Collaborative Fault Tolerant Control for Complex Industrial Processes: Present and Future

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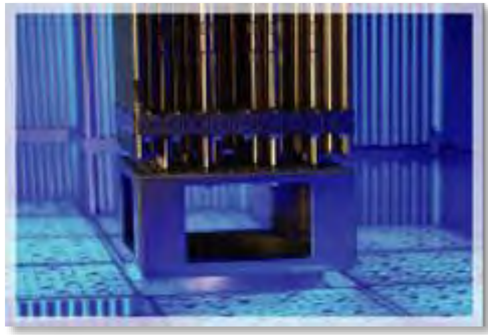
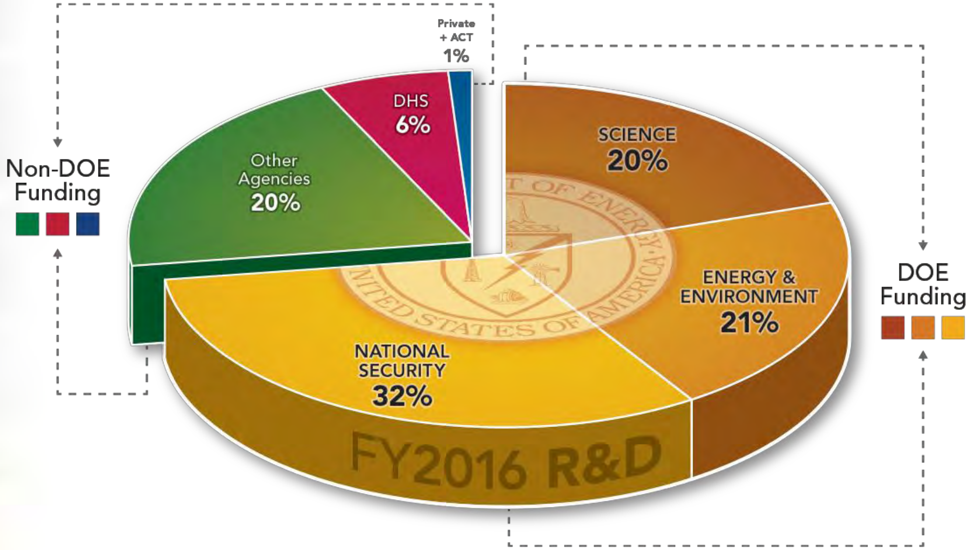


Nuclear: Energy & Regulatory

PNNL FY16 at a glance

- $920.4M in R&D expenditures
- 4,400 scientists, engineers and non-technical staff
- 104 U.S. & foreign patents granted
- 2 FLC Awards, 5 R&D 100
- 1,058 peer-reviewed publications



Control of Complex Systems Initiative (CCSI)
Leader: M Brambley, Chief Scientist: Hong Wang

http:controls.pnnl.gov

Acknwledgemets

We started in this area of work in 2003, with the following funding supports:

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- The university of Manchester, UK;
- Chinese NSF, Chinese Academy of Science, Northeastern University;
- (2016 -) US Department of Energy, PNNL

These are gratefully acknowledged

Outlines

- Background and problem statement – why “collaborative”
- Collaborative fault tolerant control for robot arm (Manchester Work)
- Collaborative fault tolerant control for transportation systems (PNNL Work)
- Collaborative fault tolerant control for industrial processes:
  a stochastic distribution control case (Manchester Work)
- Summary and future perspective

Background – complex systems

- Complex systems consists of a number of sub-systems collaboratively working together

- Examples are:

- ❑ Industrial processes
- ❑ Transportation systems
- ❑ Power systems
- ❑ Robotics

Figure 1. Examples of complex systems

Three Operational Senarios – Complex Systems

- ❑ Simultaneously operated sub-systems (very much in line with consensus control [A,B])

- ❑ Sequentially operated systems (process industries)

- ❑ Hybrid operational mode

*[A] Balch, T.; Arkin, R. C. (December 1998). "Behavior-based formation control for multirobot teams". **IEEE Transactions on Robotics and Automation**. **14** (6): 926–39. doi:10.1109/70.736776*A.

[B] Jadbabaie, J. Lin, and A. S. Morse, "Coordination of groups of mobile autonomous agents using nearest neighbor rules," ***IEEE Trans. on Automatic Control***, vol. 48, pp. 988–1001, June 2003.

Operational modes for the concerned systems

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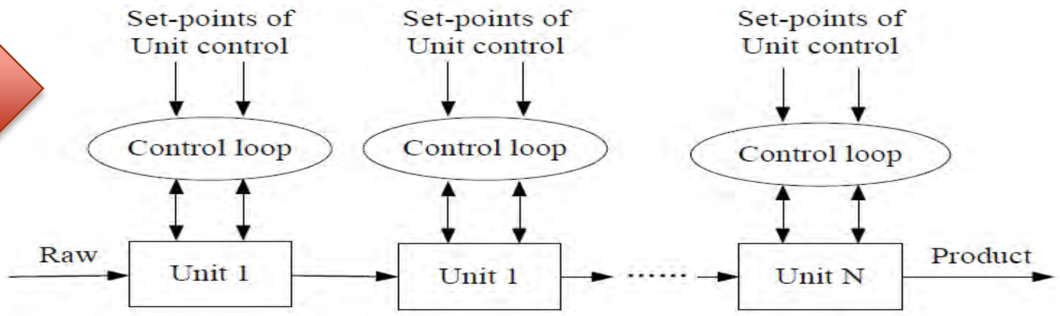
Simultaneously operated sub-systems

- ❑ Multi-agent systems where each sub-systems operates in a “parallel mode” Examples are multi-robot systems, trans-portation systems.

Sequentially operated systems

- ❑ Process industries, examples are mineral processing, steel-making, chemical plant and paper making.



Hybrid operational mode

Problem statement

Problem Statement:

If a sub-system has a fault, how can other healthy sub-systems reorganize themselves so that the whole system can still operate safely (FTC)?

This requires the following:

- ❑ Fault diagnosis of each sub-systems;
- ❑ Communication capabilities so that status of all the sub-systems can be shared in time;
- ❑ Collaborative fault tolerant control of all the healthy sub-systems

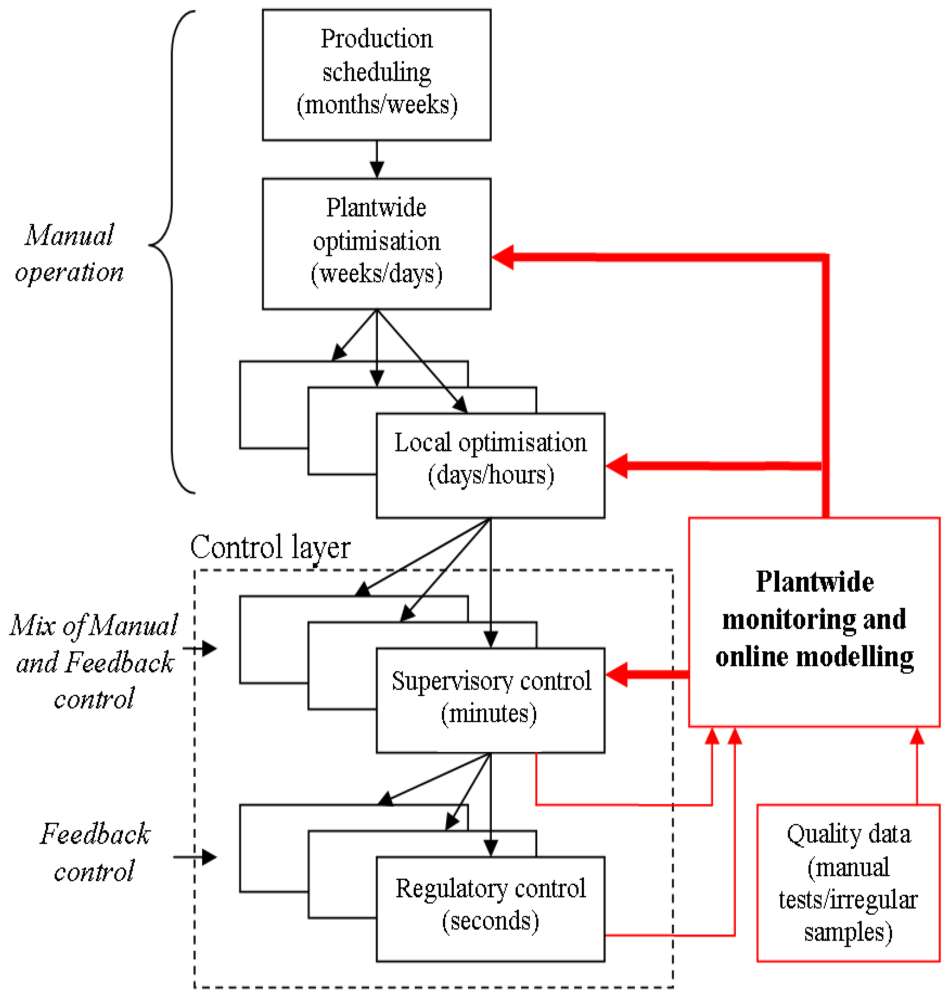


Figure 2

Can we solve this alternatively?

