How a Pseudo-Pressure Sensor Improves Diagnostics in a Solenoid Actuated Valve

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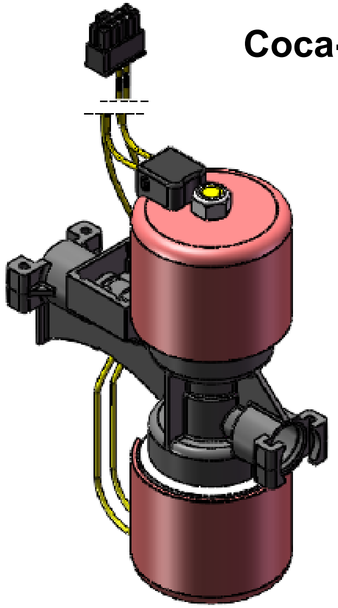
May 10, 2023.

What is the field issue?

Field issue:

- Coca-Cola Freestyle dispensers use a solenoid actuated valve called Flow Control Module (FCM) for regulating water flow.
- FCM is one of the highest replaced parts in the dispenser/field.
- **About 50% field return FCMs are good.**
- Service cost associated with these field replacements are high.
- The larger goal is to develop a diagnostics solution so that good FCMs are not getting pulled from the dispensers.

Coca-Cola Freestyle Dispensers



Flow Control Module (FCM)

FCM Diagnostics & Pseudo Pressure Sensor

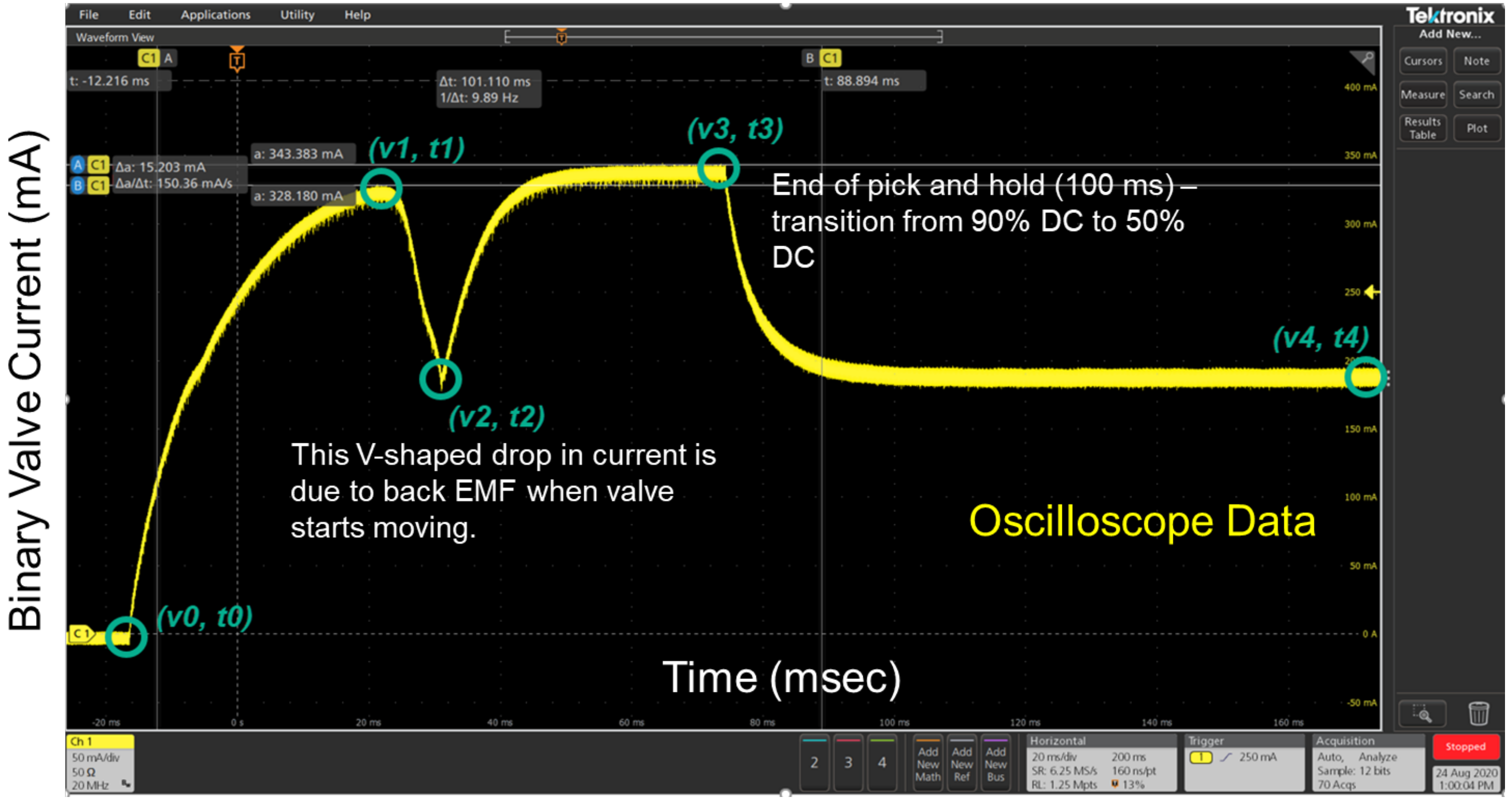
Why can't we do diagnostics now?

