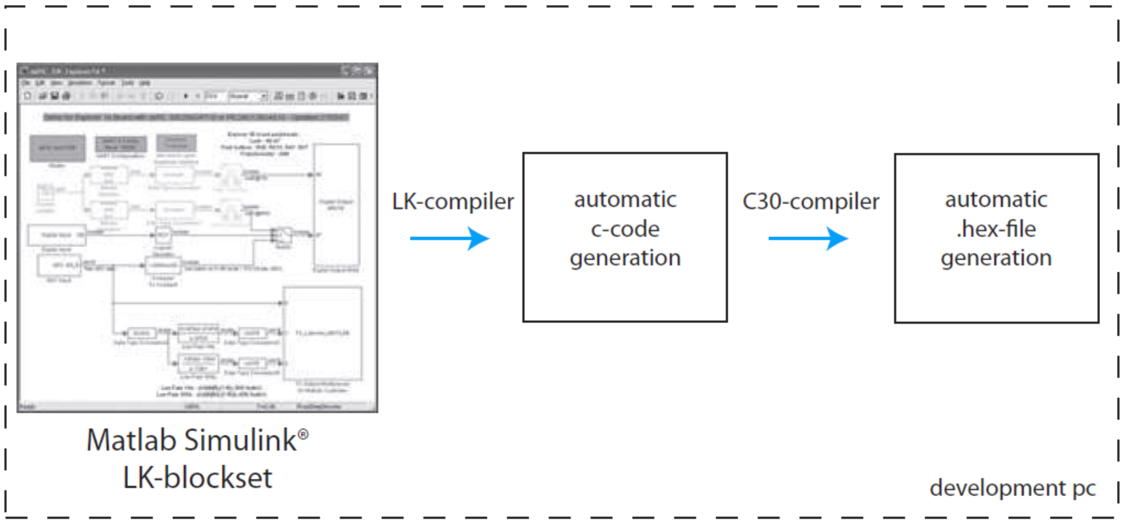

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- Controller hardware selection

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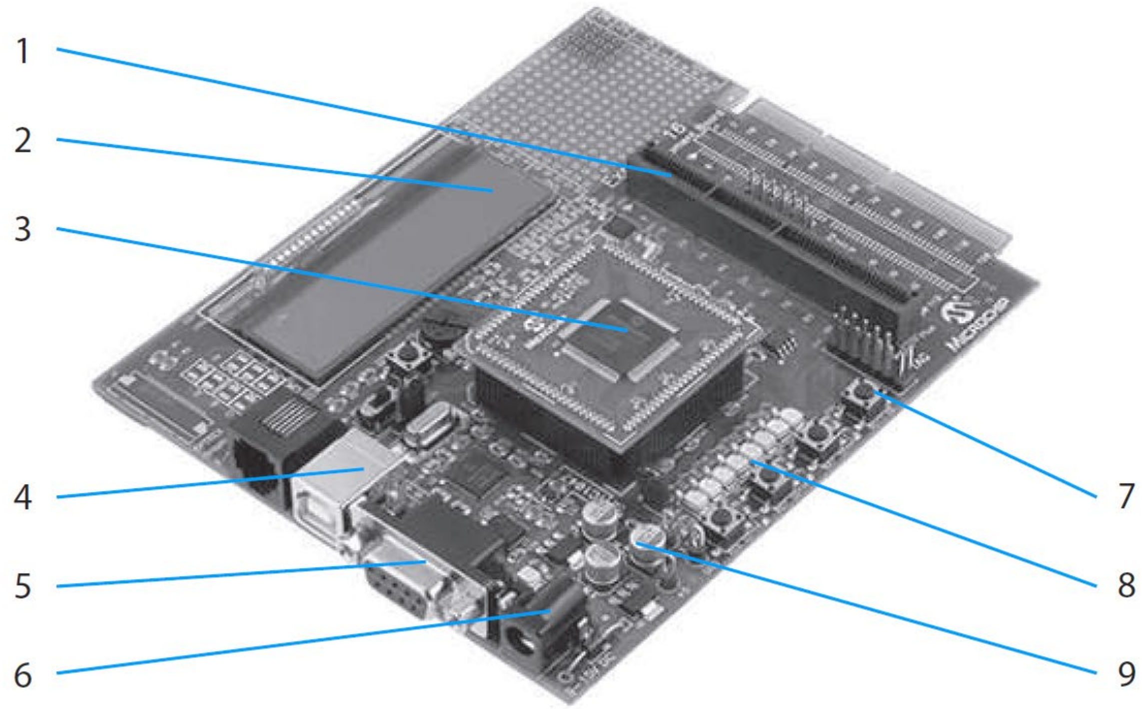


1. Expansion connector
2. Display
3. dsPIC33FJ256GP710
4. USB connector
5. RS232 connector
6. 12V DC input
7. Push buttons
8. Status LEDs
9. Voltage regulators

# [4] Steer-by-Wire Implementation

- Controller hardware IO-board

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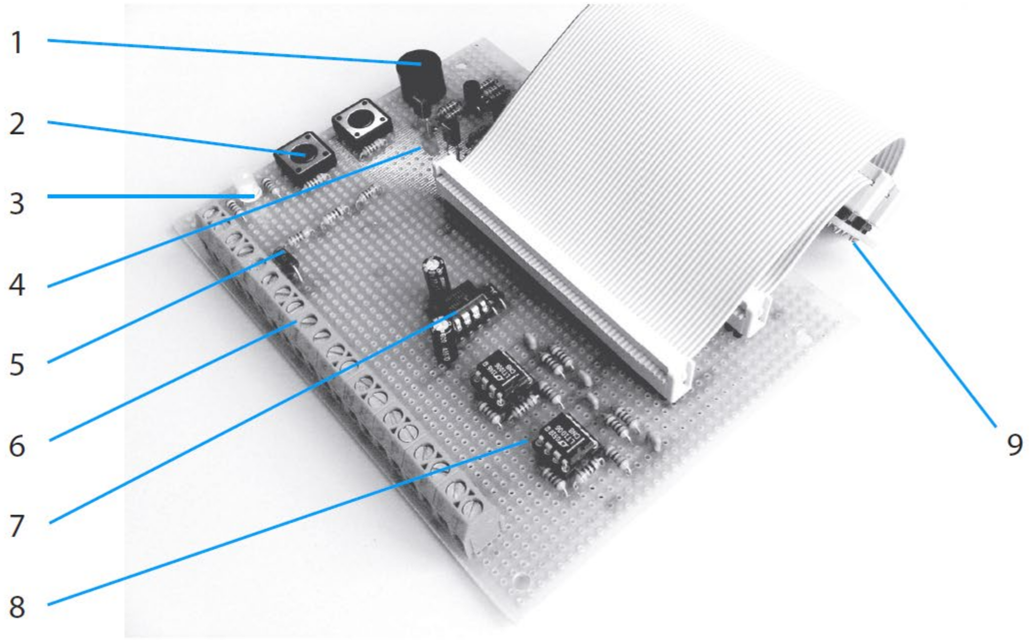


1. Buzzer
2. Push buttons
3. Bi-color status LED
4. Dual actuator enable circuitry
5. Speedsensor circuitry
6. Interface terminals
7. Negative power supply
8. Dual DAC circuitry
9. Expansion connector

# [4] Steer-by-Wire Implementation

- Position- and angular rate sensors

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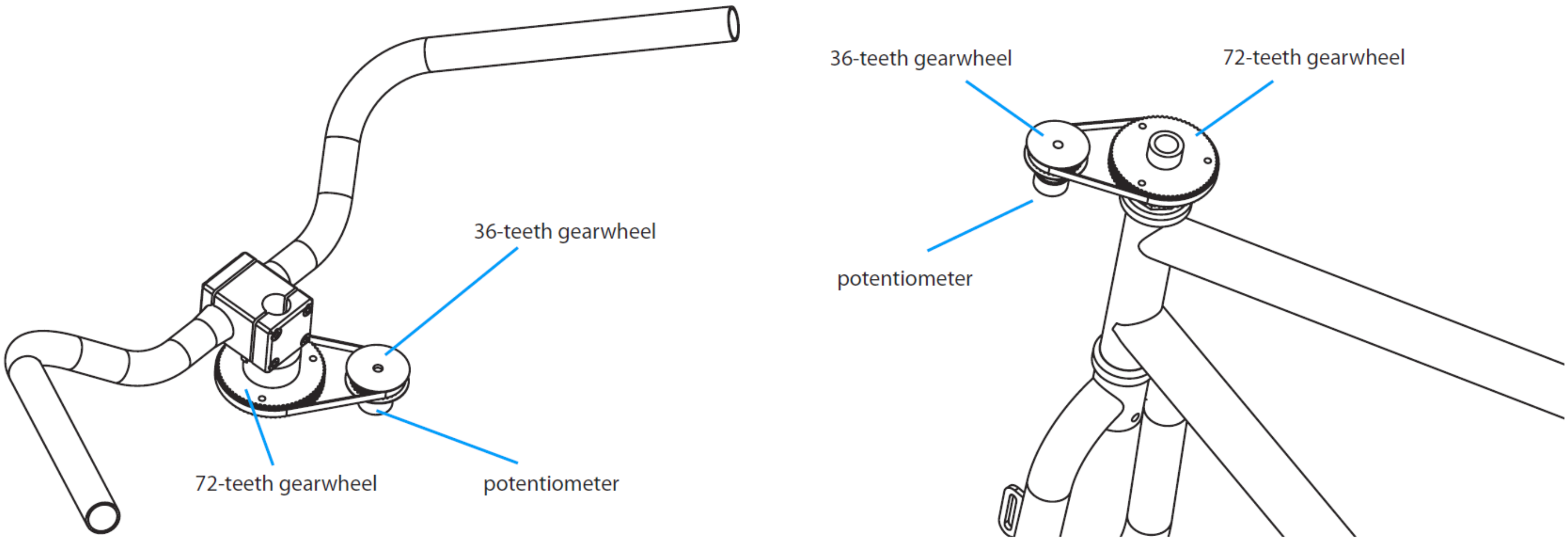