A first-insight solution would be:

- ❑ Right the whole system dynamics in a “big” state-space model
- ❑ Use the existing fault diagnosis and tolerant control to design a centralized control strategy

Difficulties:

- ❑ In-time solution is difficult to achieve, heavy computational load
- ❑ Only part of healthy sub-systems need to be made tolerant
- ❑ Model representation is difficult to perform

Collaborative tolerant control – a sub-systems approach

- In 2005, a novel concept has been reported in [1] on the collaborative fault tolerant control. The key idea is to consider complex systems composed of a number of sub-systems,
- **If a fault takes place in a sub-system then other healthy system can pro-actively tune the control systems in a fault tolerant way so that the whole complex system can still function safely.**
- This novel concept has also been applied to serially connected stochastic distribution systems, where two sub-systems have been considered where the output of the first sub-system provides a boundary condition to the second sub-system.
- It has been demonstrated that the effect of the fault onto the operation of the closed loop system can be significantly reduced – leading to a safer operation of the concerned system.

[1] L. Yao and H. Wang, A fault tolerant control scheme for collaborative two sub-systems, Proceedings of the 13th Mediterranean Conference on Control and Automation, Limassol, Cyprus, June, 27 – 29, 2005.

Case I (2003 – 2005):
A robot arm example – a two sub-systems case

Our Fault tolerant control idea is as follows

- One of two subsystems is subjected to faults
- The other healthy subsystem accommodates the control performance degradation
- The influences caused by the faults in one subsystem are compensated

Operational objective:
Keep the glass and bottle at the required level

Figure 3

System model representation

- **Sub-system 1**

$$\dot{x}_1 = A_1 x_1 + B_1 u_1 + Ef(t)$$
$$y_1 = C_1 x_1 + D_1 u_1$$

f
Process fault

- **Sub-system 2**

$$\dot{x}_2 = A_2 x_2 + B_2 \theta(t) u_2$$
$$y_1 = C_2 x_2 + D_2 u_2$$

θ
Actuator fault

- **Control objective of sub-systems 1 and 2**

$$G(y_1, y_2) = 0$$

Keep the glass and bottle at the required level

Fault diagnosis algorithm for sub-systems

Diagnosis algorithm of process fault	Diagnosis algorithm of actuator fault
$\dot{\hat{x}}_1 = A_1\hat{x}_1 + B_1u_1 + E\hat{f}(t) + L_1\varepsilon_1$ $\varepsilon_1 = y_1 - C_1\hat{x}_1 - D_1u_1$ The following conditions are satisfied: $(A_1 - L_1C_1)^T P_1 + P_1(A_1 - L_1C_1) = -Q_1$ $E^T P_1 = C_1$ The adaptive diagnosis algorithm: $\dot{\hat{f}} = -H\varepsilon_1 \quad (t > t_f)$	$\dot{\hat{x}}_2 = A_2\hat{x}_2 + B_2\hat{\theta}u_2 + L_2\varepsilon_2$ $\varepsilon_2 = C_2\hat{x}_2 + D_2u_2 - y_2$ The following conditions are satisfied: $(A_2 - L_2C_2)^T P_2 + P_2(A_2 - L_2C_2) = -Q_2$ $C_2 = B_2^T P_2$ The adaptive diagnosis algorithm: $\dot{\hat{\theta}} = -M\varepsilon_2u_2^T$

Simultaneous collaborative fault tolerant control

The realization of the desired output objective of each subsystem

- Tracking the given reference signal when the system is healthy

$$\left.\begin{aligned} & e_i(t) = y_i(t) - y_{iref}(t),\ (i=1,2) \\ & u_{iN}(t) = -k_i(t)e_i(t) \\ & \dot{k}_i = d_i[e_i(t)]\|e_i(t)\|, k_i(0) = k_{i0} \\ & d_{\lambda_i}(e_i(t)) := \begin{cases} \|e_i\| - \lambda, & if\ \|e_i\| \geq \lambda \\ 0\ , & if\ \|e_i\| < \lambda \end{cases} \end{aligned}\right\} \longleftarrow \lambda - tracking$$

Simultaneous collaborative fault tolerant control

- The re-configured controller

$$
\begin{aligned}
u_2' &= u_{2N}' + \Delta u_2 + \Delta G \\
&= -k_2(y_2 - y_{2ref}) + \Delta u_2 + G(y_1 + \Delta y_1, y_2 + \Delta y_2) - G(y_1, y_2)
\end{aligned}
$$

- The key problem : Ensure that $G(y_1, y_2) = 0$

$$\Delta u_2 = -\mathrm{K}\hat{f}$$

$$\|K\| < \frac{\alpha - 2T\|B_2\|\|R\|}{M\|B_2\|\|R\|}$$

- Nonlinear compensation scheme can also be used

$$\Delta u_2 = g(\hat{f}) \qquad \|g\| < \frac{\alpha - 2T\|B_2\|\|R\|}{\|B_2\|\|R\|}$$

Simulations results

Collaborative two subsystems

$$\dot{x}_1 = \begin{pmatrix} -2 & 0.7 & 0 \\ 0.4 & -1 & 0 \\ 0 & 0.2 & -3 \end{pmatrix} x_1 + \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix} u_1 + \begin{pmatrix} -1.5172 \\ 0.8621 \\ 0.1207 \end{pmatrix} f$$

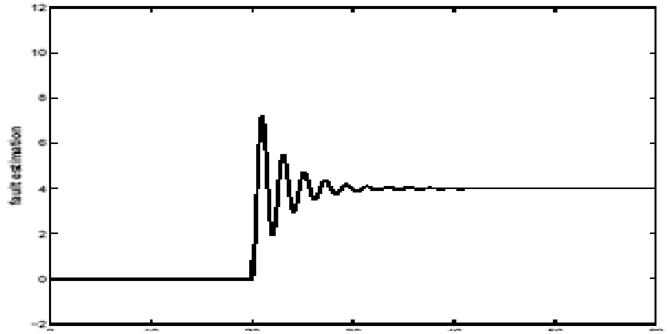
$$y_1 = \begin{pmatrix} -1 & 2 & 1 \end{pmatrix} x_1$$

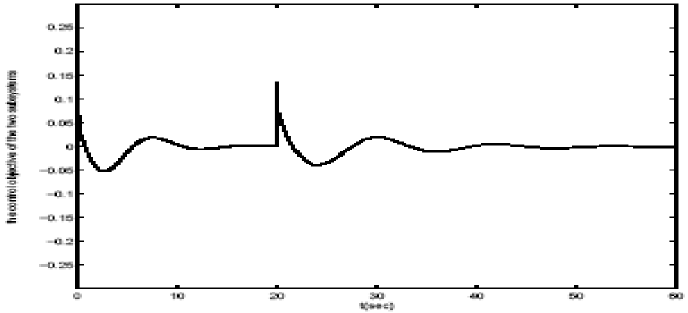
$$\dot{x}_2 = \begin{pmatrix} -9 & 10 & 0 \\ 1 & -1 & 1 \\ 0 & -15 & 0 \end{pmatrix} x_2 + \begin{pmatrix} 0.1565 \\ 0.0449 \\ -0.0204 \end{pmatrix} u_2$$

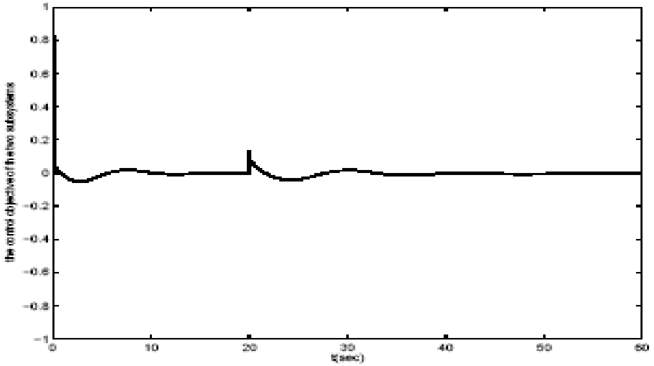
$$y_2 = \begin{pmatrix} 1 & 1 & -1 \end{pmatrix} x_2$$

$$y_1 - 2y_2 = 0$$

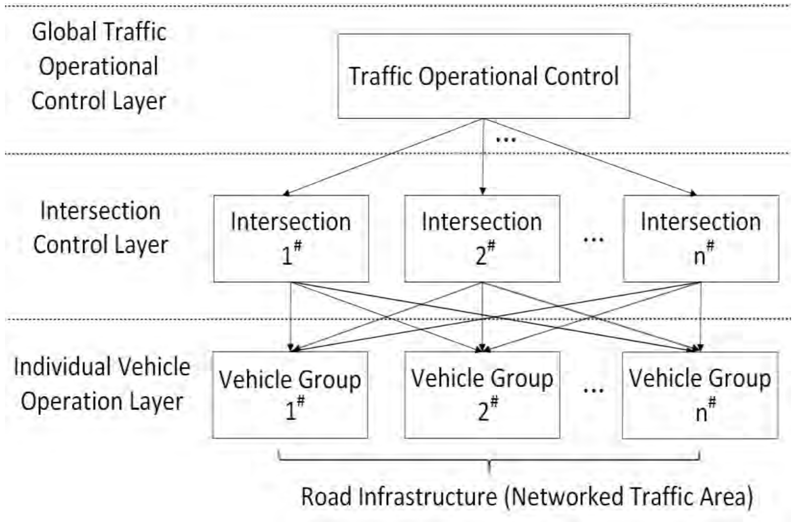
$$f = \begin{cases} 0, & t < 20 \\ 4, & t \geq 20 \end{cases}$$







Simultaneously operated system: transportation systems as an example



- ❑ Information flow
- ❑ Mass flow
- ❑ Energy flow [1]

Available data:

- ❑ Data from fixed sensors such as probe detector, intersection camera images
- ❑ Moving data such as the data provided by individual vehicles

Intersection operational control – non-signalized approach with 100% CAVs

Using the V2V communication capabilities, signal infrastructure can be omitted as the CAVs can manage themselves in passing through intersection

[2] H. Wang, H. M. Aziz and S. Young, Control of networked traffic flows distribution – a stochastic distribution system perspective, the 1st International Conference on Internet of Things and Machine Learning, Liverpool, October, 2017.