- We don't have a pressure sensor in the line.
- We can't tell the difference between FCM fault and upstream pressure loss.
- Adding pressure sensor not an option.
  - We can't retrofit the field.
  - Physical sensors add cost
  - Sensors can become another failure point.

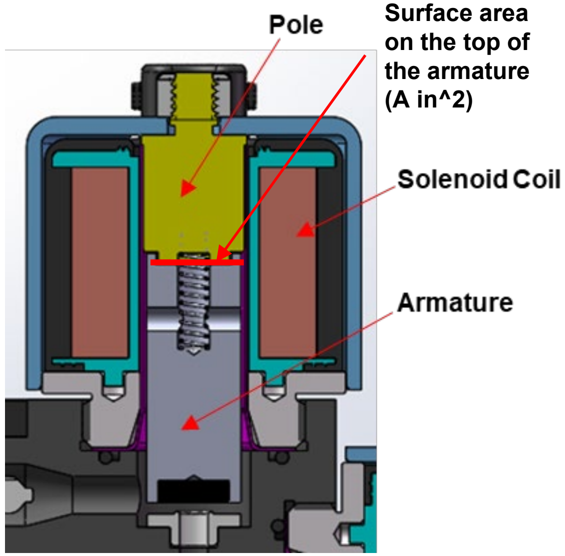
Pseudo Pressure Sensor

- Alternate option to a physical pressure sensor.
- It is a software solution.
- **This pseudo sensor is the focus of this presentation.**
  - What is it?
  - How was it developed?
  - How was it deployed?

Physics Behind Pseudo Pressure Sensor



Binary valve cross section



Equating electric and mechanical work, there is a correlation between pressure and current at which the valve starts to move.

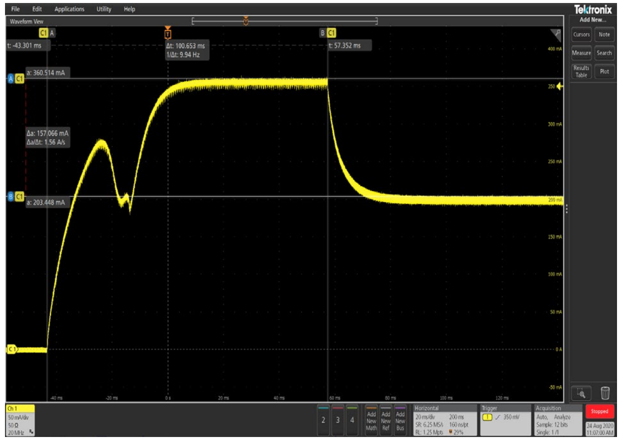
Mech work = Pressure*Area*distance

Electrical work = Current * Voltage

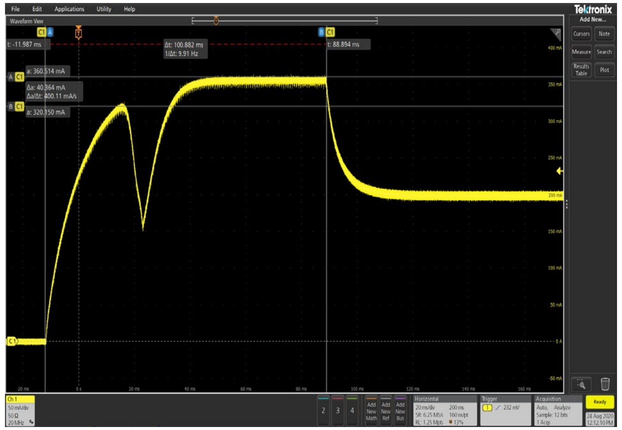
Physics Behind Pseudo Pressure Sensor Contd.

- See how the V-shaped drop in current travels as the pressure increases.
- The reverse will be true as the pressure drops – the valve will start opening quicker and you will see the V-shaped drop at a lower current.
- Note, we don't have oscilloscope quality data in the dispenser. We have low fidelity Op-Amp based current sensor feedback.