(a) (b)

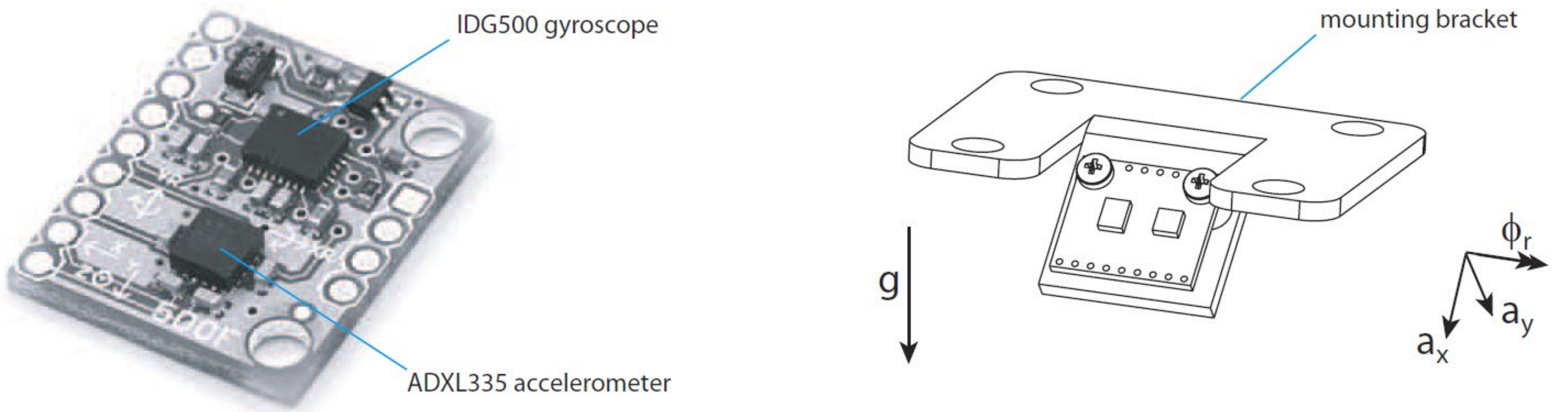
# [4] Steer-by-Wire Implementation

- Roll angle- and roll rate sensor

# [4] Steer-by-Wire Implementation

- Roll angle- and roll rate sensor

- Roll angle estimation by combining sensor data




(a) (b)

# [4] Steer-by-Wire Implementation

- Forward speed sensor

- Conventional DC-motor used in reverse.

# [4] Steer-by-Wire Implementation

- Actuator selection

  1) Power- and torque requirements

  2) Physical limitations (mass, size etc)

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- Actuator selection

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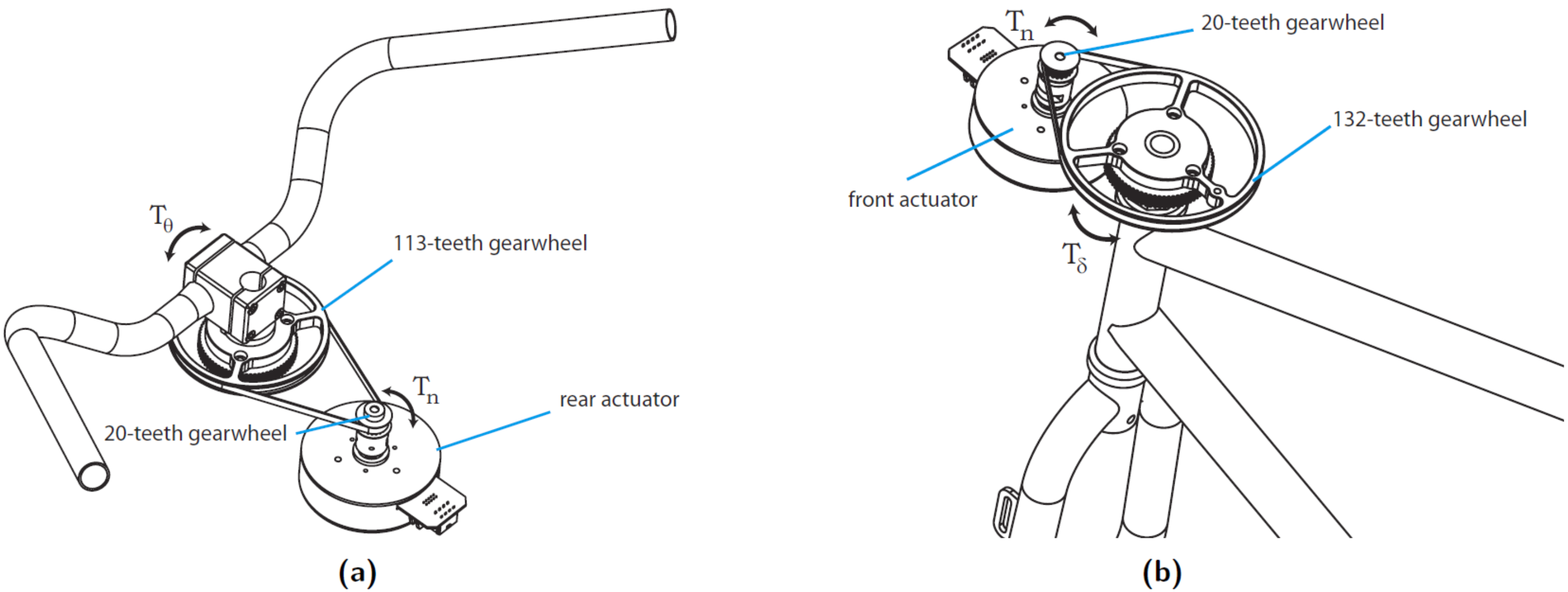
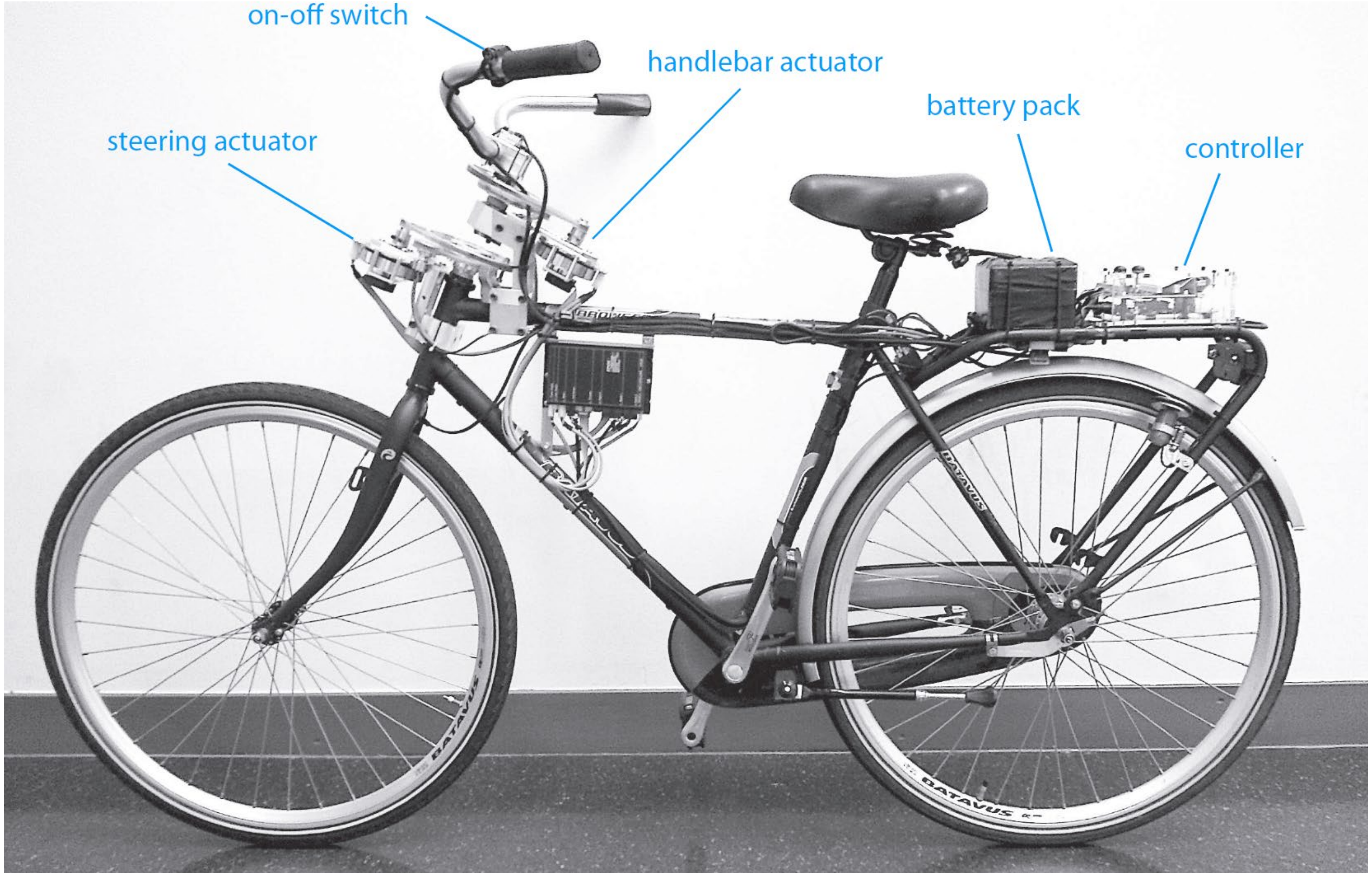