Case II: Connected and Autonomous Vehicles (CAVs) through non-signalized intersection for traffic flows

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- With 100% CAVs, communications of V2V allow vehicles to pass through smoothly with safety constraints
- Modelling and control for interactive CAVs movement is required
- Collaborative fault tolerant control is required if one CAV has a fault, where other CAVs should “fly” in a fault tolerant way.

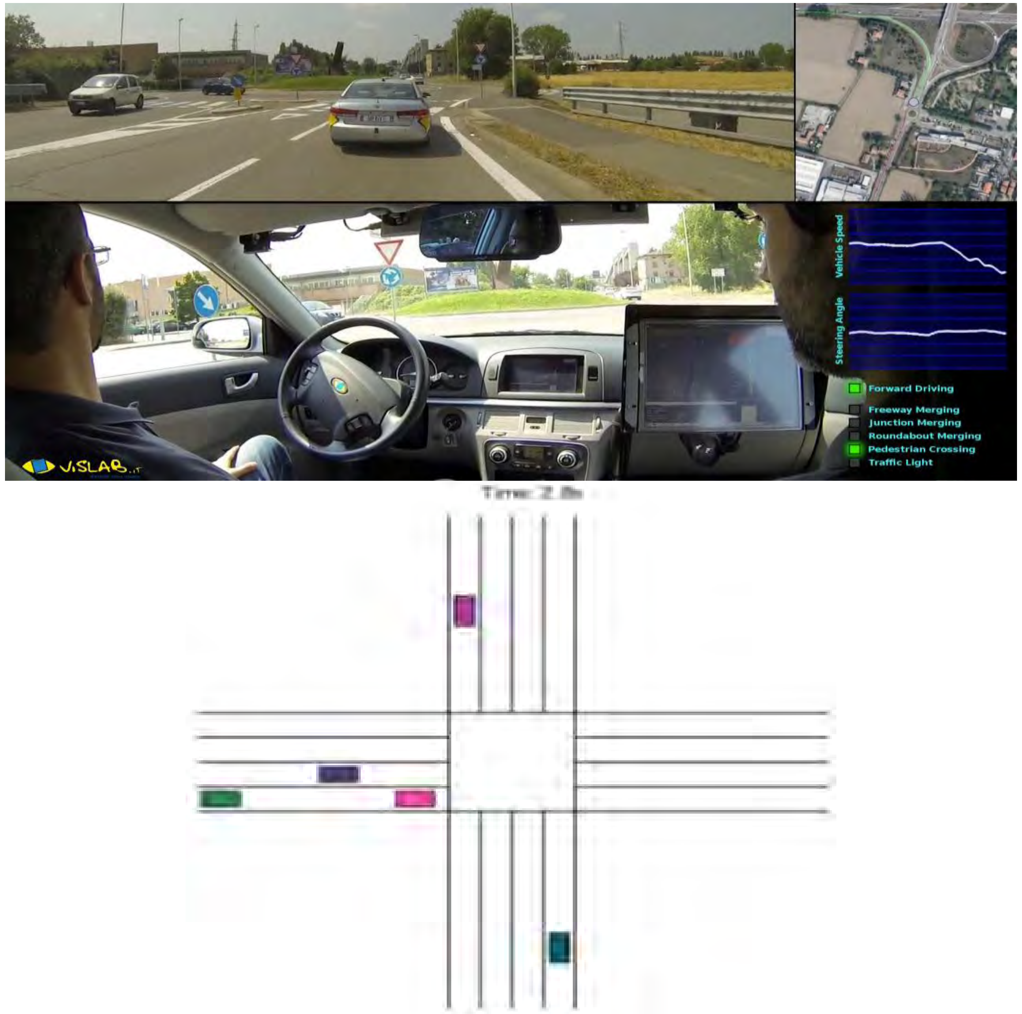


Figure 4 :Video from ppt of the paper by C Liu et al at ACC2018 titled *Improving Efficiency of Autonomous Vehicles by V2V Communication*

Modelling at vehicle level taking into V2V communications

Modelling: Model the vehicle dynamics taking into account of V2V information in terms of speed and possition

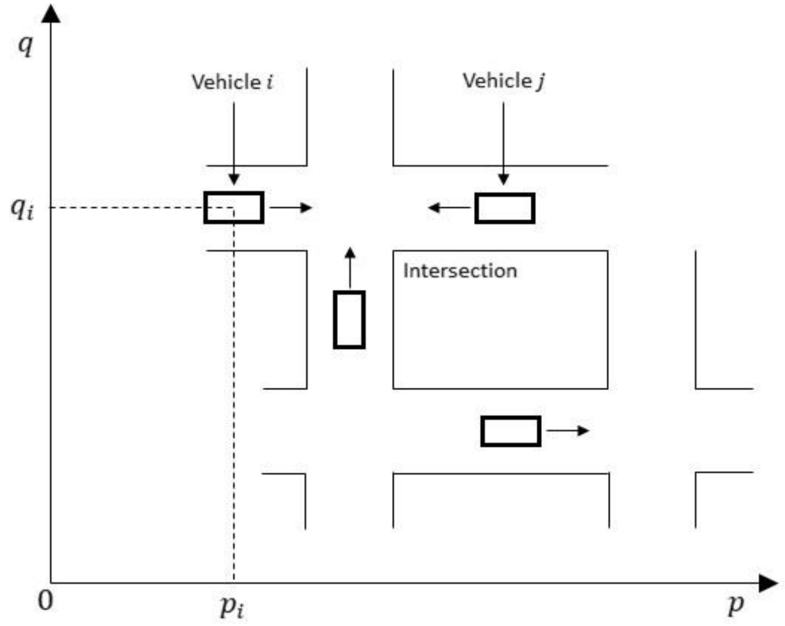


Figure 5. Networked intersections

- We consider an N number of CAVs approaching an intersection as shown in Figure 4,
- Assume that the dynamics of the ith CAV is a self-closed loop system whose position and speed is denoted in a 2D plane shown in Figure 4 as

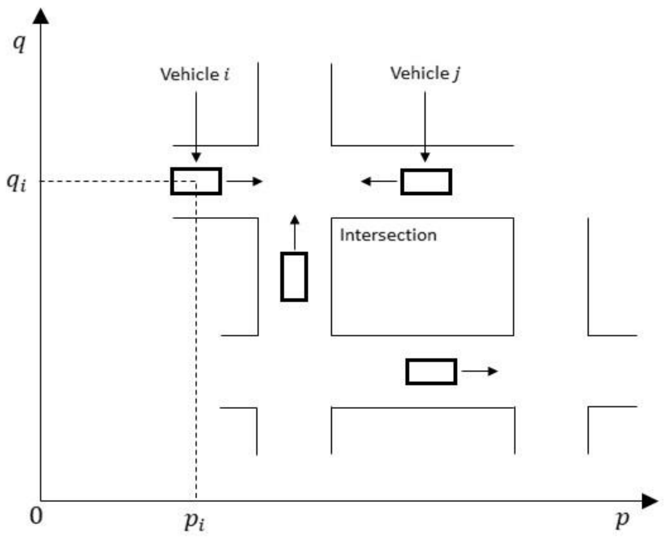
$$x_i = \begin{bmatrix} p_i \\ q_i \end{bmatrix}; \frac{dx_i}{dt} = \dot{x}_i = \begin{bmatrix} \frac{dp_i}{dt} \\ \frac{dq_i}{dt} \end{bmatrix}; (i = 1, 2, \dots, N)$$

where p_i stands for the longitude movement and q_i represents the latitude movement (i.e., lane changes) of the ith CAV in Figure 4.

Modelling at vehicle level taking into V2V communications

The position and speed are the two group of state variables defined as follows,

$$X_i = \begin{bmatrix} x_i \\ \dot{x}_i \end{bmatrix} \in R^4; \quad (i = 1, 2, \dots, N) \tag{1}$$



In this regard, the dynamics of the ith CAV (the ith agent or sub-system) can be expressed in the following form

$$\dot{X}_i = A_i X_i + B_i r_i + \sum_{i \neq j}^{N} C_{ij} X_j + E_i f_i \tag{2}$$

- ❑ $\{A_i, B_i\}$ are the assumed known parameter matrices that represent the own dynamics of the concerned CAV of appropriate dimensions,
- ❑ C_{ij} are the communication coefficient matrices. If there is no communications between the ith and the jth CAV, then $C_{ij} = 0$.
- ❑ f_i is the fault of the ith CAV;
- ❑ r_i is the set-point of the position trajectory of the ith CAV.