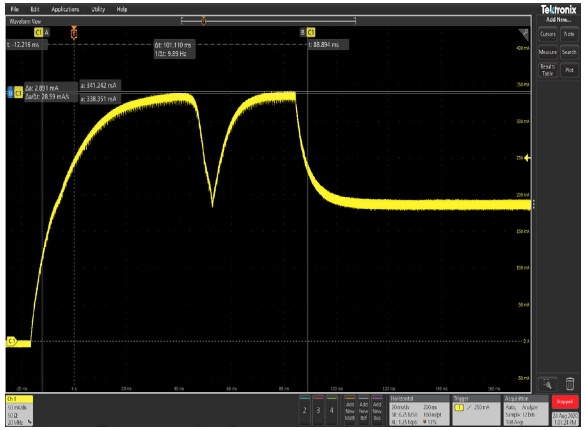
75 psi pressure



110 psi pressure



Valve almost did not open



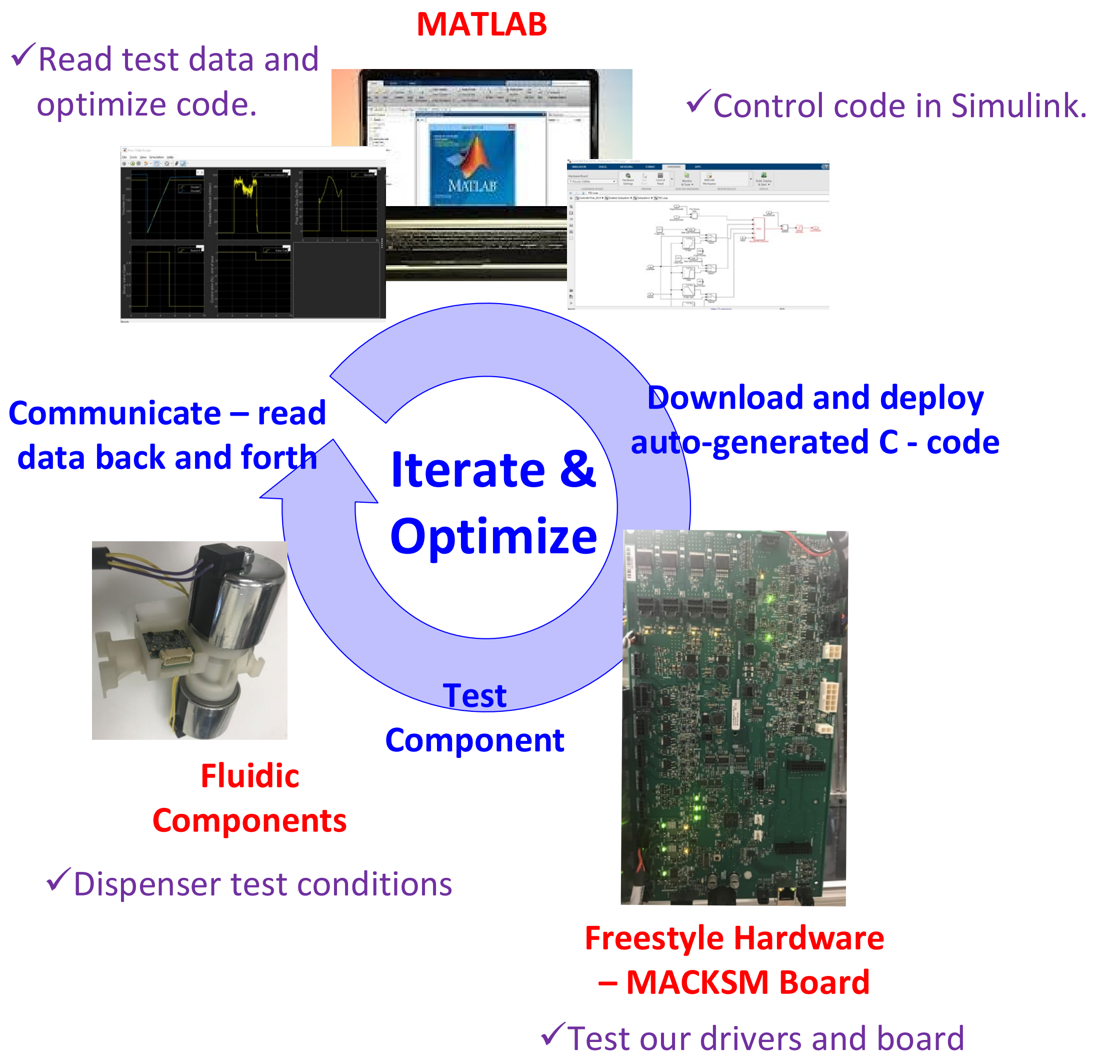
Valve did not open

140 psi pressure

Pseudo Sensor Development – Part 1: Data Collection

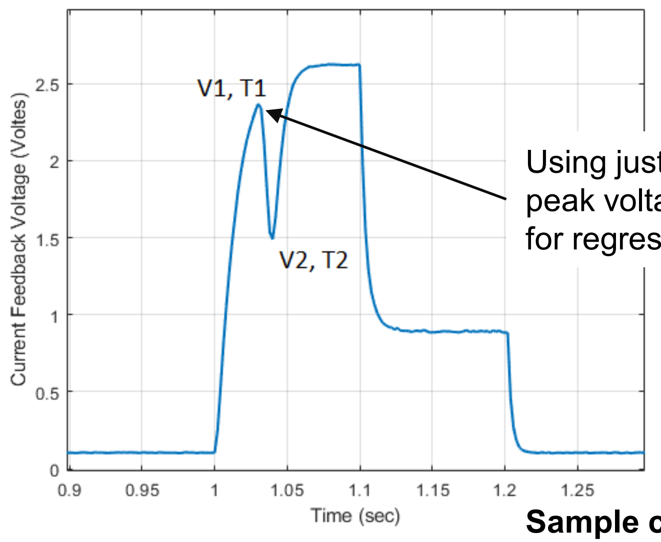
- The key is to collect data at dispenser condition using dispenser control board.
- **Data collected using hardware-in-loop (HIL) testing process**.
  - MathWorks helped develop a Hardware Support Package (HSP) for the dispenser control board.
  - HIL testing process enabled data collection at dispenser condition.