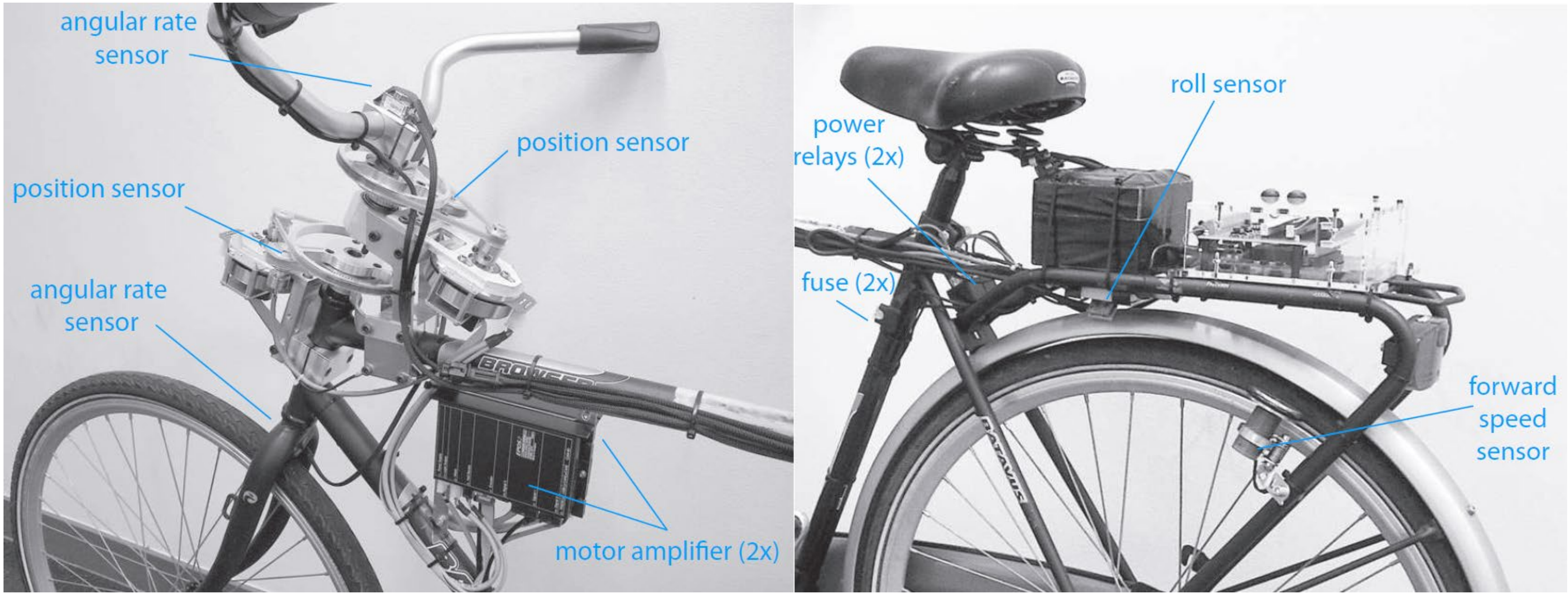
# [4] Steer-by-Wire Implementation

- Final design by combining controller, sensors and actuators

# [4] Steer-by-Wire Implementation



# [4] Steer-by-Wire Implementation



# Presentation Overview

# [5] Experimental Tests

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- Path following experiment utilizing the Low Speed Stabilization control algorithm:

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- Testruns at 4 different forward speeds v = [5,10,15,20] km/h.

  4 different controller gains Ks = [-5,0,5,10] Ns^2/rad.

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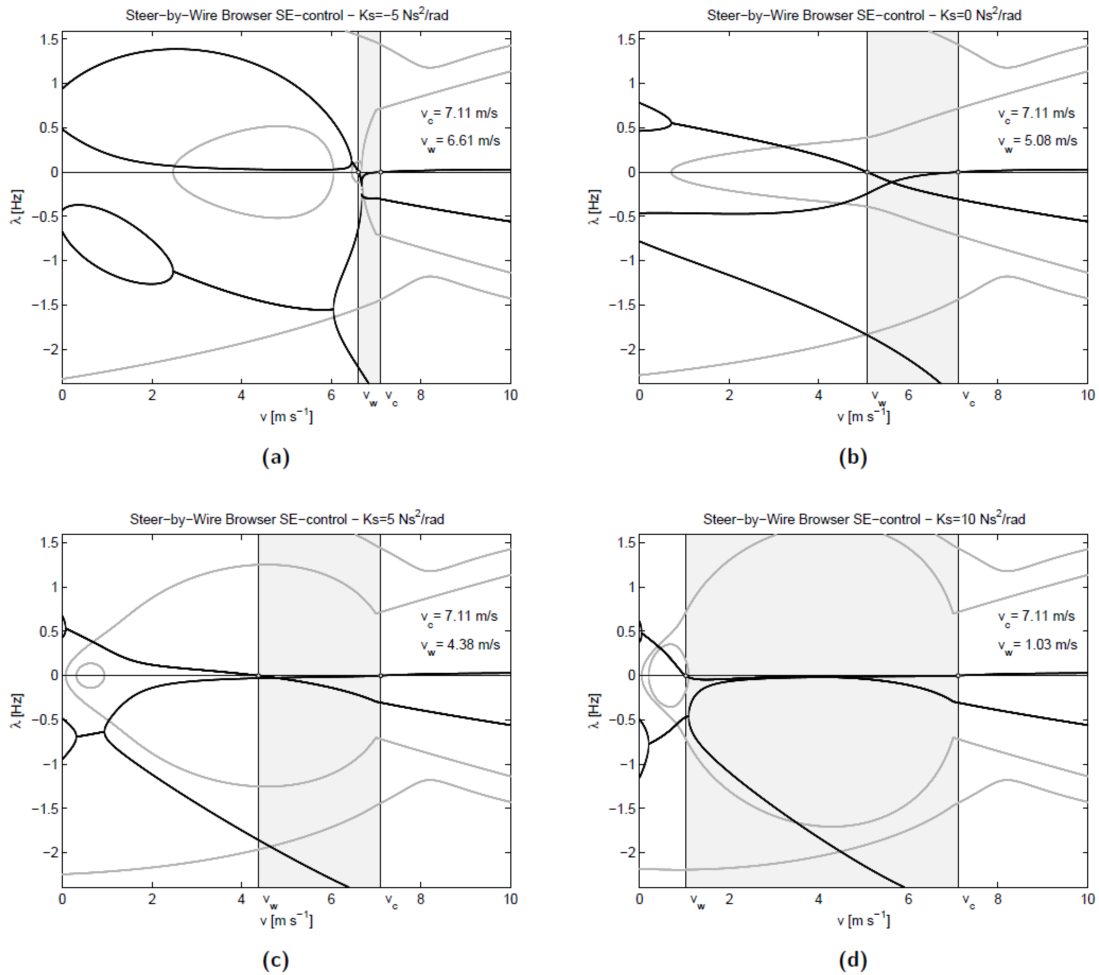
- Video

