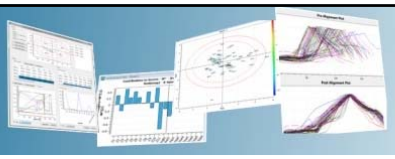

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data driven innovation

# Monitoring Combustion Processes via Digital Imaging

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ProSensus Multivariate Data Course





## Introduction

- ProSensus is a high tech company that extracts information from multivariate data to:
  - Understand processes
  - Monitor processes
  - Optimize and control processes
- Digital images (color and multi-spectral) are just one type of on-line data we use

## Objectives

- Present some ideas and examples using digital images to monitor and control combustion processes
- Show examples from different industries
- See if any OEM's or end users in audience might have interest in exploiting this technology



## Outline

- Quick overview of advanced image analysis
  - Satellite imaging example
- Industrial applications to combustion processes
  - Waste Boiler
  - Lime & ore kilns
  - BOF (steel industry)
  - Coal-fired boiler (power generating station)
- Discussion

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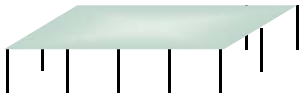
## Multivariate Images

- Image space is composed on many pixels
- Each pixel has more than 1 variable
  - Color image: R, G, B values
  - Multispectral image: an entire spectrum (eg. NIR)
- A stack of images at different wavelengths





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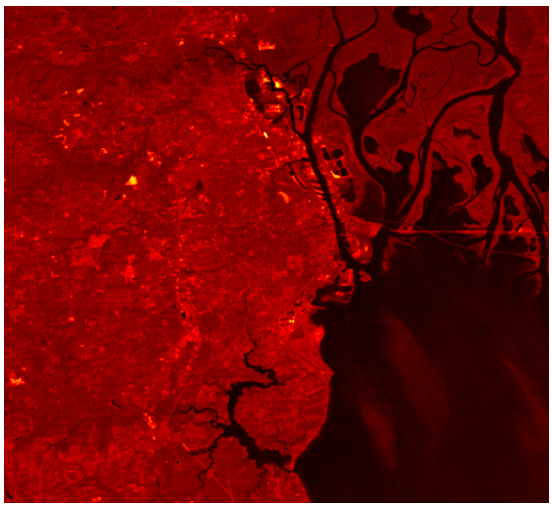
## Motivating Example – Remote Sensing
## Mobile, Alabama



- Landsat images
- 4 wavelengths(RGB+NR)

- Shown is a false color composite image

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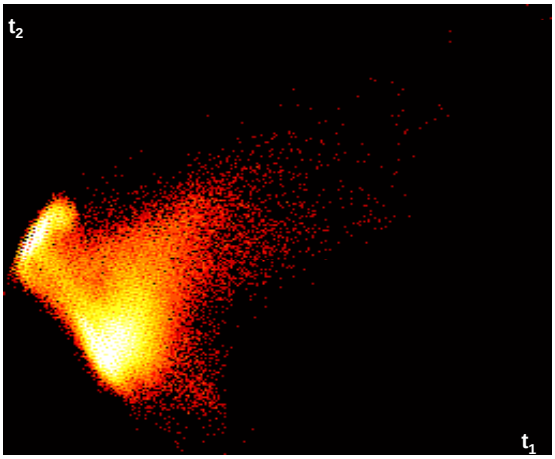
# Decomposition of image to lower dimensional space

Employ multivariate statistical methods (PCA) to reduce images to 2 dimensional space where each pixel is located according to the similarity of its spectral content



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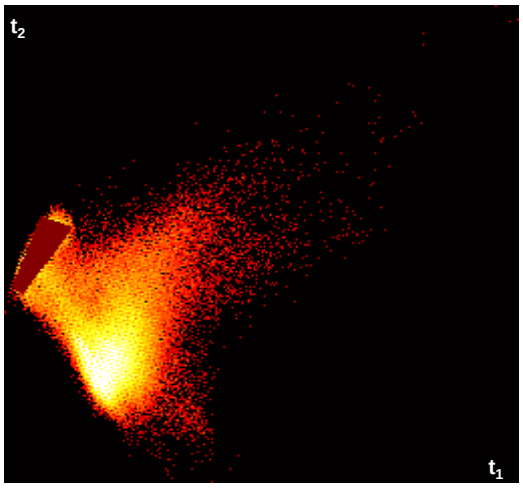
# Masking in the Score Space



