Sensor Accuracy in Vehicle Safety

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Global Business:
- Software
- Support
- Consultancy
- Training

Expertise:
- Modelica / C++ Software
- Simulation Libraries
- Systems Engineering
- Tech. Consultancy
- FMI Tool Development
What we do?

- **Modelica model libraries**
  - Developers of commercial Modelica modelling solutions:
    - Engines,
    - FlexBody,
    - Powertrain Dynamics,
    - Vehicle Dynamics for Motorsports,
    - Simulator,
    - SystemID
    - XML Reader libraries

- **FMI tools**
  - Developers of the FMI Blockset which adds FMI support to Simulink and Microsoft Excel
What we do?

• Software distributors
  – Dassault Systemes distributor specialised in Systems Engineering tools: Dymola, Reqtify, ControlBuild, AUTOSAR Builder and CATIA
  – rFpro, Driver-in-the-Loop software

• Engineering consultancy
  – Model development and analysis services
  – Process development and improvement
  – Integration of models with HiL, MiL, DiL tools and processes
    • Optimisation of models for real-time fixed step simulation
    • Coupling to HiL and DiL platforms
Sensor Accuracy & State Estimation: Growing Relevance in Automotive Engineering...
Sensor Accuracy in Vehicle Safety

- Advanced Driver Assistance Systems more prevalent
  - Adaptive Cruise Control
  - Lane Keeping Assist
  - Electronic Stability Control

- Tracking states now critical
  - Reliance on accurate state estimation
  - Safety req: **Redundant measurement**

- Therefore:
  - High precision sensors are required for
    - Yaw rate sensor
    - Accelerometers
    - Wheel speeds (vehicle speed)

Electronic Stability Control
Measurement and estimation of Yaw rate

- Gyro at CoM
- Accelerometers for lateral accelerations
  - A diagonal sensor placement configuration has been proposed as a good trade-off between longitudinal and lateral.
  - Longitudinal: Poor steady-state yaw rate estimate and is prone to drift
  - Lateral: Low accuracy for low rates, unknown yaw rate sign
- Using wheel speed sensors at wheels
  - Poor during braking / bump disturbances: Tyre slips occur.
  - Affected by variations of the tyre rolling radius with load, pressure, temperature, wear, etc.
- Kalman filter for sensor fusion
Yaw rate estimation using accelerometers

- Yaw rate est. by lateral accelerometers placed diagonally compared to ideal yaw rate sensor
  - Ideal yaw rate (blue) vs estimate using 2 accelerometers
  - Drift depends on the yaw acceleration
    - Top plot – sinusoidal yaw rate of 0.5 rad/s at 1Hz
  - Cannot predict yaw rate under steady state cornering
    - Middle plot is steady state yaw rate of 0.5 rad/s
  - Estimation is affected by pitch and roll
    - Bottom plot is steady state yaw rate of 0.5 rad/s and sinusoidal pitch of 1.6 degrees at 5Hz
  - Accuracy is sensitive to location and orientation of sensors relative to CoG
The need for physical modelling

- Complex systems covering many domains
  - Mechanical, Electrical, Hydraulic, Pneumatic, Thermal, Chemical, Control, Magnetic, …

- Prototypes too late to verify interface

- It’s not practical to validate control systems using prototypes

- Need to use **predictive models** to make simulation useful for control development from an early stage
Functional and Predictive models

- A Functional model is one that captures the **key function** of the model
- A Predictive model allows us to **predict** the behaviour and explore it’s **characteristics**

**Clutch (Koppeling):**

- **Functional model**
  - Would reduce the relative speed across the clutch in a **predefined** manner (assumed physics)
  - The controlling parameter would be the engagement time

- **Predictive model**
  - Include model for friction - torque transfer a function of the clutch clamp load, relative speed, temperature, …
  - The parameters would include the geometry and friction characteristics
  - The engagement time could be **predicted** under different operating scenarios (**modelled physics**)
Dymola Simulation Software
Dymola Simulation Software

- Multiphysics simulation
  - Mechanics (1D, MultiBody), 1D Thermofluids, Control, Thermal, Electrical, Magnetics….

- Promotes multilevel model reuse
  - Components represent physical parts: valves, gears, motor
  - Connections between parts describe the physical connection (mechanical, electrical, thermal, signal, etc.)

- Easily share and reuse libraries across the business
Model Definition in Dymola: Modelica Code!

- Dymola provides easy access to the Modelica code behind models.
- You can also work in the “drag and drop” diagram environment with sophisticated connection-objects which ensure high fidelity interfaces!

```modelica
model Inertia
    extends Interfaces.Rigid;
    parameter SI.Inertia J=1 "Moment of Inertia";
    SI.AngularVelocity w "Angular velocity";
    SI.AngularAcceleration a "Angular acceleration";
equation
    w = der(phi);
    a = der(w);
    flange_a.tau + flange_b.tau = J * a;
end Inertia;
```
Freely available, open source, standardised
Developed and maintained by the Modelica Association
- An independent, international not-for-profit organisation
- Established in 1996
- Currently over 100 members from academia, tool vendors and industrial end-users

Organised into project groups for the Modelica Language, Modelica Standard Library and FMI
The Modelica Standard Library contains basic models in many engineering domains
Modelling Approach