# [5] Experimental Tests

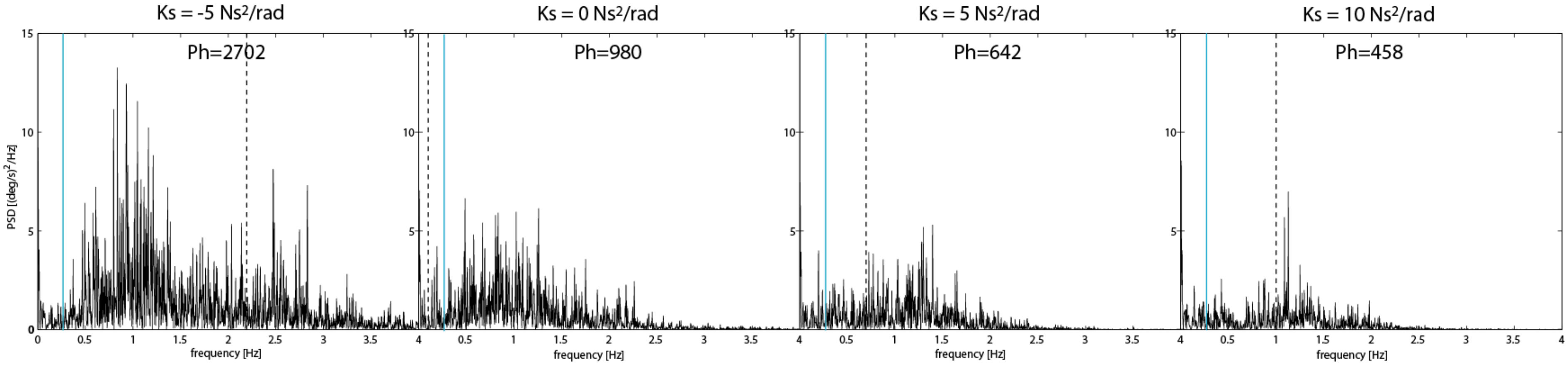
- Eigenvalue plots SBW-bicycle

- Ks = -5 Ns^2/rad (a)
  Ks = 0 Ns^2/rad (b)
  Ks = 5 Ns^2/rad (c)
  Ks = 10 Ns^2/rad (d)



# [5] Experimental Tests

- PSD (power spectral density) plots of the handlebar rate at 5 km/h:



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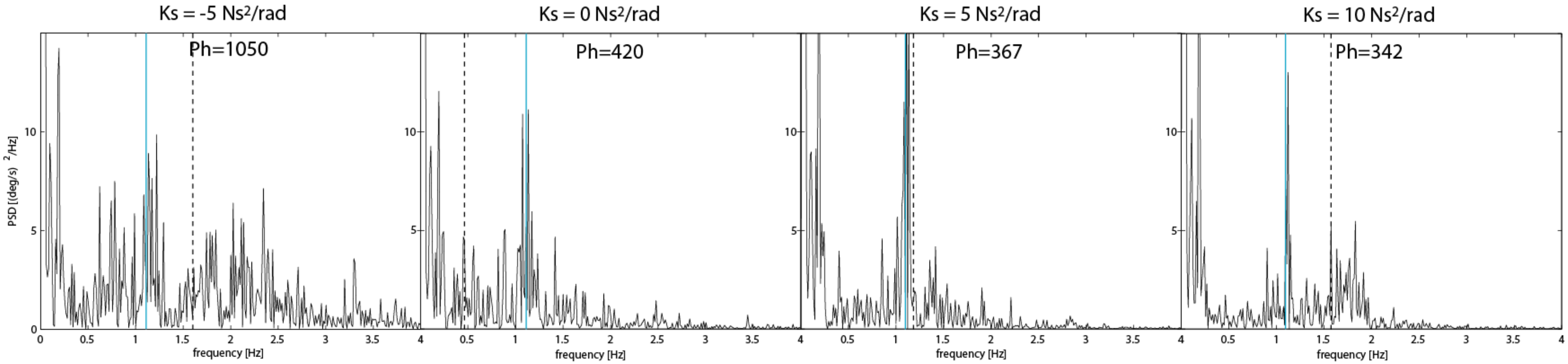
- PSD (power spectral density) plots of the handlebar rate at 20 km/h:



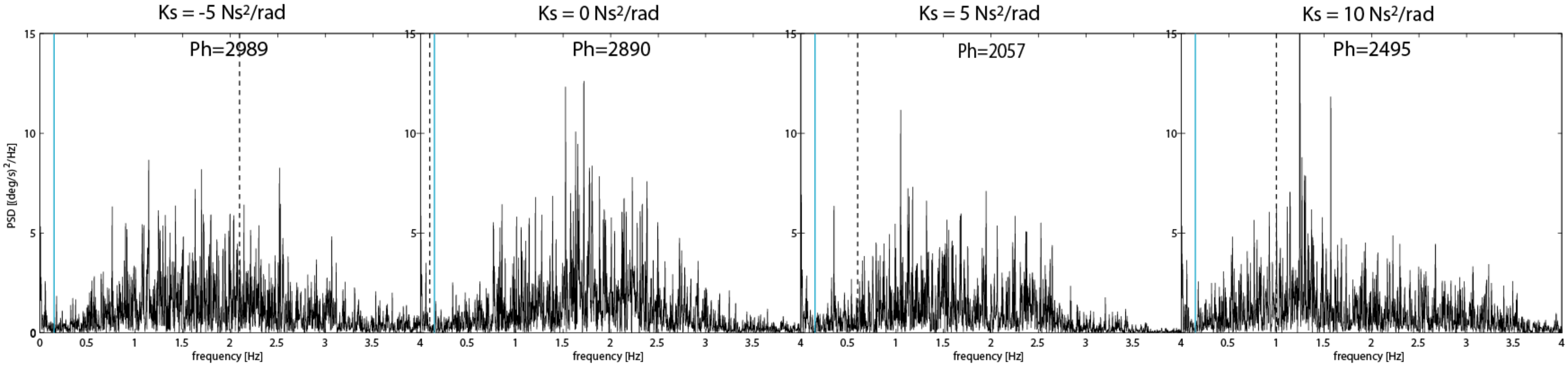
# [5] Experimental Tests

- Up to now only vehicle dynamics enhancement is discussed.

- What about rider perception? Steer torque feedback!

# [5] Experimental Tests

- PSD (power spectral density) plot of the handlebar rate at 5 km/h without steer torque feedback:



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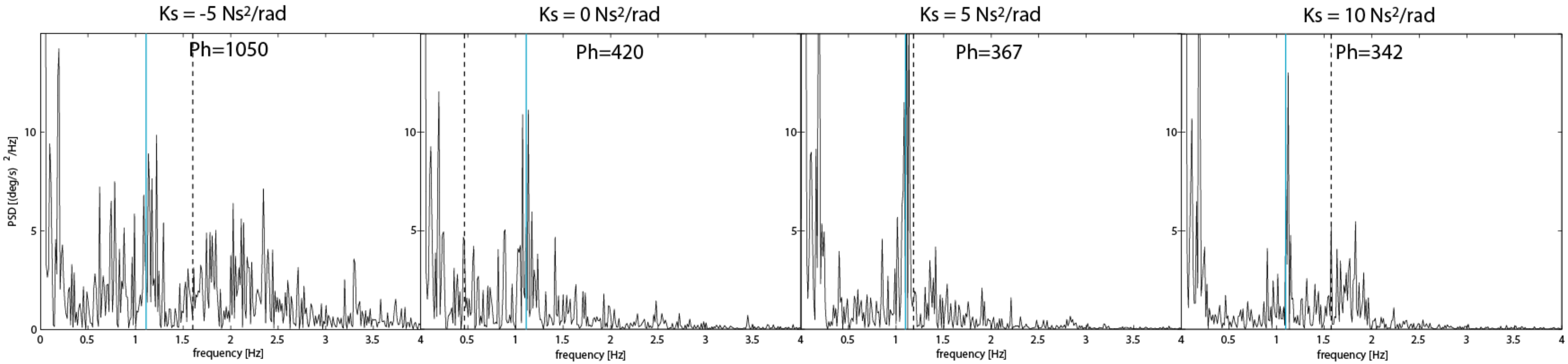


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# Presentation Overview

# [6] Conclusions and Recommendations

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- Conclusions:

1) At 5 km/h a two times reduction in rider steer effort is observed by applying the lateral stability algorithm.

The Lateral Stability Enhancement algorithm shows a reduction in rider steer effort, where the stabilized bicycle is as easy to control at 5 km/h as an uncontrolled bicycle at 20 km/h.

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  The Lateral Stability Enhancement algorithm shows a reduction in rider steer effort, where the stabilized bicycle is as easy to control at 5 km/h as an uncontrolled bicycle at 20 km/h.

  2) The experiments show the importance of steer torque feedback, as the steer effort is about three times higher at 5 km/h, if the steer torque feedback is disabled.

  At higher forward speeds, the importance of the steer torque feedback contribution reduces. At higher forward speeds, visual- and vestibular cues apparently become more important.