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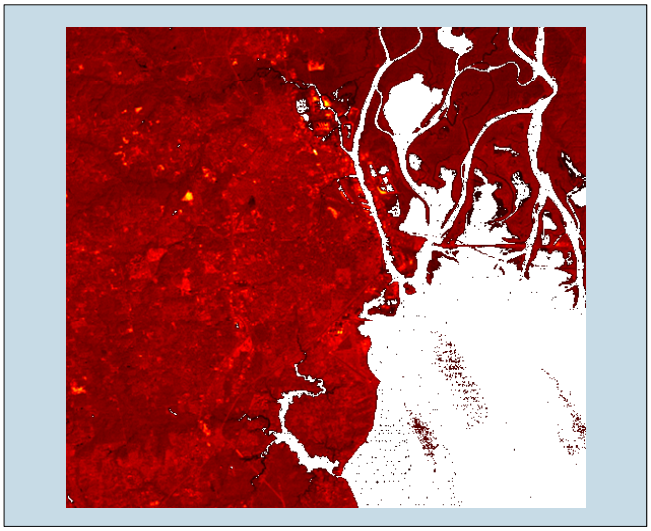
## Mapping back into the Image Space





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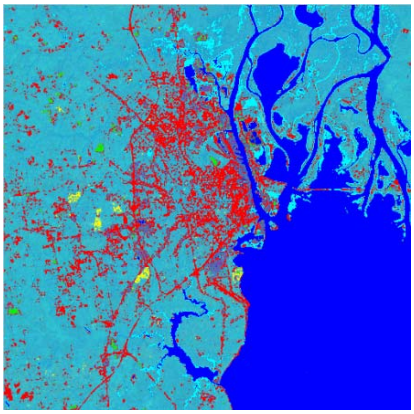
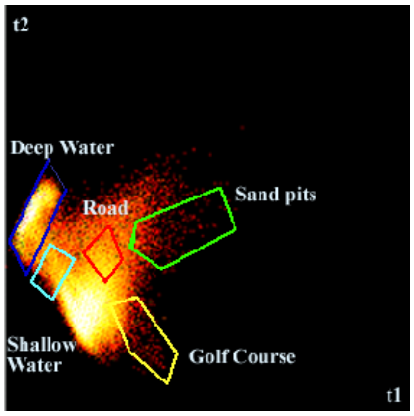
## Concept of Masking in the Score Space

Illustrates ease with which one can segment features





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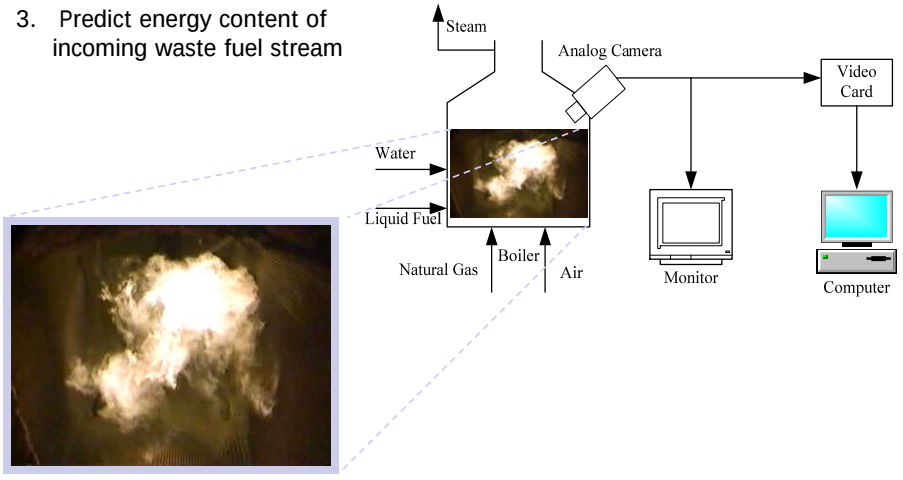
# Prediction & Monitoring of Combustion Systems