Modelling at vehicle level taking into V2V communications

If we define the whole state vector as

$$x^T = [X_1^T \quad X_2^T \cdots X_{N-1}^T \quad X_N^T] \in R^{1\times 4N}$$

Then

$$\dot{x} = Ax + Br + Ef$$

with the following output equation only for the position of each CAVs.

$$y = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix} = Fx; \quad F = diag(\aleph, \dots, \aleph); \aleph = \begin{bmatrix} 1 & 0 \end{bmatrix} A = \begin{bmatrix} A_1 & C_{12} & \cdots & C_{1N} \\ C_{21} & A_2 & \cdots & C_{2N} \\ \vdots & \vdots & \vdots & \vdots \\ C_{N1} & C_{N2} & \cdots & A_N \end{bmatrix} \in R^{4N\times 4N};$$

$$B = diag(B_1, \dots, B_N) \in R^{4N\times N}$$

$$E = diag(E_1, E_2, \dots, E_N) \in R^{4N\times N}; f = \begin{bmatrix} f_1 \\ \vdots \\ f_N \end{bmatrix} \in R^{4N}; r = \begin{bmatrix} r_1 \\ \vdots \\ r_N \end{bmatrix} \in R^{4N}$$

Adaptive fault diagnosis algorithm at individual CAV level

For this purpose, the following adaptive diagnostic observer is constructed [3].

$$\dot{\hat{X}}_i = A_i\hat{X}_i + B_i r_i + \sum_{i\neq j}^{N} C_{ij}\hat{X}_j + E_i\hat{f}_i + L(x_i - \hat{x}_i)$$

where $\hat{X}_i$ is the estimate of X_i and $\hat{f}_i$ is the diagnosed (i.e., estimated) result of f_i, L is a gain matrix to be designed. Define the state estimate error and the fault estimation error as

$$e_i = \hat{X}_i - X_i$$
$$\tilde{f}_i = \hat{f}_i - f_i$$

Then the following diagnosis result can be obtained, *where the detailed formulation, including the selection of the gain matrix L, will be given in the final paper using Lyapunov stability theory*.

$$\frac{d\hat{f}_i}{dt} = -(\hat{x}_i - x_i)$$

where $\hat{x}_i$ is the estimate of the unknown x_i due to a fault.

Collaborative tolerant control – a multi-objective optimization

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When a fault occurs the purpose of collaborative fault tolerant control design is to select the set-points to each CAVs in the group so that the following multi-objective constrained optimization is achieved.

$$\max_{r} \dot{x}_i; \quad (i = 1, 2, \dots, N)$$

s.t.

$$\|x_i - x_j\| > \delta; \quad i \neq j$$ Safety constraints

$$\|\dot{x}_i\| < M; (i = 1, 2, \dots, N)$$ Speed constraints

The problem can be transferred into making the speed of each vehicle to be as close as possible to its maximum allowable speed M with a time interval average.

$$\mathrm{Mim}_{r} \frac{1}{T_2 - T_1} \int_{T_1}^{T_2} (M - \dot{x}_i)^2 \, dt \qquad i = 1, 2, \dots, N$$

Collaborative tolerant control – a multi-objective optimization

Select the set-points to each vehicle so that the following optimization problem is solved

$$\min_r J = \min_r \int_{T_1}^{T_2} [(\tilde{M} - Hv)^T (\tilde{M} - Hv) + \rho \dot{r}^2] dt$$

Subjected to constraints (6) and (10), where $\rho > 0$ is a pre-specified weighting coefficient.

The second term in the index is the penalty onto the rate of changes of the set-points so as to minimize unnecessary energy consumption.

Subjected ALSO to the safety constraints

Collaborative tolerant control – set-point tuning for CAVs

Assuming that the i_*th CAV has developed a fault, then the collaborative fault tolerant control for other healthy CAVs would be to tune their set-point

$$r_{j\neq i_*} = r^*_{j\neq i_*} + \Delta r_{j\neq i_*}$$

where the incremental change of set-point represented as $\Delta r_{j\neq i_*}$ is given by [4]

$$\Delta r_{j\neq i_*} = \sum_{j\neq i_*} \theta_j X_j$$

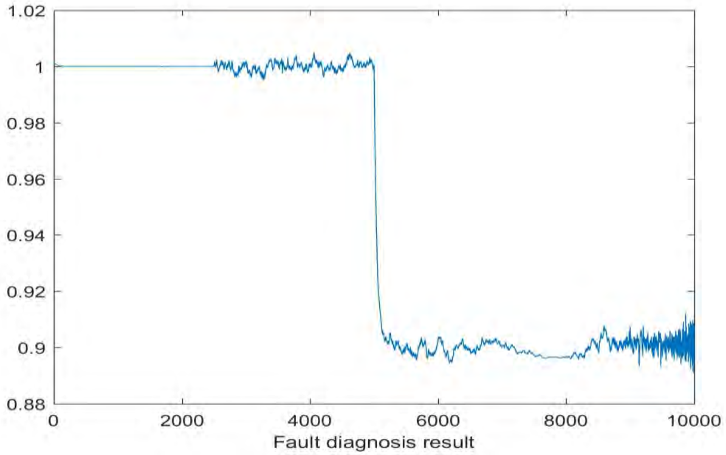
where

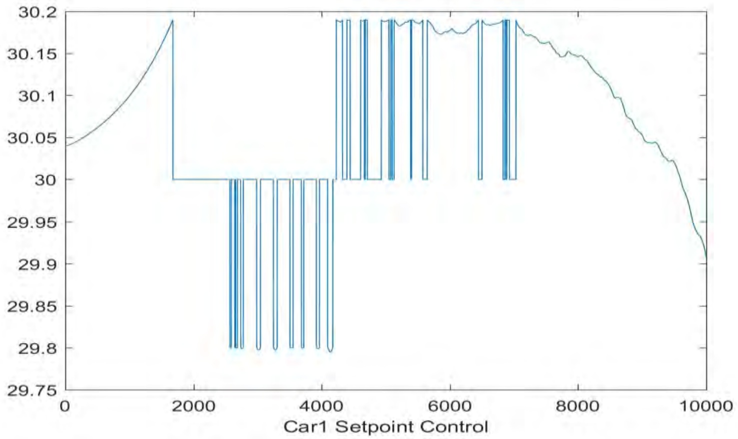
θ_j is an adaptive feedback gain matrices linked with fault diagnosis via the communication to the jth CAV.

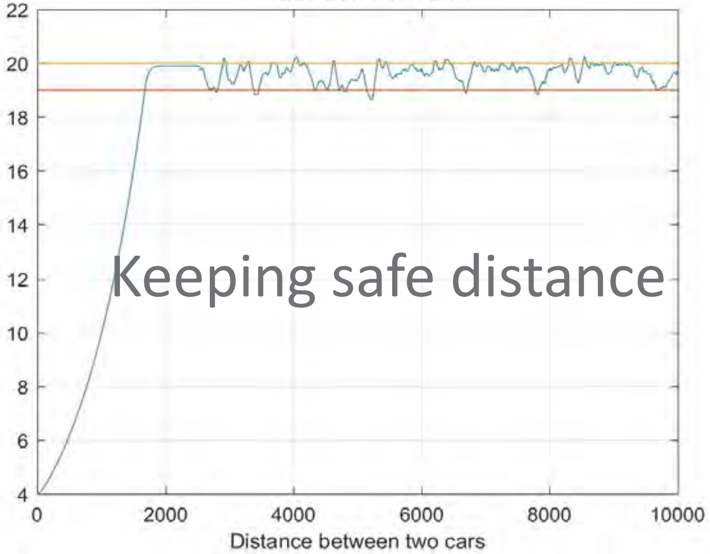
Collaborative tolerant control – set-point tuning for CAVs

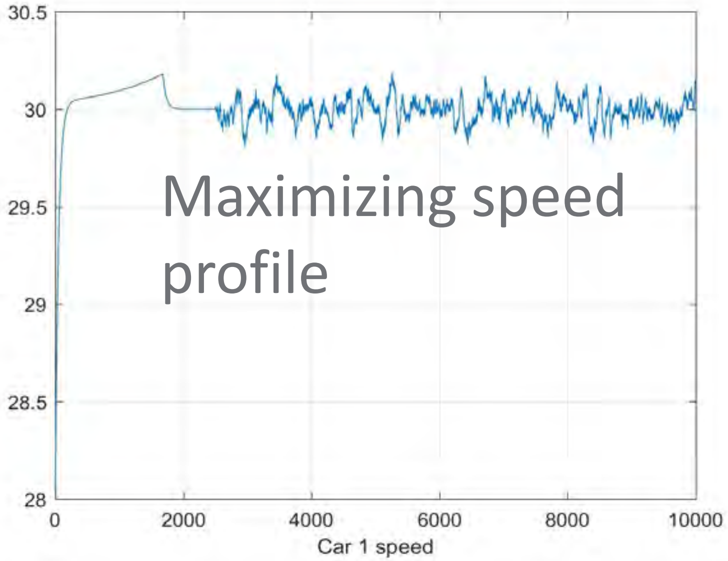
Fault diagnosis

Collaborative Fault tolerant control









Case III: Collaborative tolerant control – floatation process in mineral processing as a sequential systems

Flotation process is a typical phase in mineral processing:

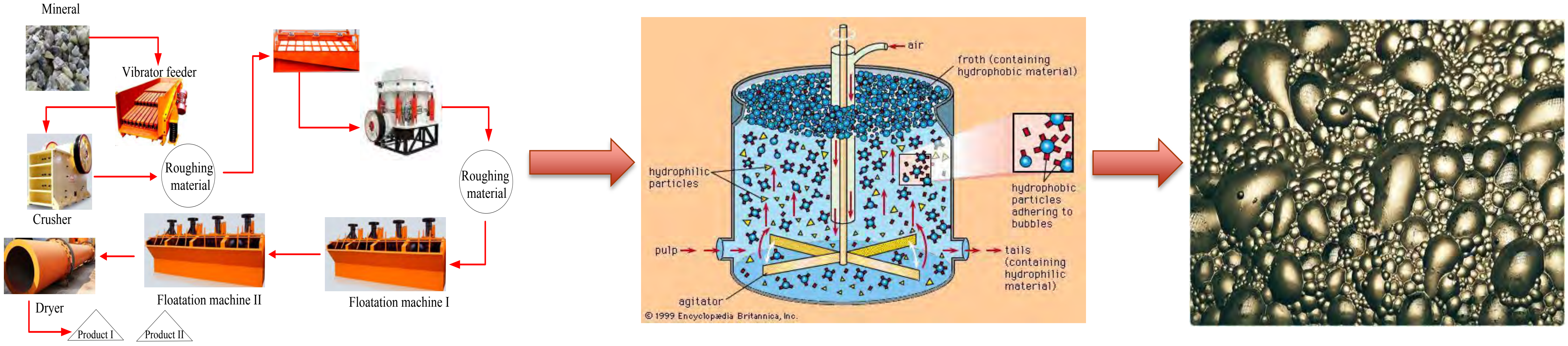


Figure 6. Process flow diagram of mineral flotation

- ❑ A series of flotation tanks are connected and bubble distribution size and color of each tank indicate how well the process operates
- ❑ It is seriesly connected stochastic distribution system where each tank provide the boundary conditions for the follow-up tanks
- ❑ Chemical additives are used at each stage