Example: Inverted Pendulum

• To design and tune the controller requires a model of the system

• The systems contains the following:
  – Mechanics of the cart and pendulum (DoFs & momenta)
  – Electric motor to drive the cart
  – Control system with sensors and actuators
Modelling Approach

Traditional methodology

- Formulate EoM
- Manually rearrange and solve
- Implement the solution
- Problems with this approach:
  - Cannot easily change the properties of individual components (mass, length, resistance, etc.)
  - Cannot easily reuse the model or subsystem models for other tasks – items appear repeatedly
  - Non-trivial to change the detail level in one part
  - Hard to change knowns & unknowns
Modelling Approach

Modelica based approach

- Discretise the system into subsystems and components
- Define the system architecture and physical connections between subsystems
- Implement the subsystem models and plug these in...
Symbolic Manipulation

- The model equations are automatically transformed into the required solution for simulation.
- Advanced mathematical techniques are used to reduce the size of the problem without removing detail from the model.

**DAE:**

![Diagram of a circuit with components R1, R2, C, and L connected to ground.](image)
Symbolic Manipulation

• Contains 659 equations
  – Using the Modelica modelling approach these are formulated as a DAE

• Symbolic manipulation automatically reduces this to:
  – 7 continuous time states
  – 92 other time varying quantities
  – All the other equations relate to constants or variables that are exactly equal to these 99

• Advantages of Symbolic Manipulation
  – Automate the often error prone process of rearranging equations in to a solution
  – Apply advanced mathematical techniques to reduce the size of the problem
  – Can deliver real-time simulation performance of Vehicle Dynamics models with over 100,000 equations (1ms time step)
Benefits...

• Models can easily be replaced with more detailed representations
  – Model architecture remains the same
  – New subsystem models can be plugged in.

• Subsystems can easily be reused for different analysis tasks
  – For example, invert the physical model to determine the control inputs required
  – Here the angular response of the pendulum to a disturbance is prescribed and the required input to the power supply will be calculated
Modelica Application Libraries

- Air Conditioning
- Belts
- Build Tools
- eDrives
- Engines
- FlexBody
- Flexible Bodies
- Fuel Cell
- Heat Exchanger
- Human Comfort
- Hydraulics
- Liquid Cooling
- Pneumatics
- Powertrain Dynamics
- Simulator
- Smart Electric Drives
- SystemID
- Terrain Server
- TIL Suite
- Vapor Cycle
- Vehicle Dynamics
- VDLMotorsports
- XMLReader
Vehicle Dynamics

- Vehicle Dynamics Library
  - Template based approach to modelling
- Library of MultiBody suspension templates
  - McPherson, double wishbone, multi-link, trailing arm, …
  - Open and extendible to allow you to add your own templates
- Kinematic and compliant suspension models
  - Non-linear bushes or ideal joints
  - Structural compliance effects
- Wide range of experiments
  - Quarter car, half car, whole chassis, full vehicle
  - Closed loop and open loop driver models
- Generate table based suspension models automatically for real-time simulation
- Easily integrate the complete vehicle systems
  - Engine, powertrain, electric motors, batteries, thermal management, etc.
Dymola Applied to Sensor Development & Control Calibration on Automotive Systems
Compare kinematic and elasto-kinematic models

• Comparison of sensor outputs quantifies the difference in vehicle behaviour seen in the animation (right)
• Comparison of yaw rate estimation in the elasto-kinematic model (below)
Compare kinematic and elasto-kinematic models

- Kinematic suspension uses ideal joints
  - Revolutes and spherical joints
  - Blue car
- Elasto-kinematic incl. bushes compliance effects
  - Bending of upright, control arms, etc.
  - Green car
- No stability control active
- Double lane change
Controller response

- Enable ESC on the two vehicle models
  - Uses the brakes to influence vehicle stability
- Different controller calibrations
  - Results in different brake actuation
- Both models now respond similarly
Yaw rate estimation comparison

- Change to accelerometer-based estimation: different response
  - Red car uses the yaw rate estimation
  - Braking seems to occur late: On the straight after the lane change
- The yaw rate estimation drifts significantly compared to the ideal sensor
Future: Advanced Driver Assistance Systems

- ADAS get inputs from array of sensors
  - State estimation, Camera’s, Radar, Parking Sensors, etc.

- Sophisticated ADAS influences every system
  - Powertrain (engine and electric motors), brakes, steering

- Development of ADAS needs models accurately global behaviour
  - Dymola is a multi-domain modelling and simulation tool that can include Multiphysics & sensor dynamics.

- Need a tool that generates Driver/Hardware-in-the-Loop testing, calibration & validation
  - Dymola has a wide range of export options that can support all of these use cases
Conclusion

- High precision sensors are essential for the next generation ADAS
  - Sufficient accuracy is non-trivial given
    - Noise resilience requirements
    - Moving / noisy cg position
    - Cost & manufacturability constraints
    - Maintainability constraints
  - Sensor fusion is critical and creates the need for non-negligible processing power, essentially a “shadow” real-time simulator.

- Development of the control systems requires accurate models
  - Predictive models provide insight into the reaction of control-algorithms and sensor-fusion to varying environments.
  - Learning strategies can be tested in an “ideal world” and exposed to extreme conditions without committing significant resources.
  - A range of error conditions can be examined in an automated DoE style.

- Dymola is not only used in Automotive, it is applied in many industries
  - Aerospace, Energy, Robotics, etc.