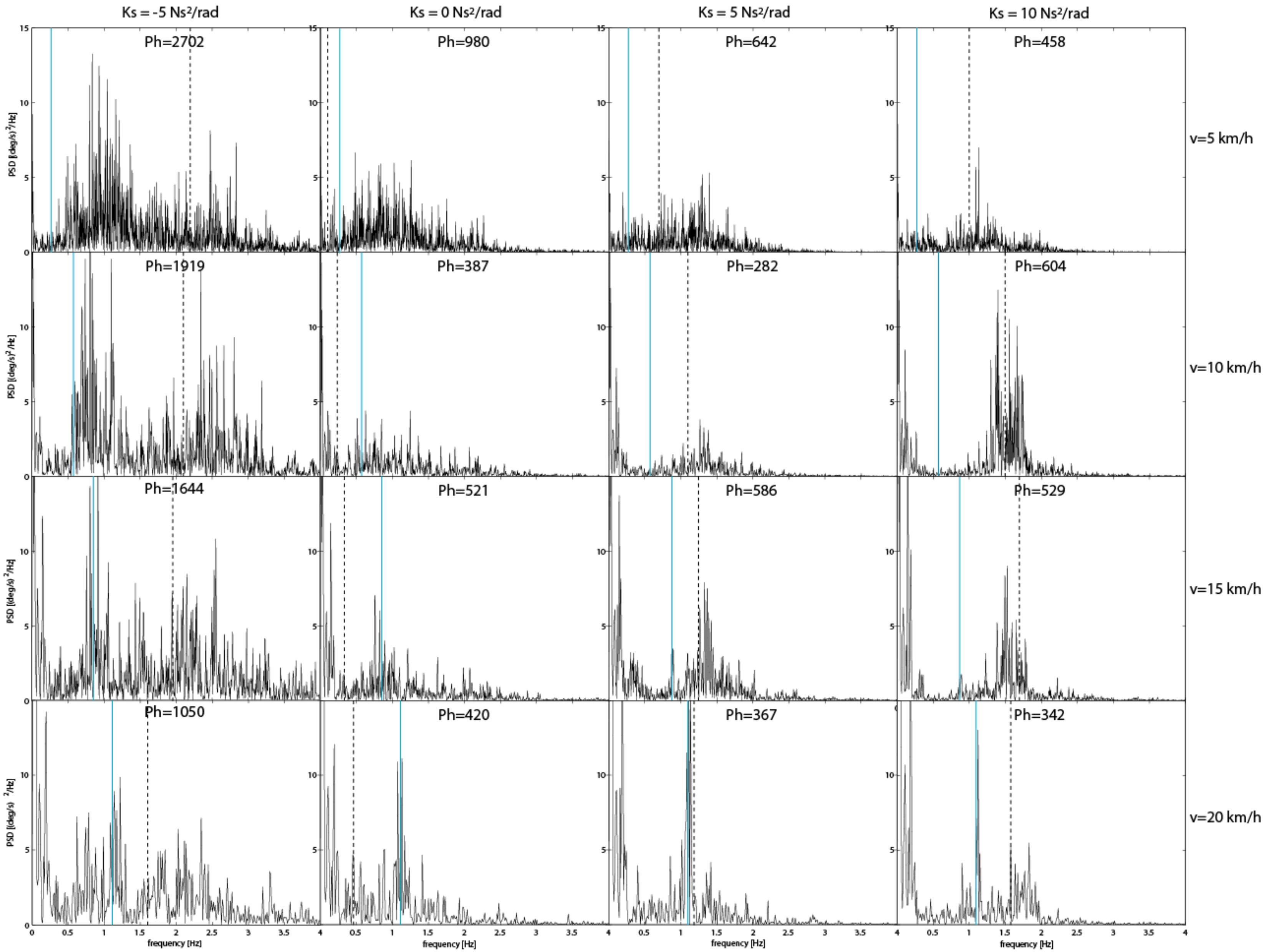
# [6] Conclusions and Recommendations

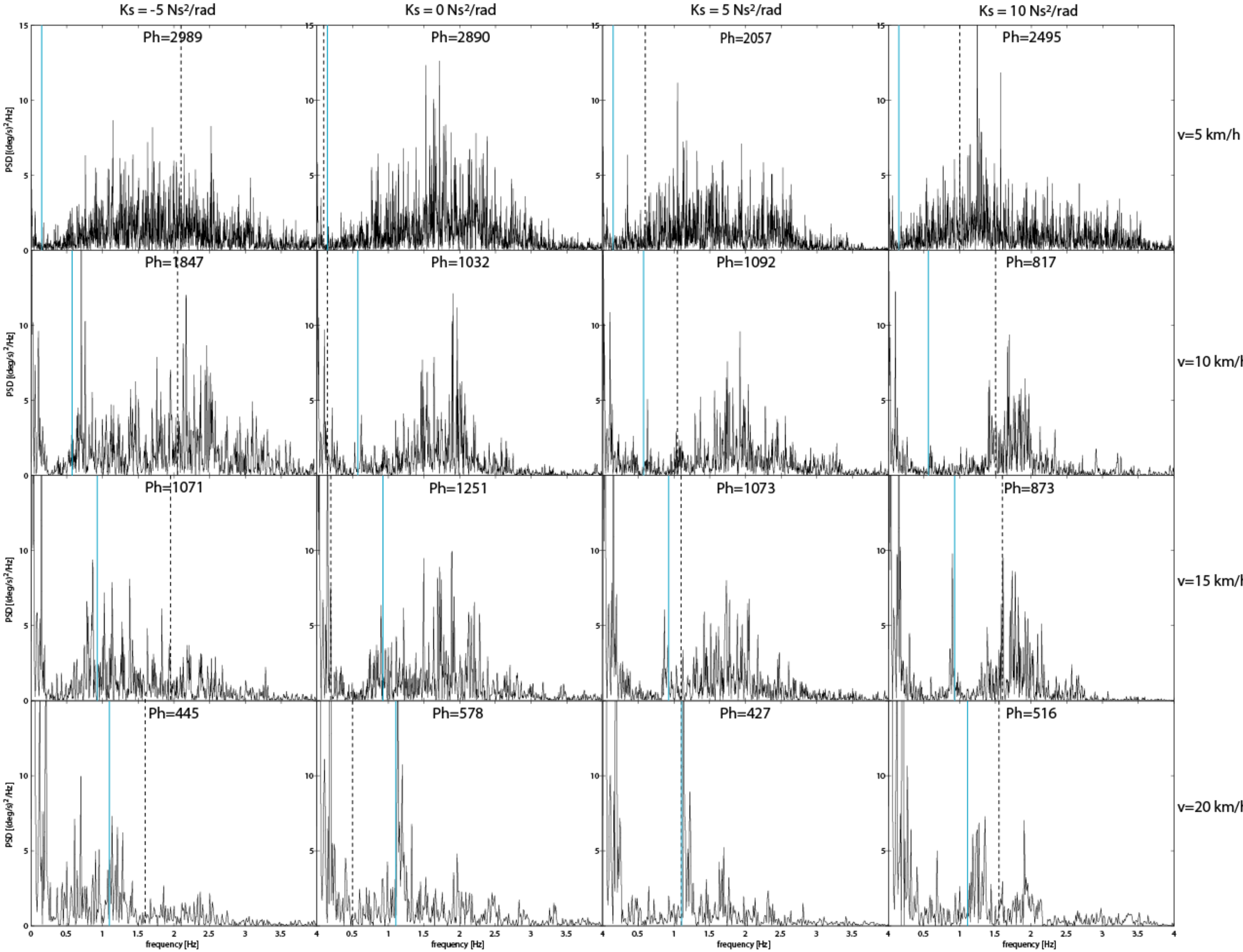
- Recommendations:

  1) A more accurate roll-angle sensor setup should be developed in order to be able to evaluate the proposed pole-placement techniques.

  2) Future research should focus on the importance of rider perception and the effect of different levels of steer torque feedback. Especially in relation to visual- and vestibular cues.