- More than 5000 pour data collected in the test bench with 10 different FCMs.
- Pressure range for data collection - 1 psi to 140 psi at 5 psi interval.

Hardware-in-Loop Testing Process



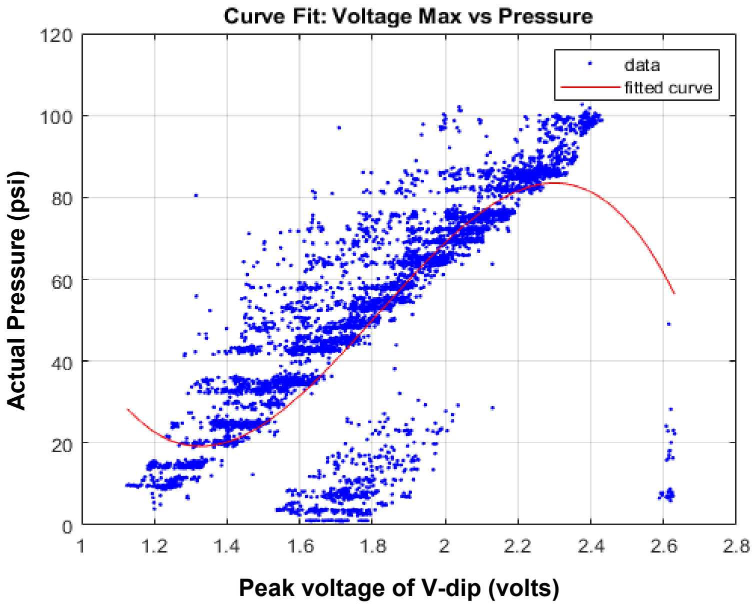
Pseudo Sensor Development – Part 2: Model Development

- **Prediction Model**: Input is binary current feedback voltage and output is a predicted pressure. Started with a linear regression model.
- Prediction model developed using MathWorks Machine Learning Toolbox.
- The only feature we considered was the peak voltage of V-dip (V1).
- It did not work. Too much error in prediction (see confusion chart).