Monitoring of a waste boiler at DuPont

1. Monitor stability of the process
2. Predict SOx and NOx emissions
3. Predict energy content of incoming waste fuel stream



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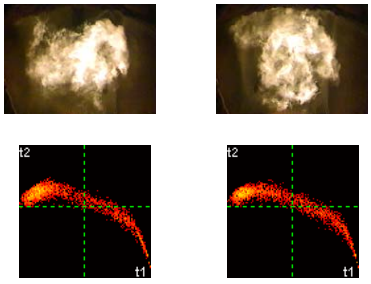
# Multi-way PCA and PLS to extract Information from Flame Images

- Multi-way PCA
  - PCA score plots very stable
  - Change only when process conditions change
- Extract feature information from score space
- Relate features to boiler performance via PLS regression




Yu, H. and J.F.MacGregor, "Monitoring flames in an industrial boiler using multivariate image analysis", Amer. Inst. Chem. Eng. J., 50, 1474-1483, 2004.

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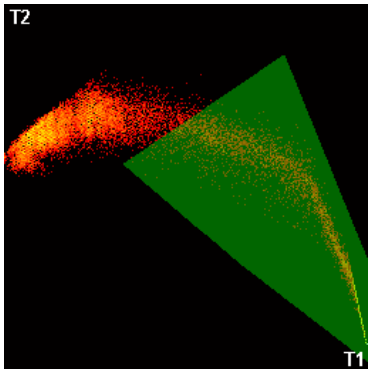
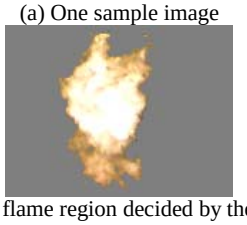
# Example of feature extraction: Flame luminous region



(b) Score plot and mask


(a) One sample image


(c) The flame region decided by the mask



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# Example of Calculation of Flame Luminous Region Features

- Area: $A = \sum_{i,j} \mathbf{TT}_{i,j}, \quad \forall (i, j), \mathbf{M}_{i,j} = 1$
- Brightness: $B = \sum_{i,j} \mathbf{TT}_{i,j} \cdot \mathbf{L}_{i,j}, \quad \forall (i, j), \mathbf{M}_{i,j} = 1$

$$\mathbf{L}_{i,j} = [\mathbf{R}\ \mathbf{G}\ \mathbf{B}]_{i,j} \cdot \begin{bmatrix} 0.299 \\ 0.587 \\ 0.114 \end{bmatrix}$$

- Uniformity: $U = \sqrt{\frac{\sum_{i,j} \mathbf{TT}_{i,j} \cdot \mathbf{L}_{i,j}^2 - \sum_{i,j} \mathbf{TT}_{i,j} \cdot \mathbf{L}_{i,j}}{\sum_{i,j} \mathbf{TT}_{i,j}}} = \sqrt{\frac{\sum_{i,j} \mathbf{TT}_{i,j} \cdot \mathbf{L}_{i,j}^2 - B}{A}}, \quad \forall (i, j), \mathbf{M}_{i,j} = 1$

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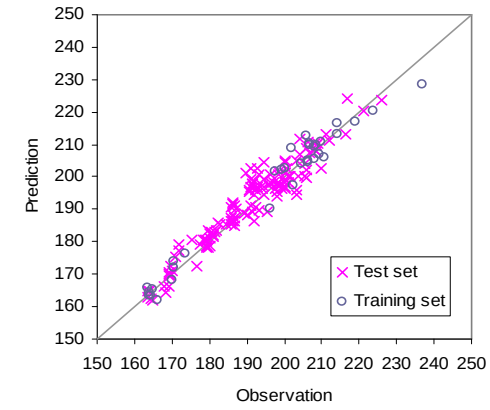
# PLS Prediction of Steam Flow Rate

Illustration of information contained in the flame images – (not a useful prediction)