Collaborative tolerant control – floatation process in mineral processing

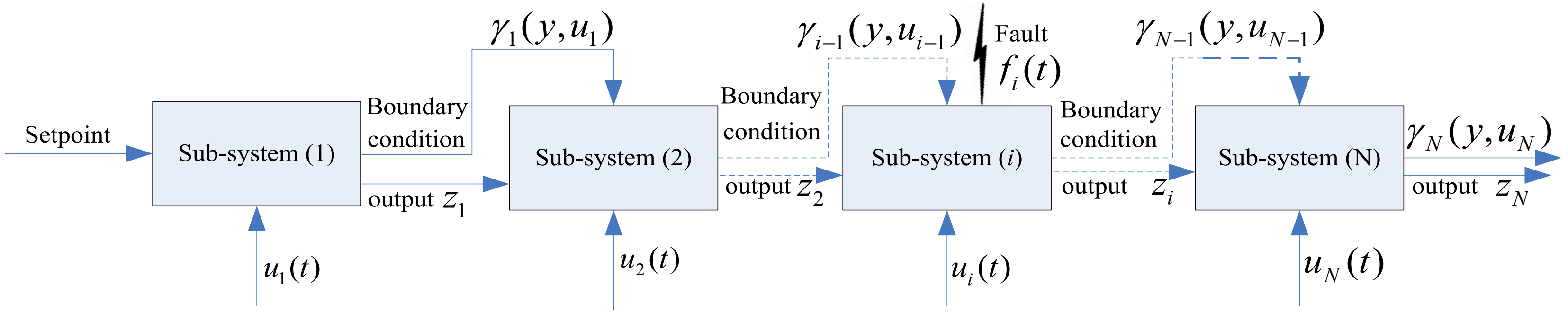
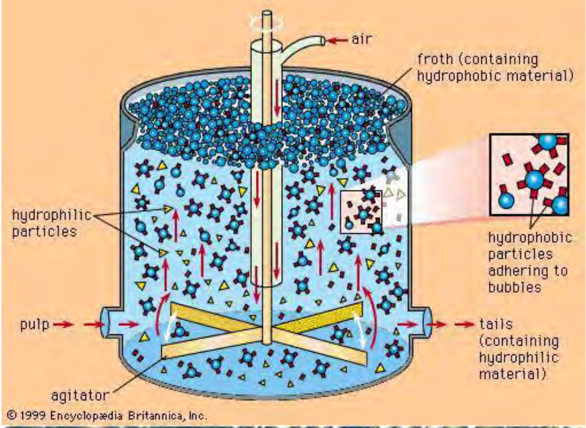


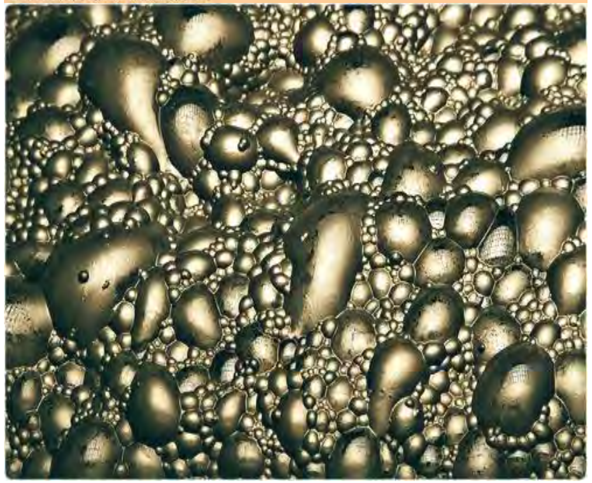
Figure 7. The structure of interconnected SDC system

Tasks.

1. Each subsystem is described as an output SDC system, i.e., the whole output is an output PDF.
2. Each subsystem except the first one is effected by the output PDF of the previous subsystem as a boundary conditon.
3. The fault tolerant control is realized by redesigning the setpoint of the follow-up sub-system.

Stochastic distribution model for each units





Input u

Flotation Unit (Stochastic System)

Bubble Size probability density function

$$\gamma(y,u)$$

Random inputs

Figure 8. Stochastic distribution systems – output probability density function controls

Stochastic distribution model for each units

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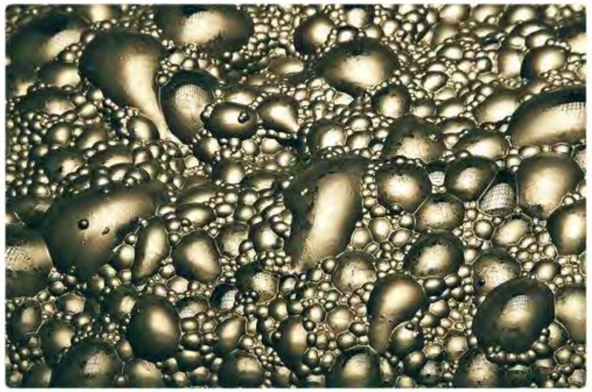
Based on the above industrial process and the motivations, the sub-system (flotation tanks) can be modelled as:



$$\dot{V}_i(t) = A_i(t)V_i(t) + A_{d_i}(t)V_i(t-d) + B_i(t)u_i(t) + J_i f_i(t)$$
$$\sqrt{\gamma_i(y, u_i)} = C(y)V_i(t) + h(V_i(t))b_n(y) + \omega_i(y, u_i)$$

where

- $u_i(t)$ is the chemical additives
- $\gamma_i(y, u_i)$ is the bulb size probability density function (PDF)

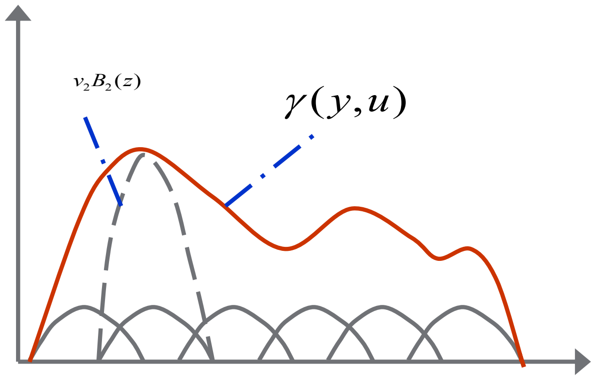


Figure 9. B-spline PDF modelling

Purpose:

Control chemical additives so that the bulb size PDFs are made to follow their target distribution shape.

Fault detection and diagnosis for each units

- An observer based fault estimation method is needed .

- The residual consists of the error of the subsystem itself and the error of the neighboring subsystem – leveraging communication capabilities

- The fault estimation parameters can be solved as stated in Theorem 1 by LMI technique.

Fault detection using output probability density function

- Detection Filter

$$\begin{cases} \dot{\hat{x}}(t) = A\hat{x}(t) + Gg(\hat{x}(t)) + Hu(t) + L\varepsilon(t) \\ \varepsilon(t) = \int_a^b \sigma(z)\left(\sqrt{\gamma(z,u(t),F)} - \sqrt{\hat{\gamma}(z,u)}\right) dz \\ \sqrt{\hat{\gamma}(z,u)} = B(z)E\hat{x}(t) + h(E\hat{x}(t))b_n(z) \end{cases} \quad (14)$$

- Objective for fault detection:

Find L such that error system is stable in the presence of F

- Estimation error system

$$\begin{aligned} \dot{e}(t) = \quad & (A - L\Gamma_1)e(t) + [Gg(x(t)) - Gg(\hat{x}(t))] \\ & - L\Gamma_2[h(Ex(t)) - h(E\hat{x}(t))] + F - L\Delta(t) \end{aligned} \quad (15)$$

Fault detection and diagnosis for each units

Diagnosis filter

$$\begin{cases} \dot{\hat{x}}(t) = A\hat{x}(t) + Gg(\hat{x}(t)) + Hu(t) + L\varepsilon(t) + \hat{F}(t) \\ \dot{\hat{F}}(t) = -\Lambda_1 \hat{F}(t) + \Lambda_2 \varepsilon(t) \\ \varepsilon(t) = \int_a^b \sigma(z) \left(\sqrt{\gamma(z, u(t), F)} - \sqrt{\hat{\gamma}(z, u)} \right) dz \\ \sqrt{\hat{\gamma}(z, u)} = B(z)E\hat{x}(t) + h(E\hat{x}(t))b_n(z) \end{cases} \quad (25)$$

where $\hat{F}(t)$ is the estimation of *F:* Λ_i (*i* = 1,2; Λ_i > 0) are learning operators to be designed