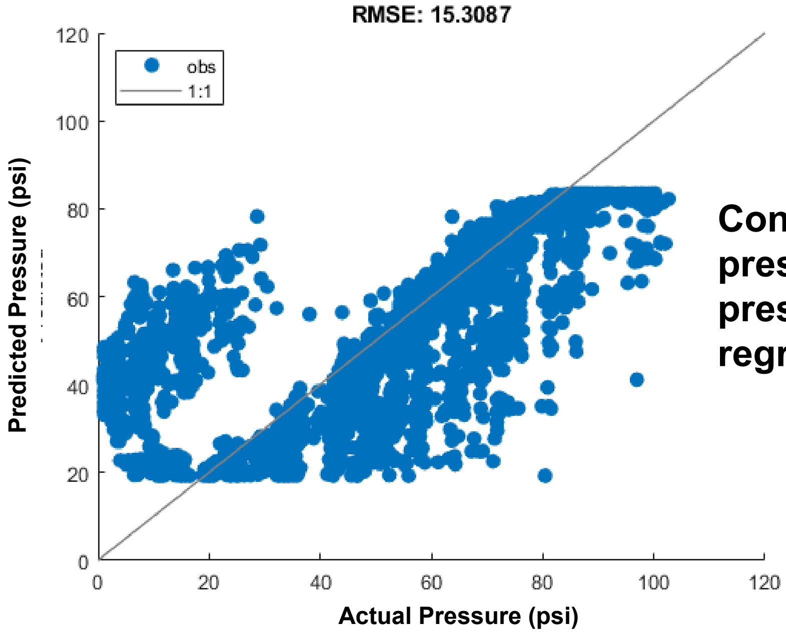


Using just the peak voltage V1 for regression.

Sample current feedback signal



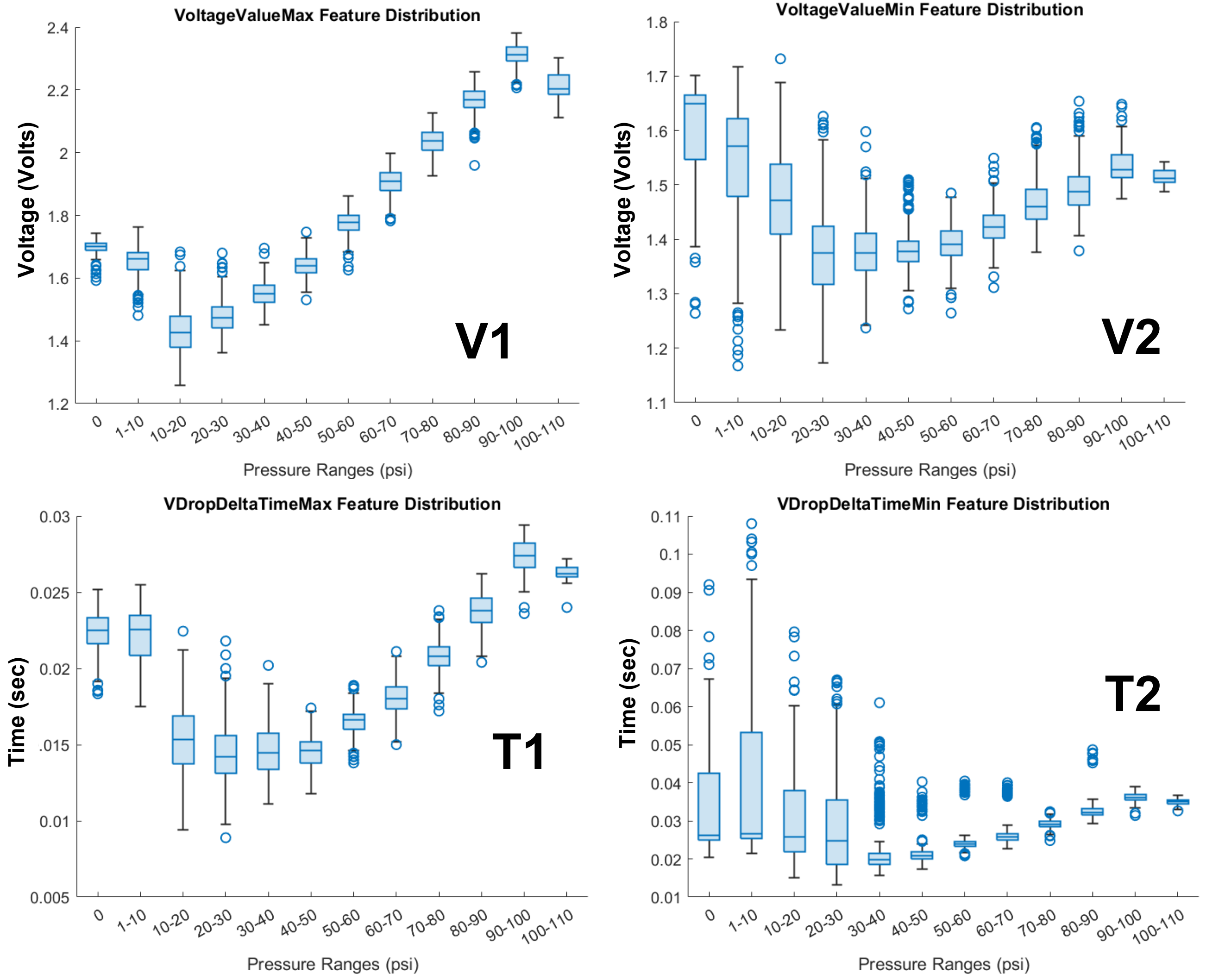
Peak voltage of V-dip (V1) verses actual pressure data, and the regression curve or model (red line).