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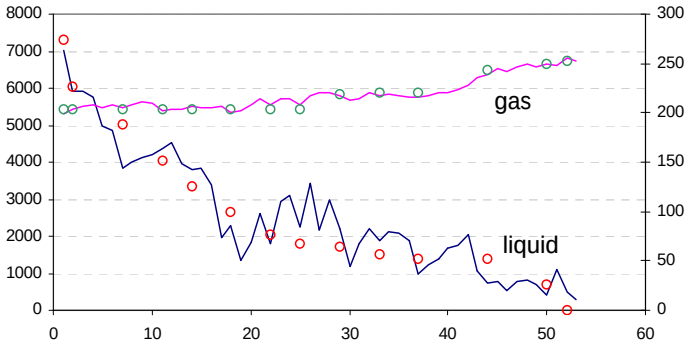
# Prediction of gas and liquid fuel flows



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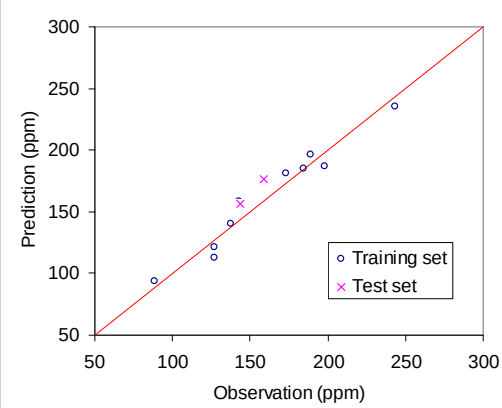
# Prediction of $NO_X$ Concentrations in Off-gas



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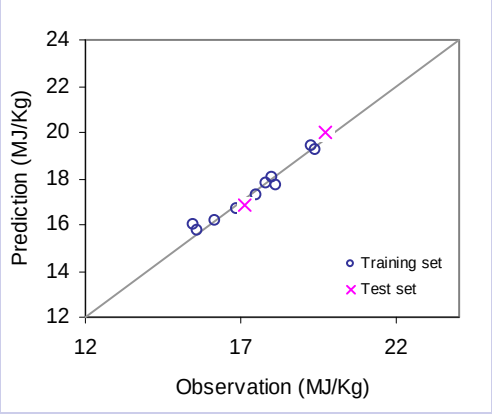
# Prediction of Energy Content of Incoming Waste Fuel Stream




Use image data plus flow rates of waste fuel and gas streams

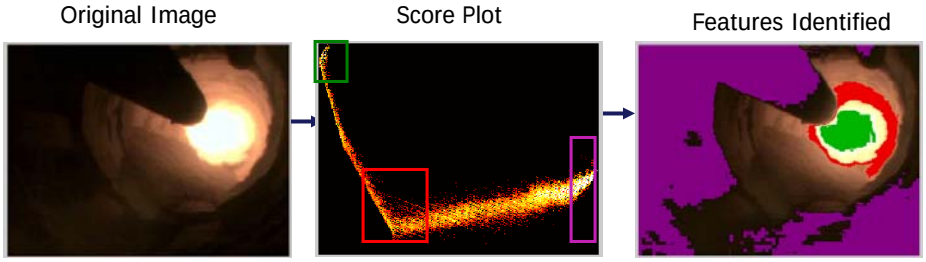
## Combustion Control of Kilns (Ore, Lime, Cement)

- The kiln flame should provide information about:
  - the energy efficiency/flame stability in the kiln
  - Fuel characteristics
  - the final exit temperature and final lime quality
- It is also important to stabilize the flame in order to prevent ring build up and run efficiently
  - Very important for kilns feeding waste fuels



## Decomposition of the Image to Extract Information

- Masking can easily identify regions of the image and how they change with time:
  1) Assessment of flame stability/flame length/fouling potential
  2) Relate these features to future exit temperature and product quality
  3) Use this information to diagnose and control combustion
     - Particularly relevant for kilns feeding waste materials with varying energy content



