Appendix K

Time-Varying Thermal Dynamics Modeling of the Prototype of the REMS Wind Sensor

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Abstract

The objective of this work is to show the results from the analysis of the thermal dynamics of a prototype of the REMS 3D wind anemometer using the tools of Diffusive Representation (DR). DR is a mathematical tool that allows the description of physical phenomena based on diffusion using state-space models of arbitrary order in the frequency domain. From open-loop experimental measurements, where a current signal with a wide frequency spectrum is injected in the heaters, time-varying dynamical thermal models are extracted for different wind velocities. This models provide the temperature evolution of the parts of the system under study as a function of the power delivered to the heat sources.

The prototype of the wind sensor used in the experimental setup is based on thermal anemometry, which is the method that has been used in multiple occasions for the challenging task of wind sensing in Mars. It is based on the detection of the wind velocity by measuring the power dissipated of a heated element due to forced convection. This technique was employed in the wind sensor of REMS (Remote Environmental Monitor System) sensor suite, on board Curiosity rover since 2012. In 2018, it is expected to be launched the InSight (Interior Exploration using Seismic Investigation, Geodesy and Heat Transport) mission to Mars. It will include the TWINS instrument (Temperature and Wind sensors for InSight mission) which is an heritage from REMS. The prototype used in the experiments, is composed of three PCBs (Printed Circuit Board) placed on a cylindrical supporting structure (boom) at 120° from each other. Each PCB contains four Silicon dice set with Platinum resistors that are used as heating elements. The thermal dynamical characterization of one of the dice and its cross-heating with the boom is going to be presented.

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TIME-VARYING THERMAL DYNAMICS MODELING OF THE PROTOTYPE OF THE REMS WIND SENSOR

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OBJECTIVES

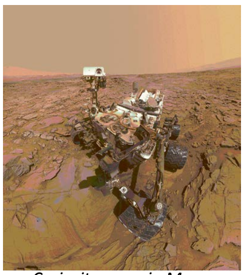
OBJECTIVES

- Time-varying thermal dynamics modeling of a 3D thermal anemometer for Mars.
- Modeling of self and cross-heating effects taking into account long term drifts due to thermal coupling.
- Black-box state-space modeling for prediction under arbitrary excitations.

WIND SENSING IN MARS

WIND SENSING IN MARS

- Wind sensing in Mars is a challeging task
  - CO_2 atmosphere
  - Pressure ≈ [6 - 12]mBar
  - Temperature ≈ [150 - 300]K
- Curiosity rover included the REMS sensor suite:
  - Humidity
  - Pressure
  - Temperature
  - Radiation
  - **Wind velocity**



Curiosity rover in Mars.

- The prototype used in the experimental setup is the engineering model of the REMS wind sensor, developed in 2008, similar in size and concept to the flight model.
- This wind sensor is based on thermal anemometry.
- Same device sensor concept (with significant changes) is scheduled to flight in InSight mission (2018) and in Mars2020 rover (2020).

PROTOTYPE DESCRIPTION

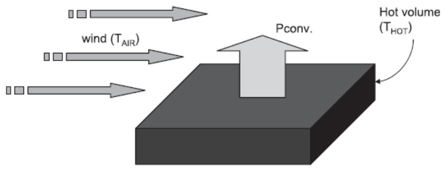
REMS PROTOTYPE DESCRIPTION

THERMAL ANEMOMETRY

Detects the wind velocity by measuring the power dissipated of a heated element due to forced convection

CONSTANT TEMPERATURE ANEMOMETRY (CTA)

The power required to maintain constant the temperature in the heating elements is the sensor output.

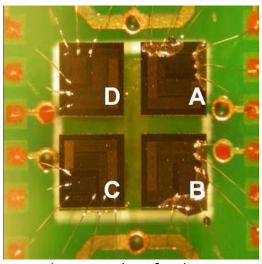


CTA concept

When the wind incides, the device is cooled, and more power is needed to keep constant the temperature

PROTOTYPE DESCRIPTION

REMS PROTOTYPE DESCRIPTION



Photography of a dice-set.

- Wind velocity and direction detection.
- Tangential wind components are measured at three points of a cylindrical structure (boom).
  - Dice-set composed of four Silicon dice (A, B, C and D) in coplanar plane (2D sensitivity)
  - Three dice-set 120º to each other (3D sensitivity)
- Each die contains Platinum (Pt) resistors for heating and sensing temperature.
- Inside boom, Pt100 resistor measures its temperature

Boom prototype used in the experiments.