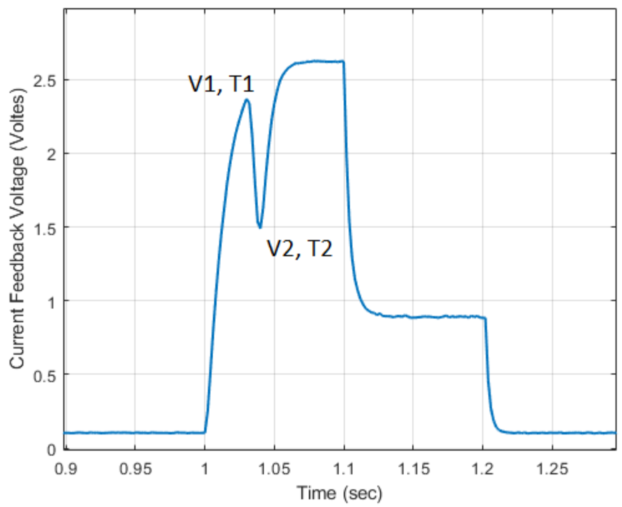


Confusion chart – actual pressure verses predicted pressure based on the regression model. .

Pseudo Sensor Development – Part 2: Model Development Contd.

- Identify other features that have a correlation to pressure.
- Features in the binary current feedback signal that have correlation to pressure.
  - Peak voltage at V-drop (V1), Peak time (T1), Dip voltage (V2), Dip time (T2), V1-V2, T1-T2.
- Features that did not have any impact are
  - Frequency, raise time, RMS values, mean, range,





Sample current feedback signal

Pseudo Sensor Development – Part 2: Model Development Contd.

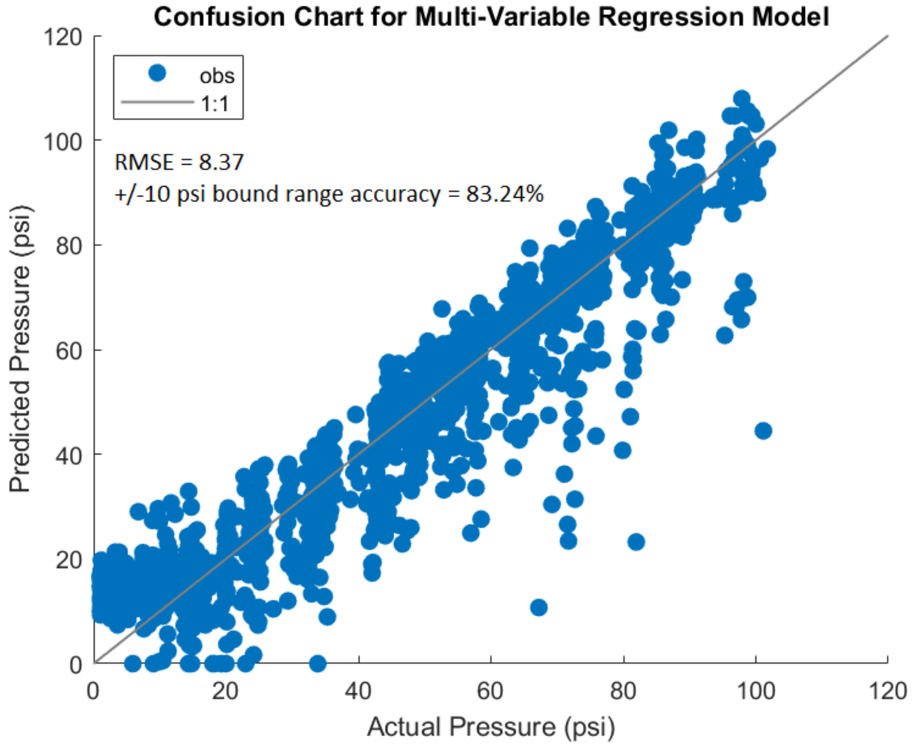
Coca-Cola freestyle

- Multi-variable regression using 6 features.
- The regression model is given below. It is a single equation using the 6 features and has 26 terms.