Error system

$$\begin{aligned} \dot{e}(t) = \quad & (A - L\Gamma_1)e(t) + [Gg(x(t)) - Gg(\hat{x}(t))] \\ & -L\Gamma_2[h(Ex(t)) - h(E\hat{x}(t))] + \tilde{F}(t) - L\Delta(t) \end{aligned} \quad (26)$$

Fault detection and diagnosis for each units

Theorem 1： *If there exist positive definite matrices* P, Q *and matrices* $\bar{R}_i$ *satisfying the following linear matrix inequality (LMI)* $\Pi < 0$, *in which*

$$\Pi = \begin{bmatrix} \bar{\Pi} & I_N \otimes PA_{d_i} & I_N \otimes PJ_i & X_1^T & X_2^T & X_3^T & X_4 \\ * & -I_N \otimes Q & 0 & 0 & 0 & 0 & X_5 \\ * & * & \bar{Y} & 0 & 0 & 0 & 0 \\ * & * & * & -\varepsilon_1 I & 0 & 0 & 0 \\ * & * & * & * & -\varepsilon_2 I & 0 & 0 \\ * & * & * & * & * & -\varepsilon_3 I & 0 \\ * & * & * & * & * & * & -\alpha I \end{bmatrix}$$

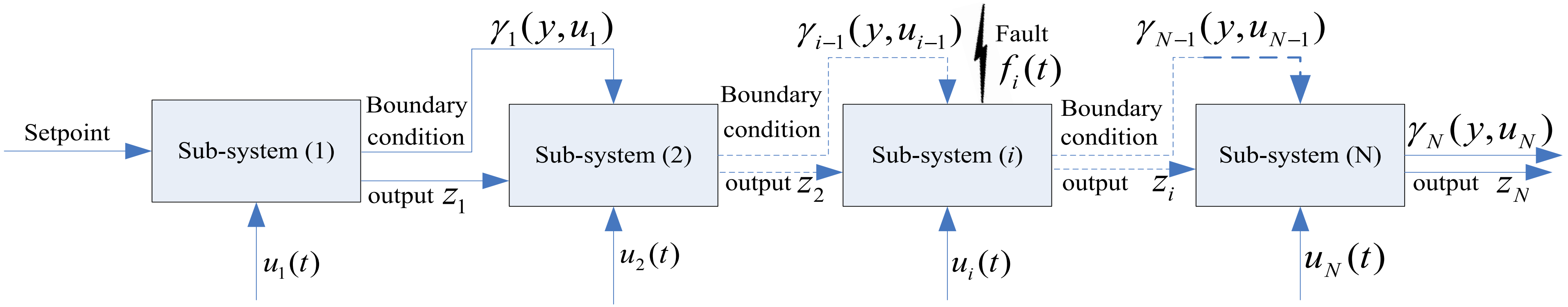
and $\bar{\Pi} = I_N \otimes \left(PA_i + A_i^T P\right) - (L+G) \otimes \left(\bar{R}\Sigma_1 + \Sigma_1^T \bar{R}^T\right) + (\varepsilon_1 + \varepsilon_4) I_N \otimes U_i + I_N \otimes Q + \alpha (I_N \otimes H_i)^T (I_N \otimes H_i) + \beta I$

$\bar{R}_i = PK_{s_i}$, $X_1^T = (L+G) \otimes PK_{s_i}\Sigma_2$, $X_2^T = (L+G) \otimes PK_{s_i}$, $X_3^T = (L+G) \otimes \Gamma_{i2}$, $X_4 = (L+G) \otimes P\bar{G}_{i1}$, $X_5 = (L+G) \otimes P\bar{G}_{i2}$,

$\bar{Y} = -2I_N \otimes \Gamma_{i1} + \frac{1}{\varepsilon_4} Y^T Y + \varepsilon_5 I$, $Y^T = (L+G) \otimes \Gamma_{i2}\Sigma_2$, *then the fault diagnosis algorithm (9) can realize the state estimation error* $e_v(t)$ *and the fault estimation error* $e_f(t)$ *uniformly and ultimately bounded. The observer gain* K_{s_i} *can be calculated by* $K_{s_i} = P^{-1}\bar{R}_i$.

Collaborative fault tolerant control algorithm

- A nominal controller for fault-free collaborative system is designed first and guarantee that the ouput PDF can track the given PDF well.
- The system set-point is tuned when faults occur in the collaborative system and keep the nominal controller unchanged.



Collaborative fault tolerant control algorithm

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The set-point is redesigned as:

$$\bar{V}_g = V_g + \Delta V_g \qquad \Delta V_g = -\sum_{i=1}^{N} \bar{K}_i \hat{f}_i(t)$$

The unknown parameters in the redesigned set-point can be solved by the following Theorem 2:

Theorem 2: *For the collaborative stochastic distribution dynamic system under controller (14), the given positive constants* $\eta, \kappa, \mu_1, \mu_2$ *and positive matrices* $P, S > 0$, *suppose that there exists matrices* R *and* $\bar{K}_i$ *such that the following LMI* $\Xi < 0$ *is solvable, then the collaborative stochastic distribution system is stable and the PDF tracking error is bounded with* $K = R^T Q^{-1}$, *in which*

$$\Xi = \begin{bmatrix} \Theta + \kappa H H^T + \eta I & A_d Q^T & 2M & P^T M \bar{K}_N & X_6 \\ * & -\hat{S} & 0 & 0 & Q\bar{G}_{N_2}^T \\ * & * & -\mu_1^2 I & 0 & 0 \\ * & * & * & -\mu_2^2 I & 0 \\ * & * & * & * & -\kappa I \end{bmatrix}$$

$\Theta = AQ^T + QA^T + \hat{S} + BR^T + RB^T$, $H^T = \begin{bmatrix} H_N^T & 0 & 0 & 0 \end{bmatrix}$, $Q = \left(P^T\right)^{-1}$ *and* $X_6 = Q\bar{G}_{N_1}^T + R\bar{G}_{N_3}^T$.

Experimental results

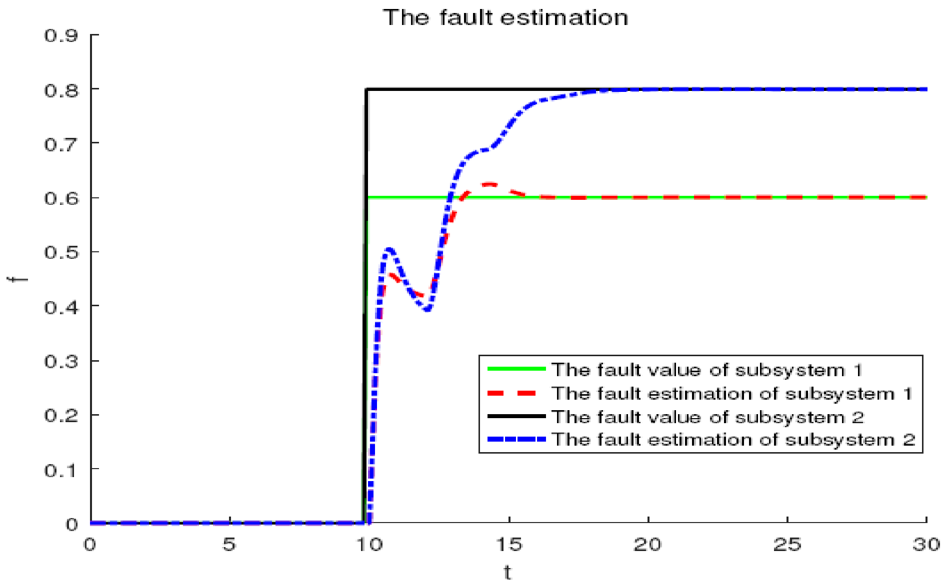


Fig. 3. TheThe fault estimation value of subsystems.

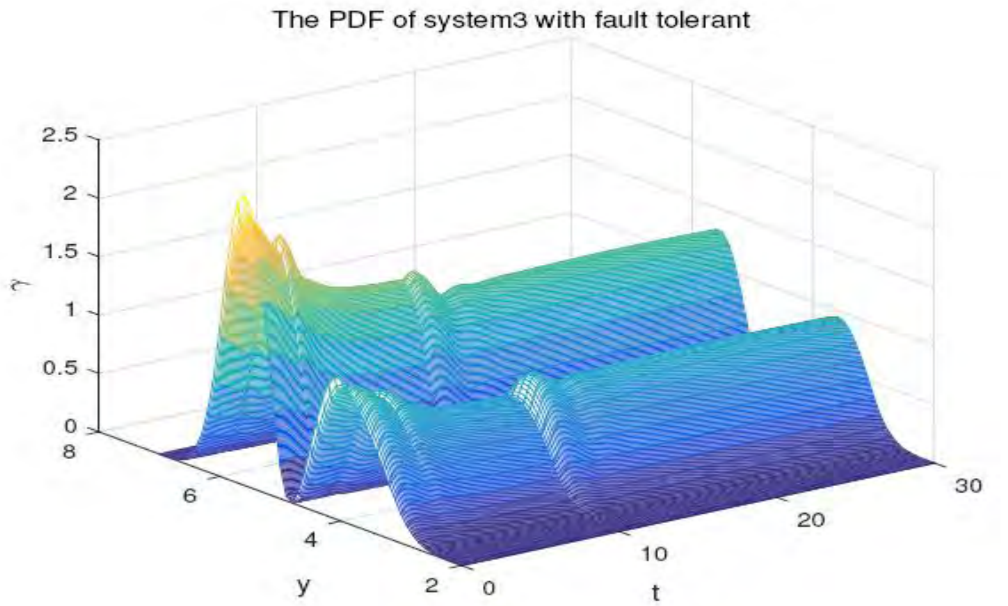


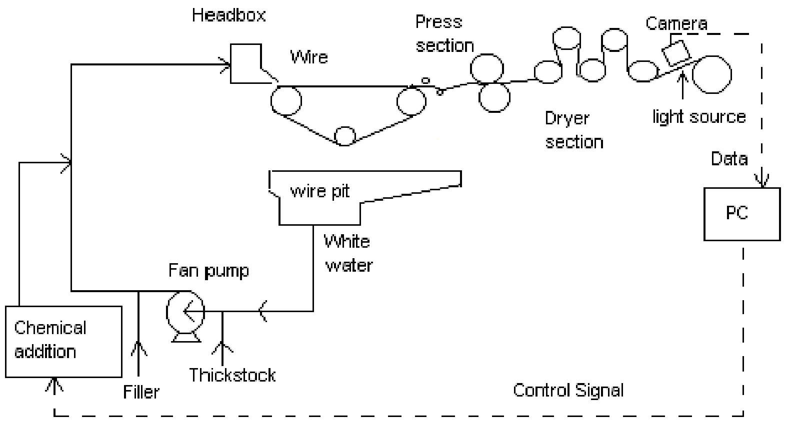
Fig. 4. The output PDFs of the whole control process when faults are constant.