OPEN-LOOP CHARACTERIZATION

OPEN-LOOP CHARACTERIZATION

- Time-varying thermal models are extracted from open-loop experiments using Diffusive Representation.
- These models provide the temperature dynamics of the components of the system under study as a function of the power delivered to the heat sources.
- Pseudo Random Binary Sequences (PRBS) of current are injected into the heat sources, while the temperature of different components of the system is sensed.
- During the experiment, different wind velocities are applied.
- The obtained thermal models follow the experimental data.

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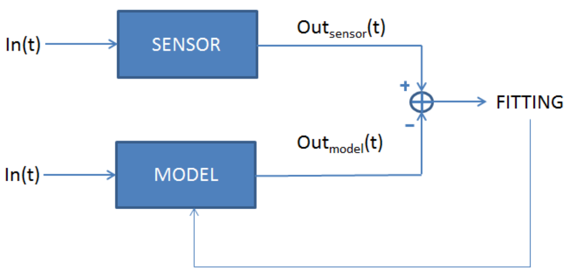
THEORETICAL GROUNDS

TOOLS: DIFFUSIVE REPRESENTATION (DR)



Description of thermal systems using models of arbitrary order.

- ζ_k is the frequency mesh
- $\Psi_k(t)$ contains the state of the system under actuation $In(t)$
- $\eta_k(t)$ represents how the system behaves

$$\frac{d\Psi_k(t)}{dt} = -\zeta_k \Psi_k(t) + \eta_k(t) In(t), \qquad \Psi_k(0) = 0$$

$$Out_{model}(t) = \sum_{k=1}^{K} \Psi_k(t)$$

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THEORETICAL GROUNDS

SELF AND CROSS-HEATING EFFECTS

SELF - HEATING

Injection of power into the own device's heat sources.

CROSS - HEATING

Injection of power into heat sources in parts of the structure different from the one in which temperature is sensed.

$$\frac{d\Psi_k^X(t)}{dt} = -\zeta_k \Psi_k^X(t) + \eta_k^{XX} P_X \qquad \Psi_k^X(0) = 0 \qquad k = 1 \ldots K$$

$$K \neq J \qquad \{\zeta_k\} \neq \{\upsilon_j\}$$

$$\frac{d\Phi_j^Y(t)}{dt} = -\upsilon_j \Phi_j^Y(t) + \eta_j^{XY} P_Y \qquad \Phi_j^Y(0) = 0 \qquad j = 1 \ldots J$$

η_k^{XX} represents thermal behaviour of device X as a function of power injected into itself.

Temperature in device *X*

$$\hat{T}_X(t) = \sum_{k=1}^{K} \Psi_k^X(t) + \sum_{j=1}^{J} \Phi_j^Y(t)$$

Self-Heating contribution!

Cross-Heating contribution!

η_k^{XY} represents thermal behaviour of device X as a function of power injected into device Y.

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EXPERIMENTAL SETUP

WIND TUNNEL DESCRIPTION

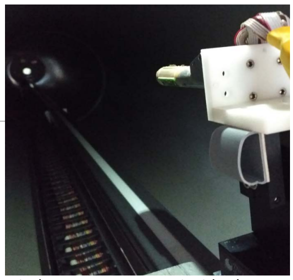
- Air atmosphere
- Pressure ≈ 240mBar
- Temperature = 298K
- Velocity range: [6 - 30]m/min

Mars equivalent wind velocities

- CO_2 atmosphere
- Temperature = 223K
- Pressure = 7mBar
- same Reynolds number

[2 – 10]m/s

- Five meter linear wind tunnel (rail inside)
- Pan and tilt system



Wind sensor prototype inside the tunnel.