# Questions?


Ks = -5 Ns²/rad
Ks = 0 Ns²/rad
Ks = 5 Ns²/rad
Ks = 10 Ns²/rad
Ph=2702
Ph=980
Ph=642
Ph=458
Ph=1919
Ph=387
Ph=282
Ph=604
Ph=1644
Ph=521
Ph=586
Ph=529
Ph=1050
Ph=420
Ph=367
Ph=342
v=5 km/h
v=10 km/h
v=15 km/h
v=20 km/h
PSD [(deg/s)²/Hz]
frequency [Hz]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v=20 km/h
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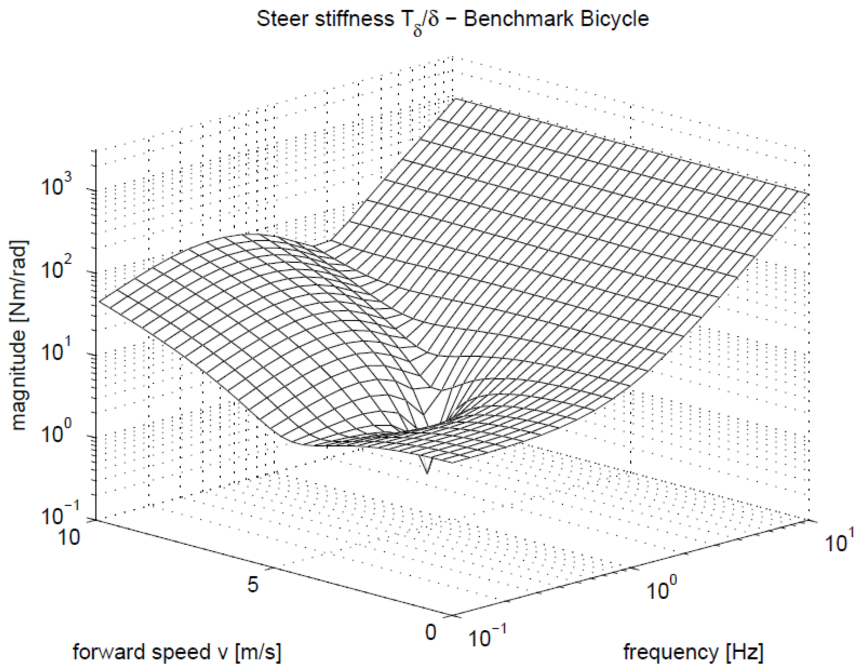
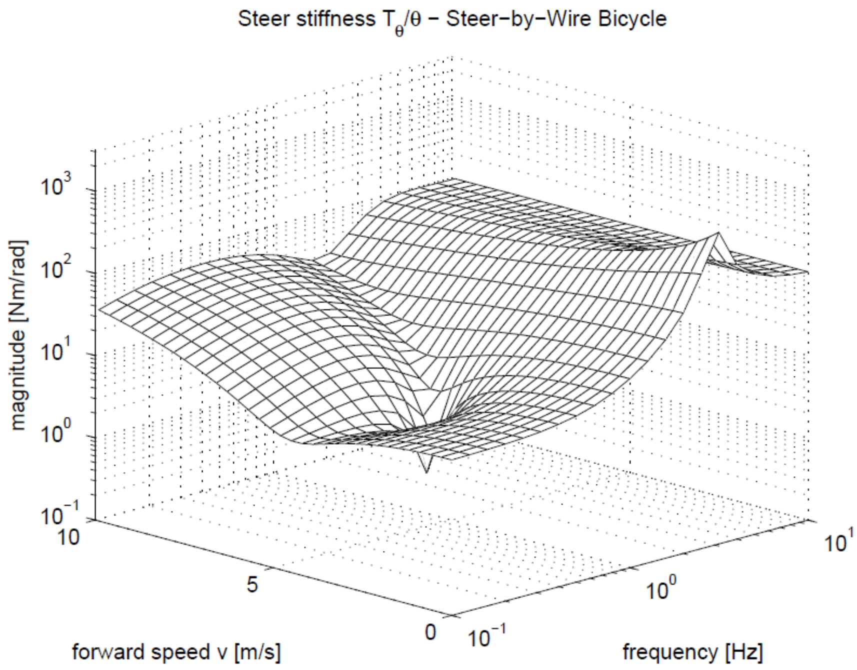
Ph=2890
Ph=2057
Ph=2495
Ph=1847
Ph=1032
Ph=1092
Ph=817
Ph=1071
Ph=1251
Ph=1073
Ph=873
Ph=445
Ph=578
Ph=427
Ph=516
PSD [(deg/s)²/Hz]
frequency [Hz]

# Steer stiffness

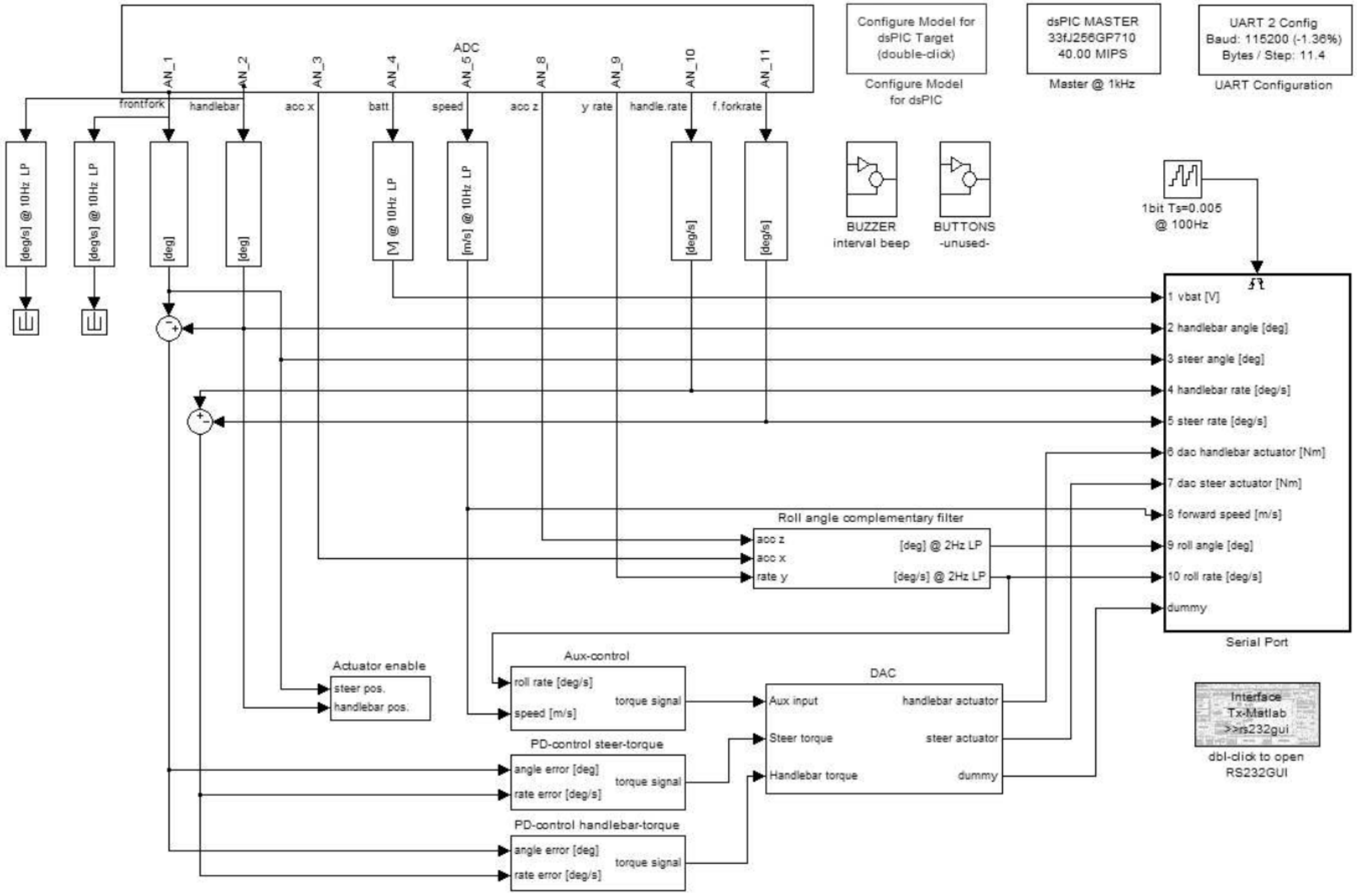
$$H_{BB}(s) = \frac{T_\delta(s)}{\delta(s)}$$