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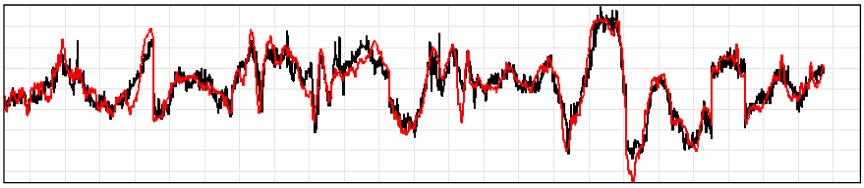
## Product Quality & Exit Temperature Predictions

- Information from on-line images and process data were combined
  - Lime Kiln in pulp and paper industry

**Prediction of final exit temperature: 2 hours in advance**



**$R^2$ = 82% , $Q^2$ = 79%**

Measured
Predicted



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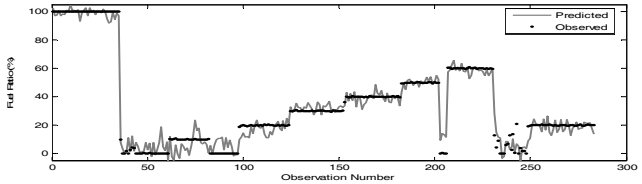
## Another example: Ore Roasting Kiln

### Prediction of fuel ratio and flow

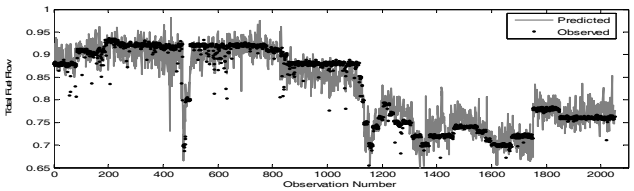
**Shows that other useful information can be extracted from the flame images**

Fuel ratio

Local vs external source




Total fuel flow




G. Szatvanyi , C. Duchesne, G. Bartolacci, *Ind. Eng. Chem. Res.* ***2006, 45, 4706-4715***

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## Basic Oxygen Furnace (Steel Industry)

Goal:

- Predict end-point carbon in this batch process to:
  - reduce oxygen consumption
  - improve product quality
  - reduce carbon measurement costs (~$200 / measurement)

Method:

- Carbon is predicted using 2 minutes of flame images over the end of the heat plus process data
- Goal is to predict end-point carbon within ±0.01 %



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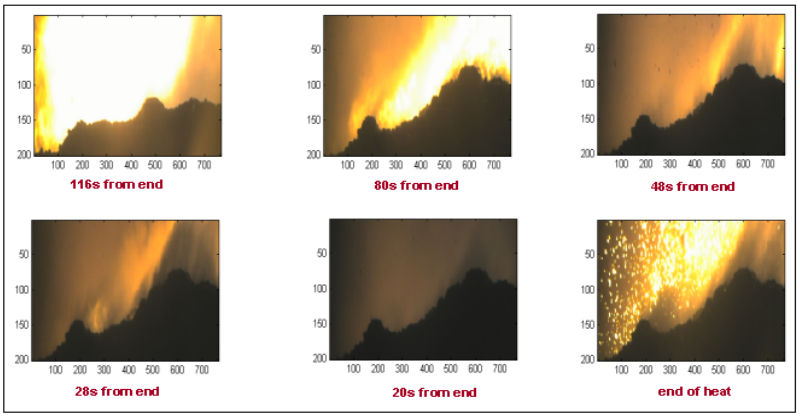
## BOF – End Point Carbon Prediction

- Images for last 2 minutes of the heat provide information needed to predict end point carbon



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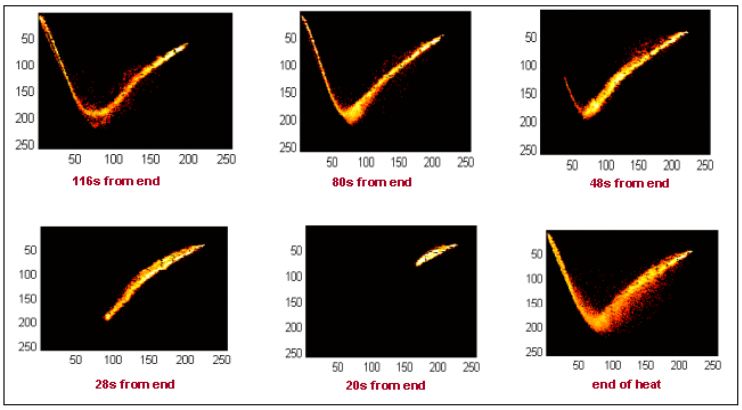
## BOF – Carbon Prediction...cont'd