$$
\begin{aligned}
Pressure = {} & P_1 + P_2V_1 + P_3V_2 + P_4T_2 + P_5(T_1 - T_2) + P_6V_1V_2 + P_7V_1T_2 \\
& + P_8V_1(T_1 - T_2) + P_9V_2T_2 + P_{10}V_2(T_1 - T_2) + P_{11}T_2(T_1 - T_2) \\
& + P_{12}V_1^2 + P_{13}V_2^2 + P_{14}T_2^2 + P_{15}(T_1 - T_2)^2 + P_{16}V_1V_2T_2 \\
& + P_{17}V_1V_2(T_1 - T_2) + P_{18}V_2T_2(T_1 - T_2) + P_{19}V_1^2V_2 + P_{20}V_1^2T_2 \\
& + P_{21}V_1^2(T_1 - T_2) + P_{22}V_1V_2^2 + P_{23}V_2^2(T_1 - T_2) + P_{24}V_2T_2^2 + P_{25}V_1^3 \\
& + P_{26}T_2^3
\end{aligned}
$$

$$P_1 \ldots\ldots to \ldots . P_{26} \; are \; constants$$

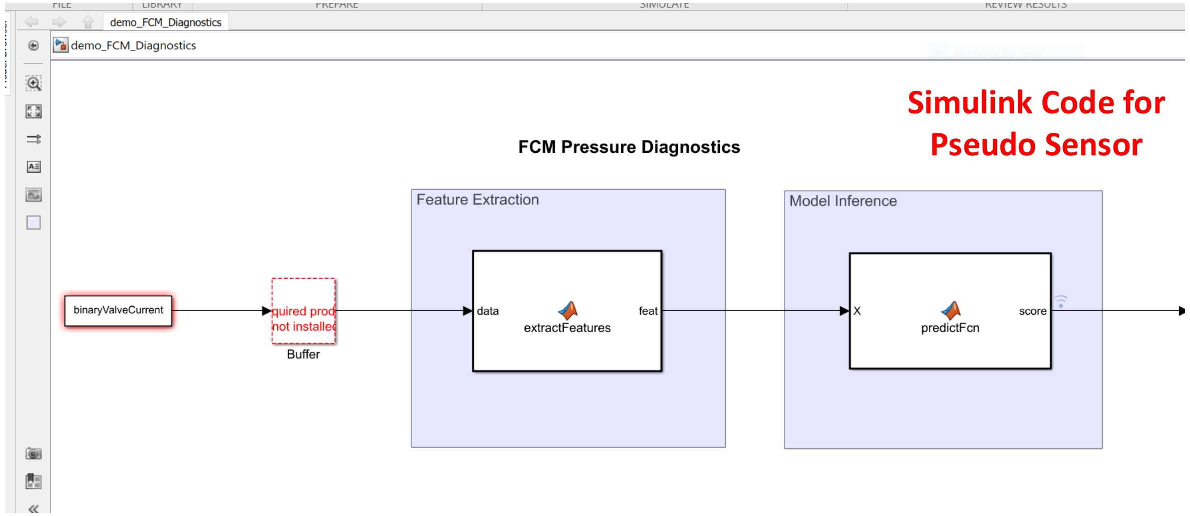
- The confusion chart for the model is shown on the right.



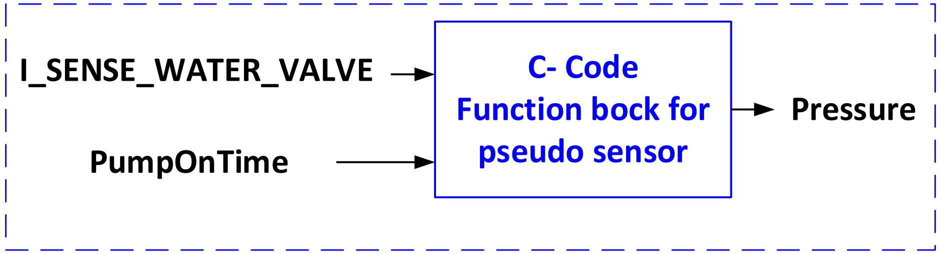
Pseudo Sensor Development – Part 3: Deployment, Testing & Validation

- Simulink model - feature extraction function & prediction model.
- This model was then deployed to a memory-constrained ARM-Cortex M microprocessor using Simulink auto code generation.
- Pseudo sensor tested at dispenser condition in the lab.