[2] Yuwei Ren* , Yixian Fang , Aiping Wang , Huaxiang Zhang , Hong Wang , Collaborative Operational fault tolerant control for stochastic distribution control system, ***Automatica***, 2018, (Accepted)

[3] Y. Ren, A. Wang and H. Wang, Fault Diagnosis and Tolerant Control for Discrete Stochastic Distribution Collaborative Systems, ***IEEE Transactions on Systems, Man and Cybernetics***, Part. A, Vol. 45, No. 3, pp. 462 – 471, 2015.

Sequential systems: papermaking process control as an example

- Papermaking industrial system has a number of production units connected in series



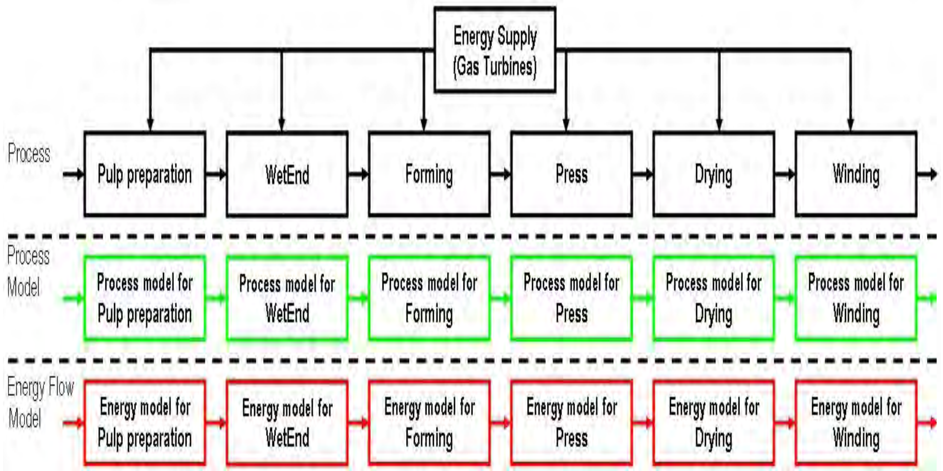


Figure 2. Establishment of sectional process and energy flow models

Figure 11. A papermaking systems

- If one unit has a fault and cannot deliver the intermeddle material with required properties, the subsequent production units need to work collaboratively in a fault tolerant way so as to ensure the product quality for the whole production line

Case IV: Collaborative Fault Tolerant Control for Papermaking

The following procedures are used for the energy saving in papermaking – a project run between Univ of Manchester and Cambridge University + two paper mills in UK (2009 – 2011)

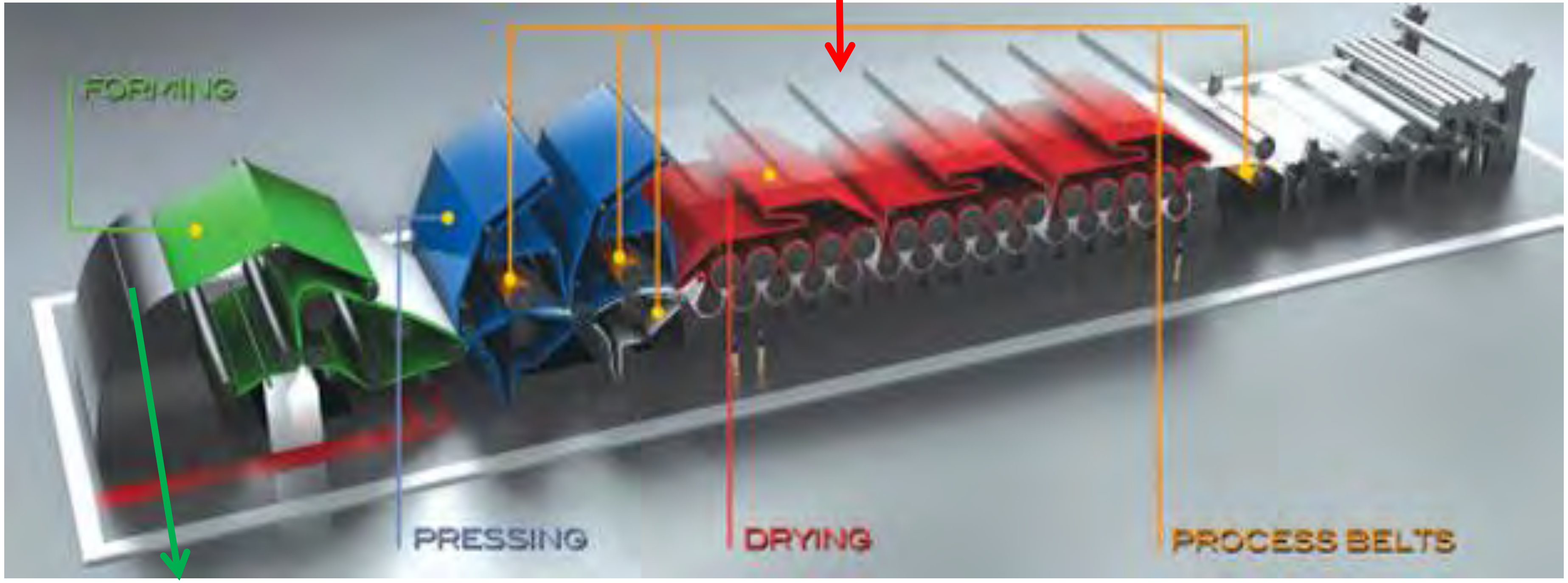
- Energy Auditing
- Data analysis through exploration: **DataExplorer** tool
- Opportunities for energy reduction via collaborative fault tolerant control

Idea:

If there is a fault in drying section so that the required water cannot be removed, can we apply more vacuum power to remove the water from the forming section?

Case IV: Collaborative Fault Tolerant Control for Papermaking

Steam



Manipulate vacuum ⟶ Improve drainage ⟶ Less steam requirement ⟶ fault tolerant effect

Case IV: Collaborative fault tolerant control for papermaking

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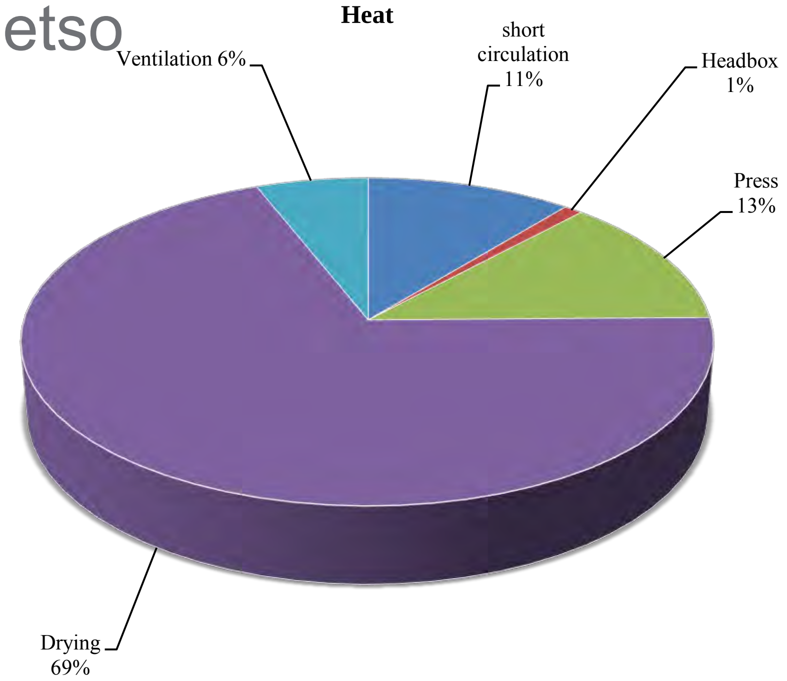
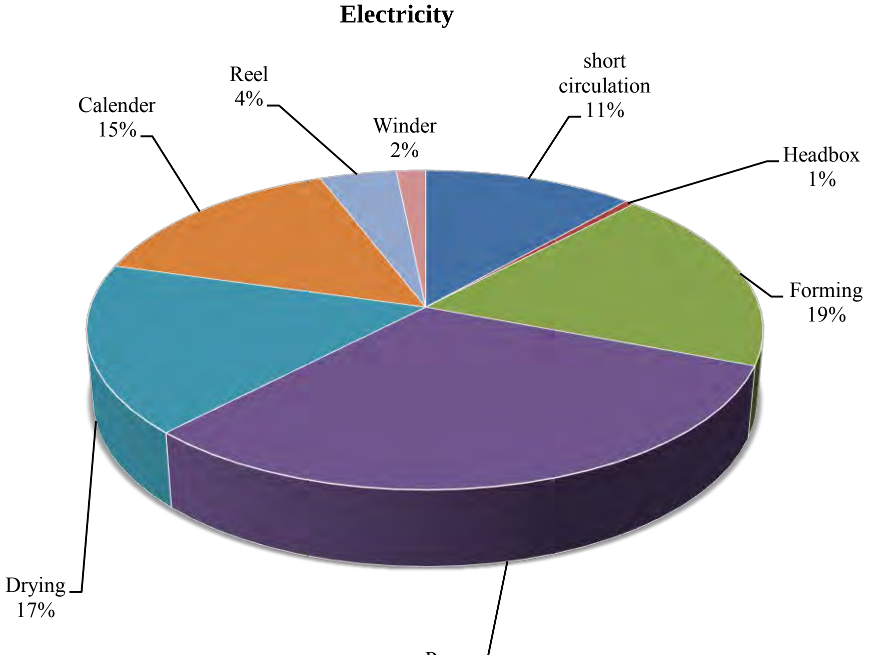
Auditing: In a typical mill, most of the heat energy is consumed by Drying Section which contributes to < 2% of water removal from sheet, but has significant effect on quality.