Corresponding score images for the last 2 minutes of the heat




- features are extracted from the score images and used to predict end-point carbon



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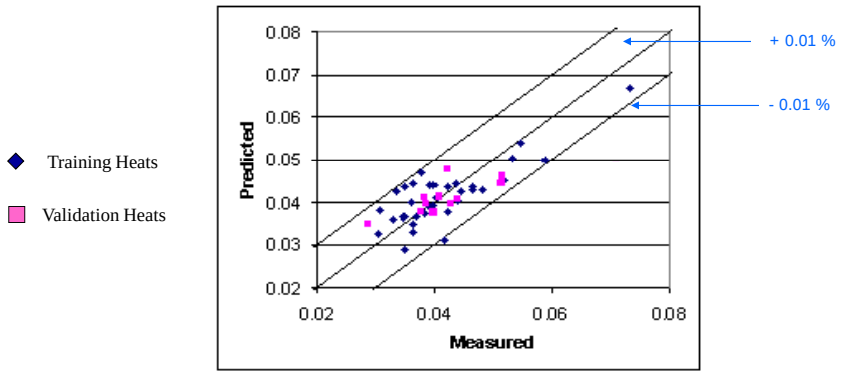
## BOF – Carbon Prediction

- Image and process data are combined to build a PLS model
- Process data includes raw material amounts & chemistry, steam flow, oxygen flow, etc.

### Model: Predicted vs Observed Carbon



## Coal fired boiler (power generating station) Coal and coal plus biomass fuel

Ontario Government funded research project

- Atikoken power generating station – Thunder Bay, ON
- Objective was monitoring and optimization of the boiler

- Three high temperature cameras were installed at the following locations
  - 8th Floor North Side – view of burners on south side
  - 8th Floor South Side – view of burners on north side
  - 3rd Floor focused on Burner 2

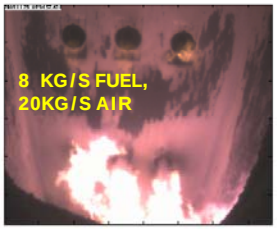


## Coal fired boiler imaging

Summary:

- Project inconclusive due to premature shutdown of station
- Cameras can determine whether or not a burner bank is balanced at low loads:
  - This shows burners on level 2 are not balanced (40MW biomass trials)


Burner 2-3 hardly has a flame




Flames are similar, though burners 2-1:2 may extend farther than 2-3


Burner 2-3 appears brightest, but other flames extend beyond image

## Individual burner monitoring

- Coal-fired flames have less information due to glowing particulates
- But the images on the individual burner (2-1) was able to predict the air to fuel ratio (80MW experiments):

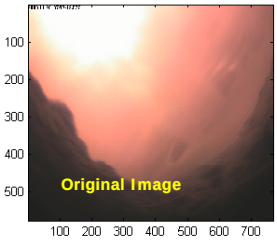
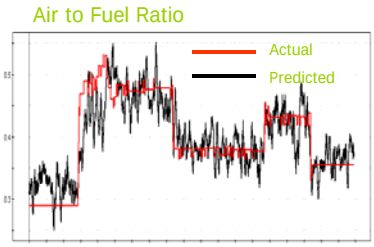