$$H_{SBW}(s) = \frac{T_\theta(s)}{\theta(s)}$$



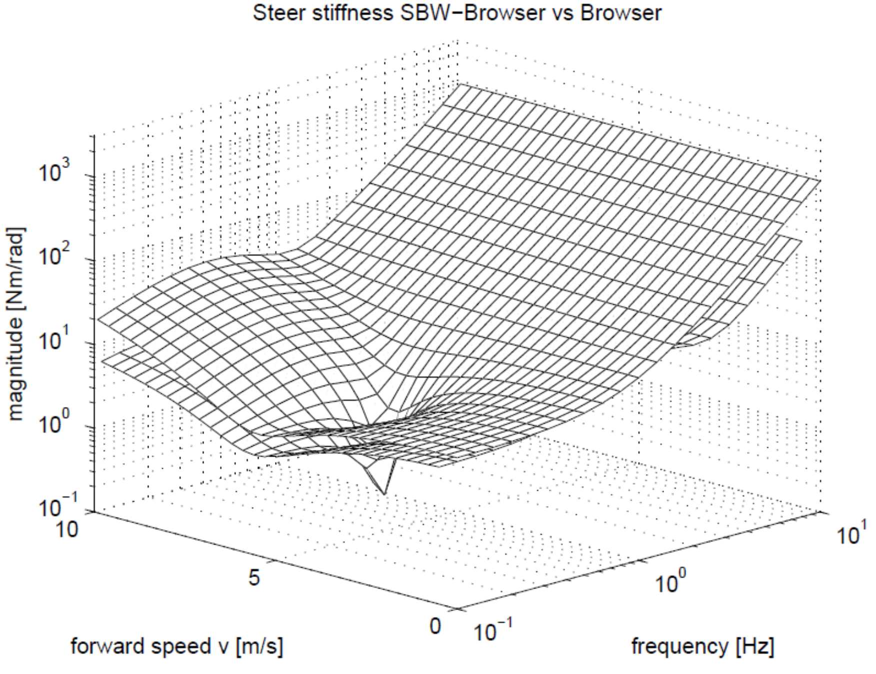



# Firmware

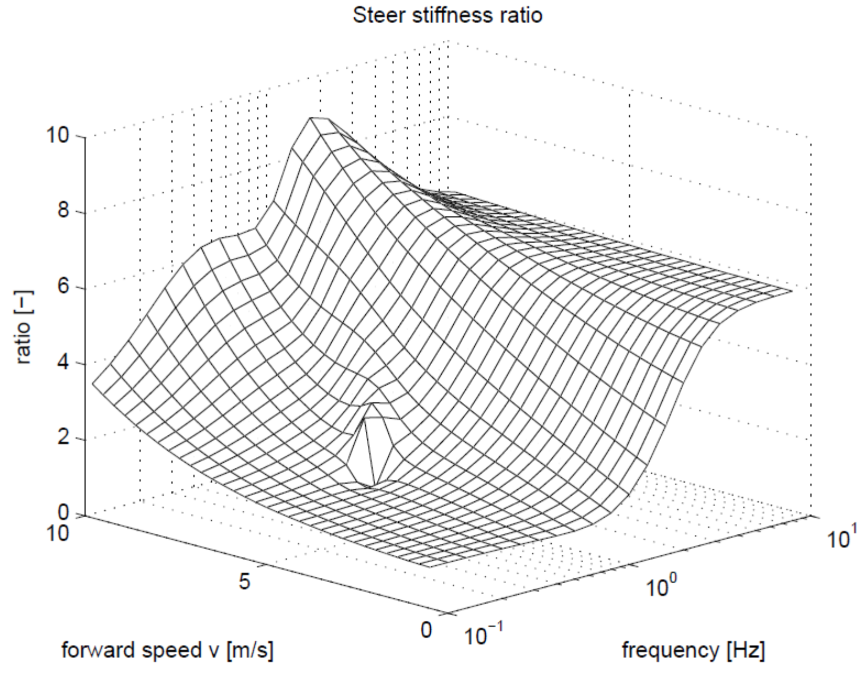


ADC
AN_1
AN_2
AN_3
AN_4
AN_5
AN_8
AN_9
AN_10
AN_11
frontfork
handlebar
acc x
batt.
speed
acc z
y rate
handle.rate
f.forkrate
Configure Model for dsPIC Target (double-click)
Configure Model for dsPIC
dsPIC MASTER 33fJ256GP710 40.00 MIPS
Master @ 1kHz
UART 2 Config Baud: 115200 (-1.36%) Bytes / Step: 11.4
UART Configuration
[deg/s] @ 10Hz LP
[deg/s] @ 10Hz LP
[deg]
[deg]
[V] @ 10Hz LP
[m/s] @ 10Hz LP
[deg/s]
[deg/s]
BUZZER interval beep
BUTTONS -unused-
1bit Ts=0.005 @ 100Hz
1 vbat [V]
2 handlebar angle [deg]
3 steer angle [deg]
4 handlebar rate [deg/s]
5 steer rate [deg/s]
6 dac handlebar actuator [Nm]
7 dac steer actuator [Nm]
8 forward speed [m/s]
9 roll angle [deg]
10 roll rate [deg/s]
dummy
Serial Port
Roll angle complementary filter
acc z
acc x
rate y
[deg] @ 2Hz LP
[deg/s] @ 2Hz LP
Actuator enable
steer pos.
handlebar pos.
Aux-control
roll rate [deg/s]
speed [m/s]
torque signal
DAC
Aux input
Steer torque
Handlebar torque
handlebar actuator
steer actuator
dummy
PD-control steer-torque
angle error [deg]
rate error [deg/s]
torque signal
PD-control handlebar-torque
angle error [deg]
rate error [deg/s]
torque signal
Interface Tx-Matlab >>rs232gui
dbl-click to open RS232GUI

# Steer stiffness ratio SBW-prototype




(a)

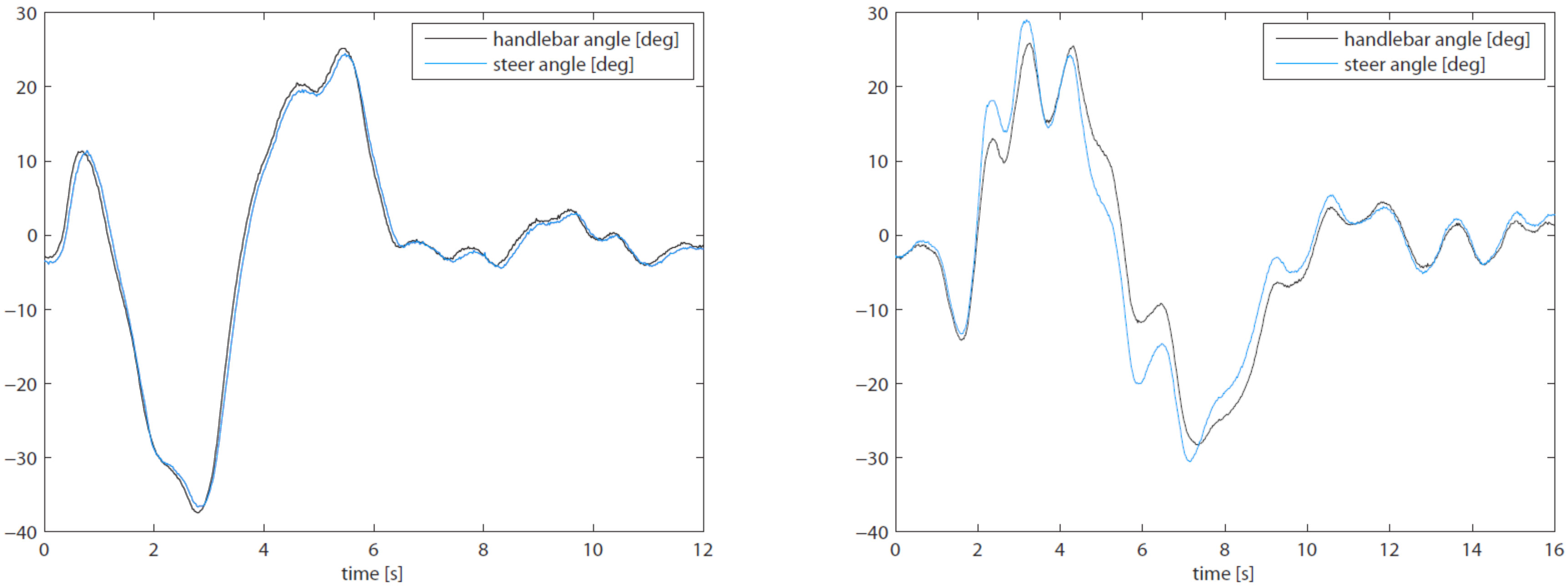



(b)

# Rider effort index Ph

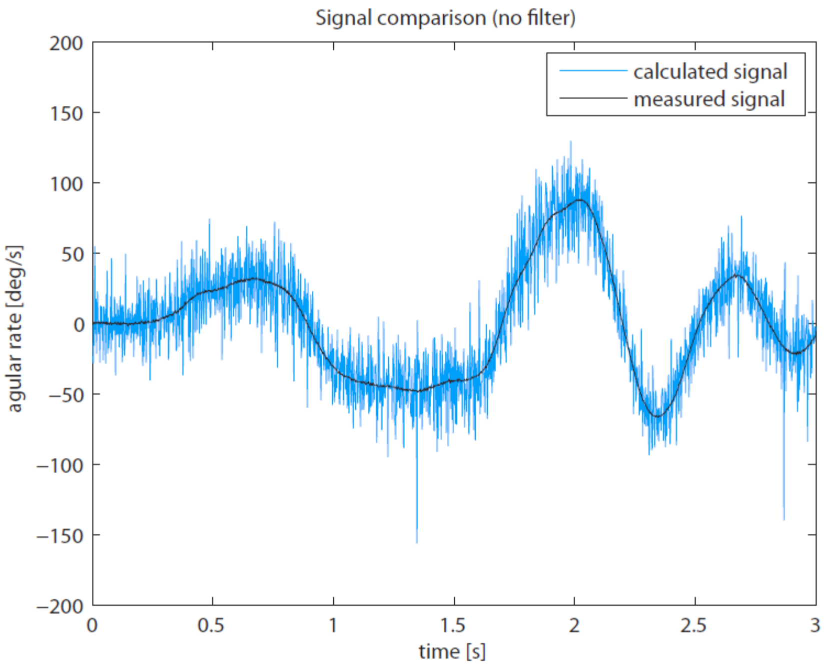
| | $K_s$=-5 Ns²/rad | $K_s$=0 Ns²/rad | $K_s$=5 Ns²/rad | $K_s$=10 Ns²/rad |
|---|---|---|---|---|
| v=5 km/h | **2702** / 2989 | **0980** / 2890 | **0642** / 2057 | **0458** / 2495 |
| v=10 km/h | **1919** / 1847 | **0387** / 1032 | **0282** / 1092 | **0604** / 0817 |
| v=15 km/h | **1644** / 1071 | **0512** / 1251 | **0586** / 1073 | **0529** / 0873 |
| v=20 km/h | **1050** / 0445 | **0420** / 0578 | **0367** / 0427 | **0342** / 0516 |