Outside of the 5m linear wind tunnel

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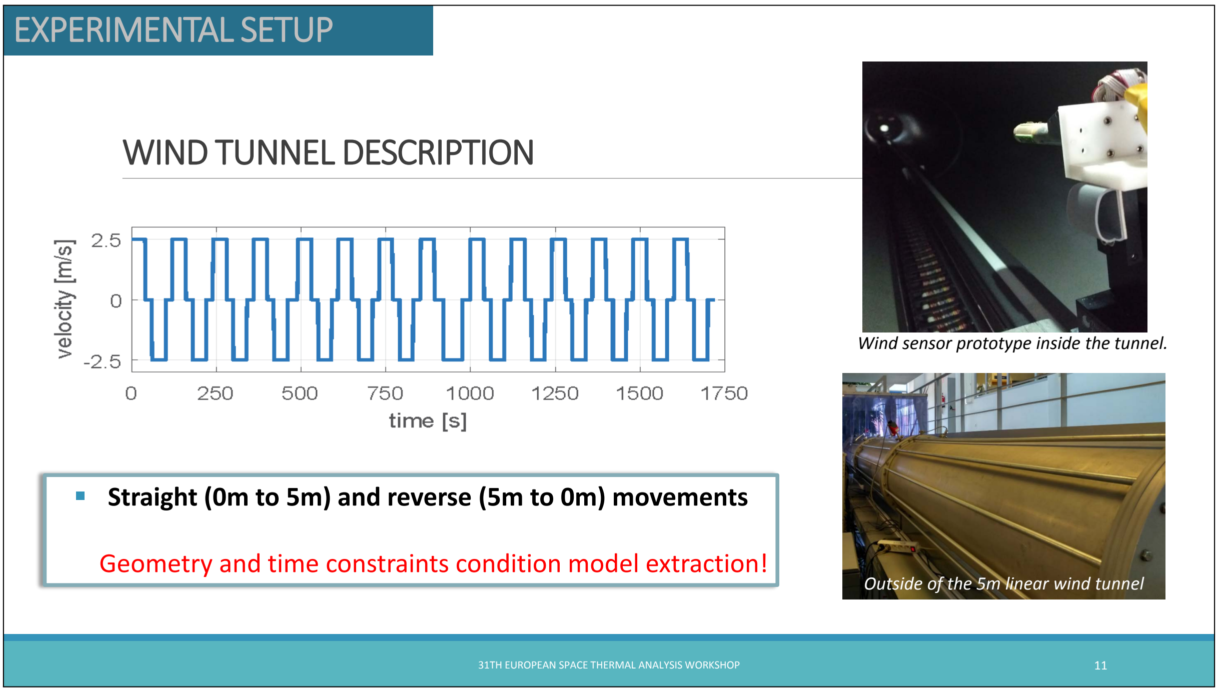
EXPERIMENTAL SETUP
WIND TUNNEL DESCRIPTION
velocity [m/s]
2.5
0
-2.5
0 250 500 750 1000 1250 1500 1750
time [s]
Straight (0m to 5m) and reverse (5m to 0m) movements
Geometry and time constraints condition model extraction!
Wind sensor prototype inside the tunnel.
Outside of the 5m linear wind tunnel
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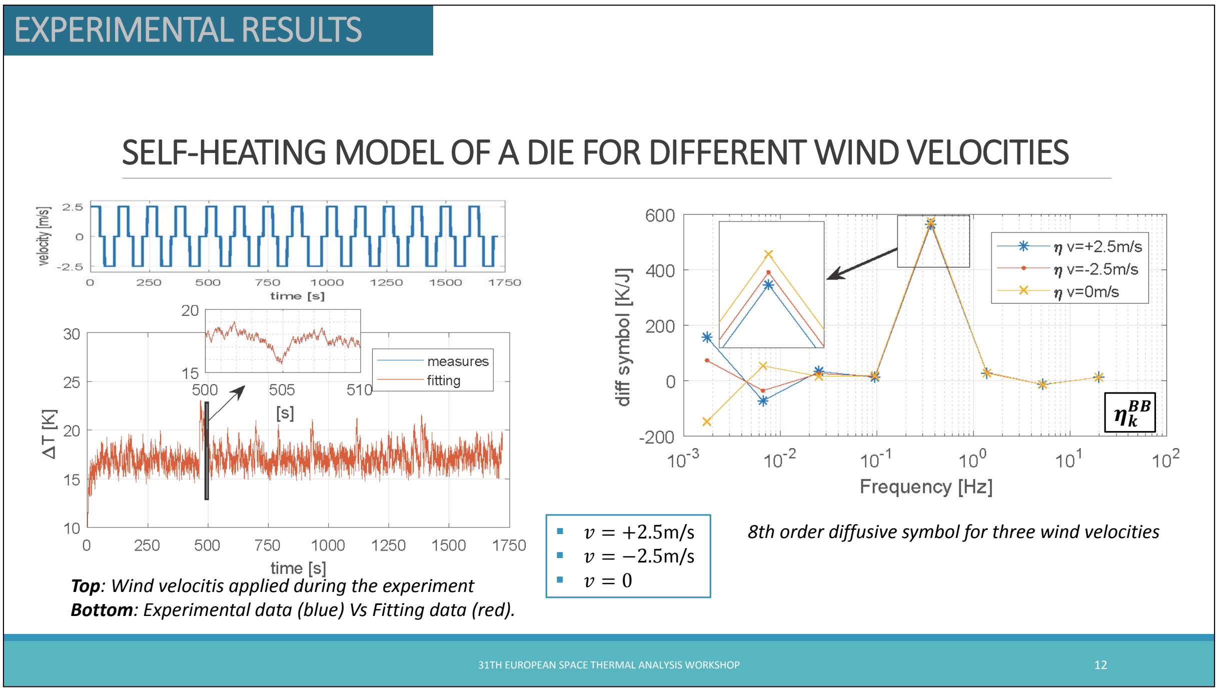
EXPERIMENTAL RESULTS
SELF-HEATING MODEL OF A DIE FOR DIFFERENT WIND VELOCITIES
velocity [m/s]
time [s]
measures
fitting
ΔT [K]
time [s]
[s]
Top: Wind velocitis applied during the experiment
Bottom: Experimental data (blue) Vs Fitting data (red).
v = +2.5m/s
v = −2.5m/s
v = 0
diff symbol [K/J]
Frequency [Hz]
η v=+2.5m/s
η v=-2.5m/s
η v=0m/s
8th order diffusive symbol for three wind velocities
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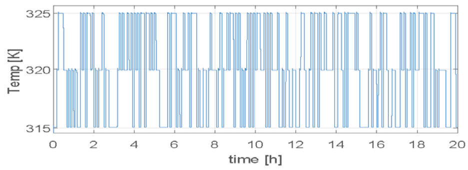
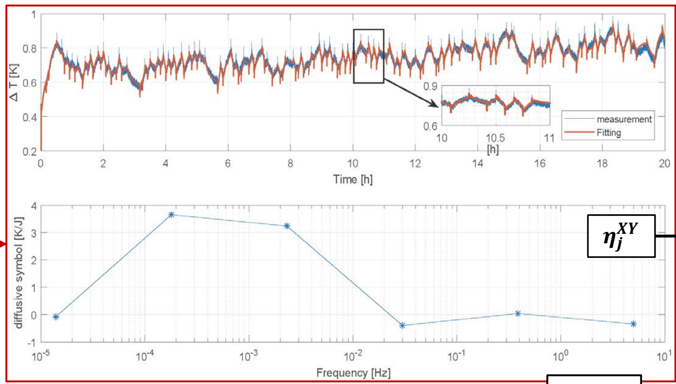
EXPERIMENTAL RESULTS