image analysis



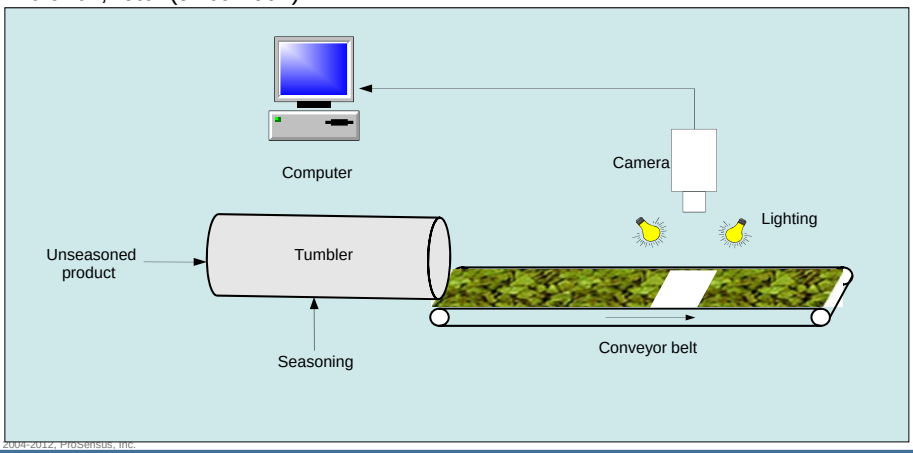

- Combustion monitoring and optimization was not completed prior to shutdown – more data are needed



## Final Incentive: Control of snack food properties

• In case you are wondering if any of this advanced imaging technology is used in practice, I leave you with one of our applications in the snack food industry.

• On-line control of snack food properties – seasoning level & distribution, texture, crunch, etc. (since 2004)



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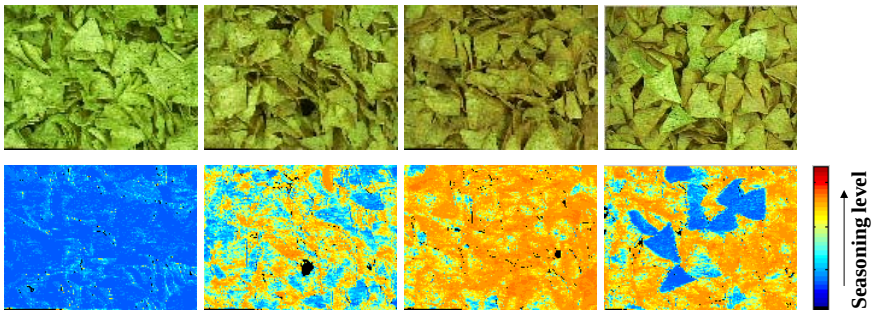
## Visualize seasoning level




Non-seasoned Low-seasoned High-seasoned Mixed



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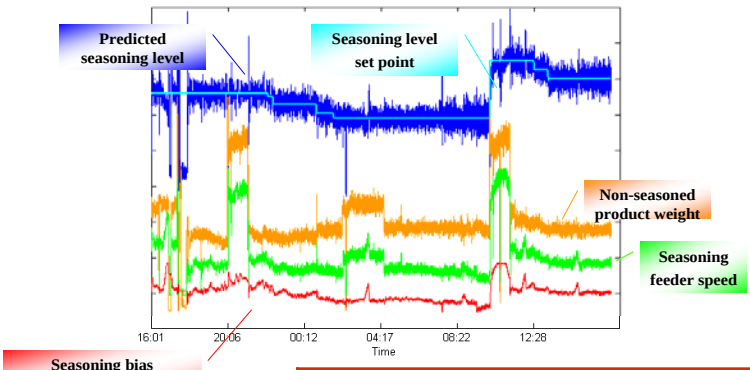
## Closed-loop Control of Seasoning Level




| | Without Automatic Feedback Control | With Automatic Feedback Control (constant set point) | With Automatic Feedback Control (set point tracking) |
|---|---|---|---|
| MAE | 0.8523 | 0.4481 | 0.4769 |

## Point of this?

- If you have eaten Doritos, Cheetos, and Ms Vickies or Frito Lay kettle fried chips, then you are already probably a user of ProSensus' technology.



## Image Analysis for Combustion Monitoring

- ProSensus now has no commercial offering in this area
  - Only have individual custom applications.
  - Not sure if there is wider interest by this community.
- Purpose of presenting here is to see if there is interest:
  - By OEM's who may want to embed this technology in their offerings.
    - Already are supplying the cameras with the boilers, etc. (maybe one should make more use of the cameras)
  - By end users who have applications that might make use of this.

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# Thank You

# Questions?



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## Contact details

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