# Lane change test



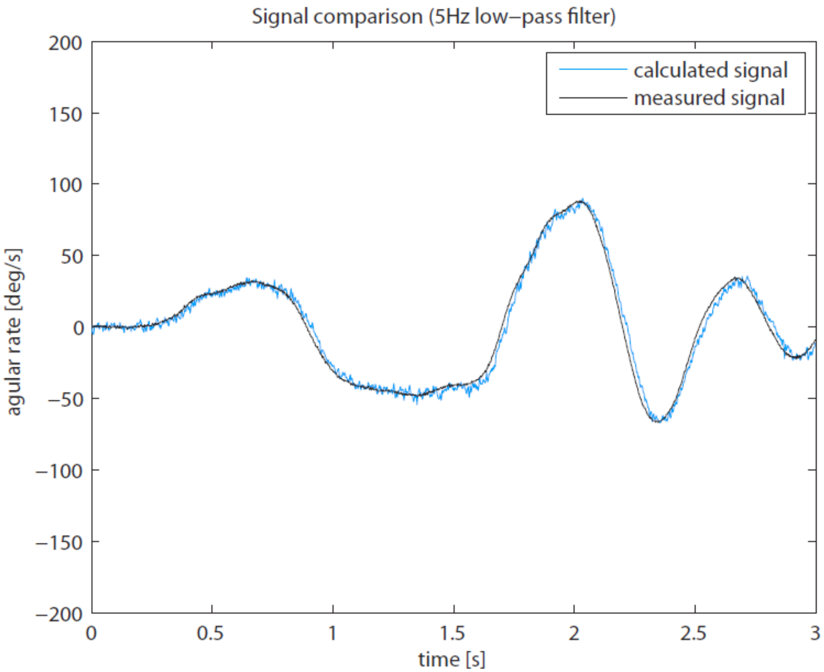

(a) (b)

# Num.diff



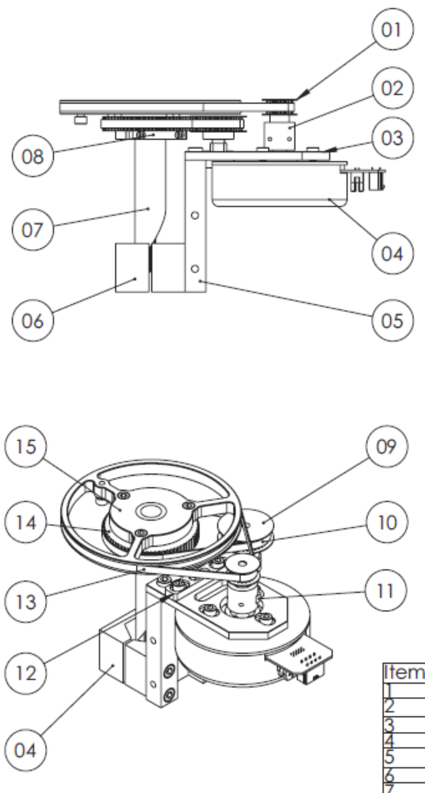
Signal comparison (no filter)
calculated signal
measured signal
agular rate [deg/s]
time [s]
200
150
100
50
0
−50
−100
−150
−200
0
0.5
1
1.5
2
2.5
3


(a)



Signal comparison (5Hz low−pass filter)
calculated signal
measured signal
agular rate [deg/s]
time [s]
200
150
100
50
0
−50
−100
−150
−200
0
0.5
1
1.5
2
2.5
3


(b)




| Item | Drawing | Part number |
|---|---|---|
| 1 | - | 0919411450 |
| 2 | stepdown | - |
| 3 | front_motormount | - |
| 4 | ec90 | - |
| 5 | frontplate_fat | - |
| 6 | front_bracket_v2 | - |
| 7 | inner_steeringstem_v2 | - |
| 8 | clamp72gear | - |
| 9 | - | 0919411457 |
| 10 | - | 0918316831 |
| 11 | clamp72small | - |
| 12 | sensor_bracket | - |
| 13 | - | 0918316861 |
| 14 | 72gearslim | 0919411480 |
| 15 | 134gear22hole | - |

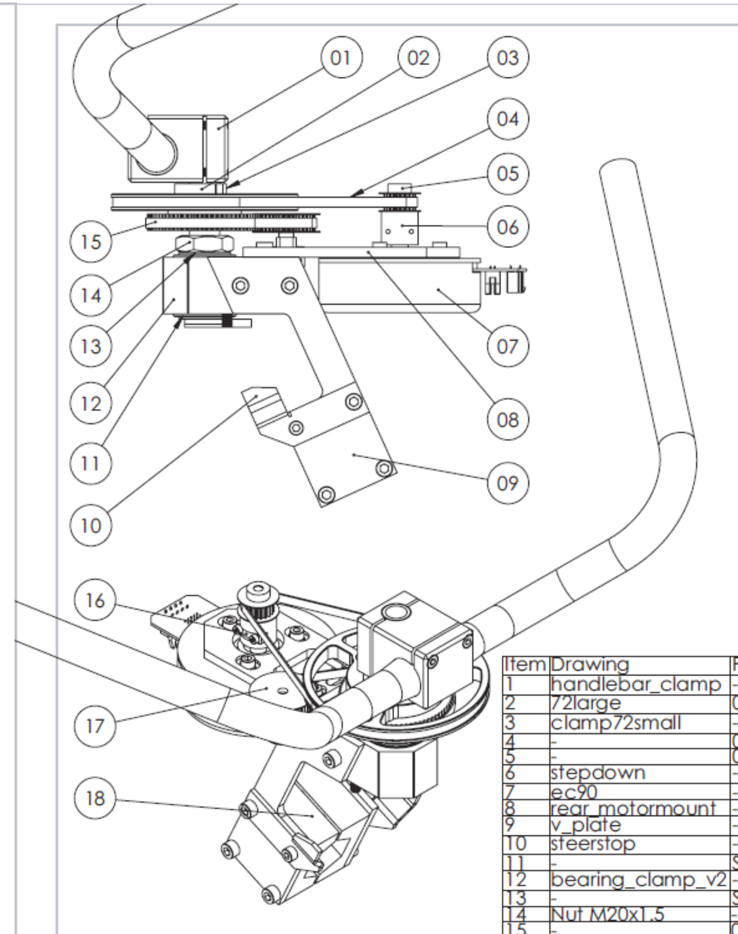
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR: | FINISH: | DEBUR AND BREAK SHARP EDGES | DO NOT SCALE DRAWING | REVISION

NAME | SIGNATURE | DATE | TITLE:

DRAWN | CHK'D | APPV'D | MFG | Q.A | MATERIAL: | WEIGHT:

DWG NO. front_mount A4

SCALE:1:5 SHEET 1 OF 1




| Item | Drawing | Part number |
|---|---|---|
| 1 | handlebar_clamp | - |
| 2 | 72large | 0919411480 |
| 3 | clamp72small | - |
| 4 | - | 0918316851 |
| 5 | - | 0919411450 |
| 6 | stepdown | - |
| 7 | ec90 | - |
| 8 | rear_motormount | - |
| 9 | v_plate | - |
| 10 | steerstop | - |
| 11 | - | SKF-32004-X/Q |
| 12 | bearing_clamp_v2 | - |
| 13 | - | SKF-32004-X/Q |
| 14 | Nut M20x1.5 | - |
| 15 | - | 0918316831 |
| 16 | clamp72small | - |
| 17 | - | 0919411457 |
| 18 | top_bracket_v2 | - |

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR: | FINISH: | DEBUR AND BREAK SHARP EDGES | DO NOT SCALE DRAWING | REVISION

NAME | SIGNATURE | DATE | TITLE:

DRAWN | CHK'D | APPV'D | MFG | Q.A | MATERIAL: | WEIGHT:

DWG NO. rear_mount A4

SCALE:1:1 SHEET 1 OF 1

# Questions?