CROSS-HEATING MODEL OF THE BOOM



Temperature in the dice during the experiment

- All dice working in closed-loop mode.
- 20h of experiment.
- Temperature switching every 5min:
  - 315K, 320K, 325K
- **Effect in boom temperature**



***Top**: Experimental data (blue) Vs Fitting data (red)*
***Bottom**: 6th order diffusive symbol.*

X: boom
Y: dice

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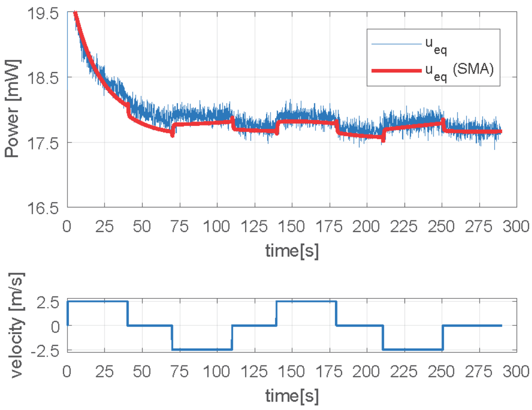
EXPERIMENTAL RESULTS

CLOSED-LOOP PREDICTION

DR state-space thermal models + Sliding Mode Controllers theory

Possible to analyze/predict the time evolution of the temperature under arbitrary excitations

- Example:
From self-heating models, the necessary power to maintain the temperature constant in die B can be predicted.



***Top**: Average power injected into heater of die B (in blue) Vs Sliding mode analysis result (in red), under closed loop control.*
***Bottom**: Sequence of the wind velocities along the experiment*

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CONCLUSIONS

CONCLUSIONS

- Time-varying thermal models of a prototype of the REMS wind sensor have been obtained for different wind velocities.
- Self and cross heating effects have been modeled.
- Obtained models help to understand the long term effects and drifts in the system.
- These state-space models may predict outputs for arbitrary excitations.

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THANK YOU!

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