Simulink Code for Pseudo Sensor



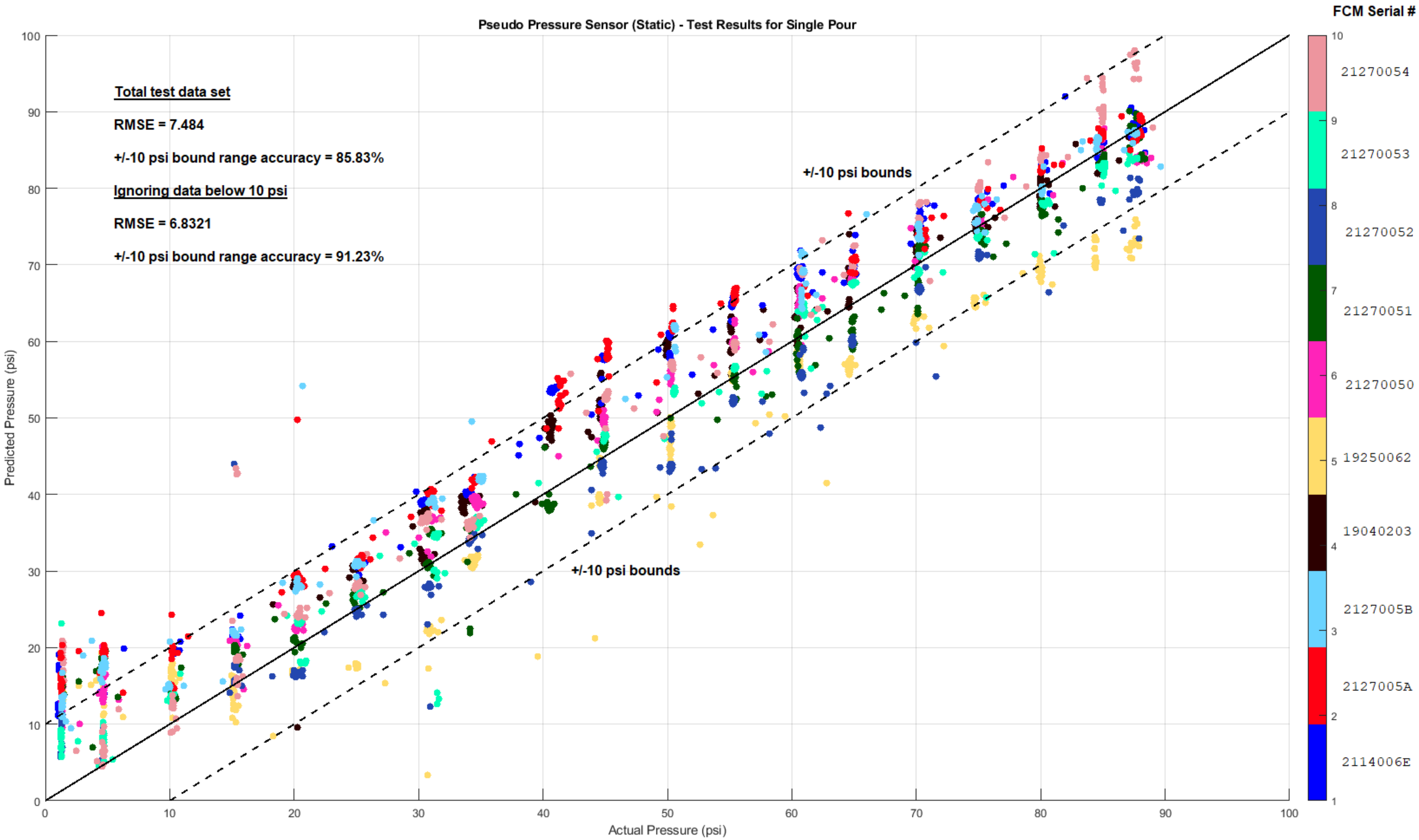
Auto-code generation



Download code to board & HIL Test

Pseudo Sensor Development – Part 3: Test Results

- 10 different FCMs tested on 2 different control boards.
- Data from 3300 tests.
- Automated test – valve opened for 200 ms and with an interval of 1 sec between pours.



Conclusion

- **FCM pseudo pressure sensor developed and deployed in dispensers in the field.**
  - **It is a software in lieu of a physical sensor.**
  - **It has transformed the FCM into a “Smart Component”**
  - **It enables effective diagnostics.**
- **Ongoing work: FCM diagnostics development using field pseudo sensor data.**

Acknowledgement

- **Arun Natarajan:** Co-lead. Concept development & controller lead.
- **Keith Gibson:** Co-lead. Concept development & electrical lead.
- **Jose Martins:** Co-lead. Did the business & economic case for the project.
- **Matthew Cox:** Data collection & testing.
- **Bin Zhang:** Firmware integration.
- **Hitesh Patel:** Hardware-in-loop tester support.
- **Sudheer Nuggehalli (Mathworks):** Machine learning and regression modeling.
- **Nick Howes (Mathworks):** Machine learning and regression modeling.
- **Roger Theyyunni (Mathworks):** Hardware-in-loop tester support.

Thank You

Seagram's
GINGER ALE
lime
Sprite
grape
Fanta
cherry
Minute Maid
LEMONADE
pink lemonade
POWERADE
strawberry
Minute Maid
sparkling
DRINKS
peach lemonade
Mello Yello
limeade
DASANI
SPARKLING
lemon lime