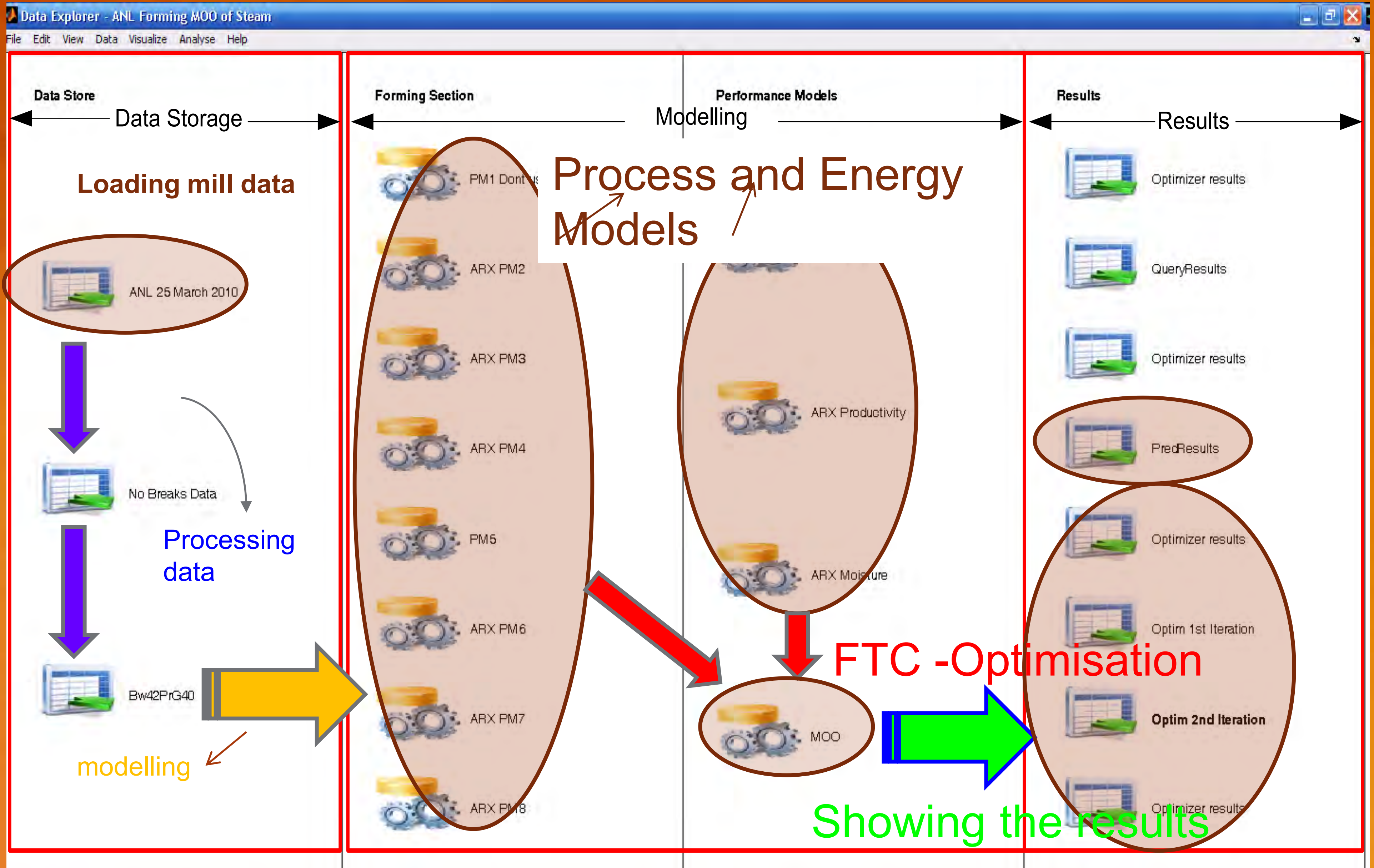
Fault in drying section can also be corrected in form section

Source: Metso





Dataexplorer for fault diagnosis in drying section



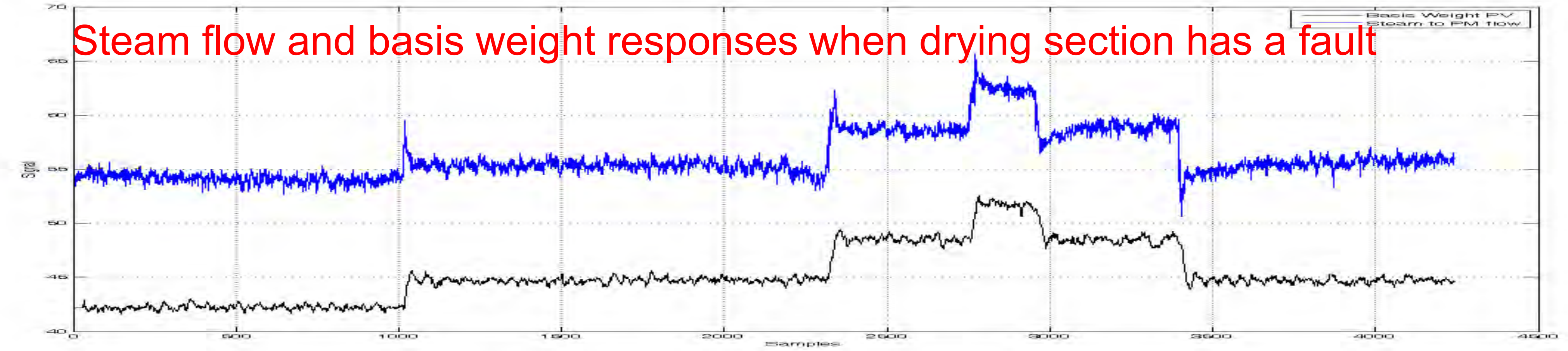
Case IV: Collaborative fault tolerant control for papermaking

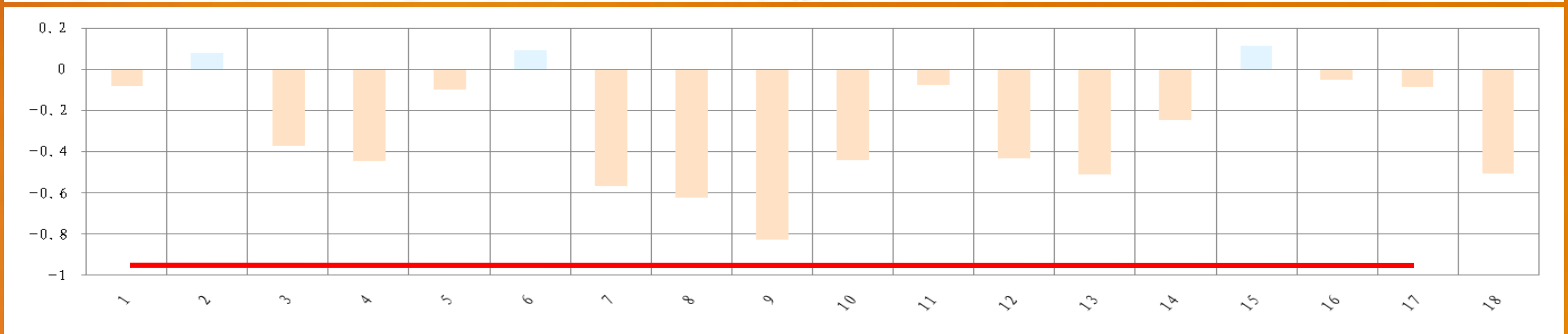
Main focus

- Considering the steam flow to the paper machine as an index for energy consumption, linear regression test is performed on data.
- Reverse fault tolerant control: **fault in drying section can lead to high energy usage which can be repaired by the forming and press sections**.
- Therefore, it might be worthwhile to investigate energy variations caused by the fault in drying section, there are opportunities for energy savings in these sections by collaborative fault diagnosis and tolerant control reversely.

[4] Puya Afshar, Martin Brown, Paul Austin, Jan Maciejowski, Hong Wang, Timofei Breikin, "Sequential modelling approach for thermal energy reduction in papermaking", regular paper, ***The Journal of Applied Energy***, Vol. 89, No. 1, January 2012, pp. 97-105

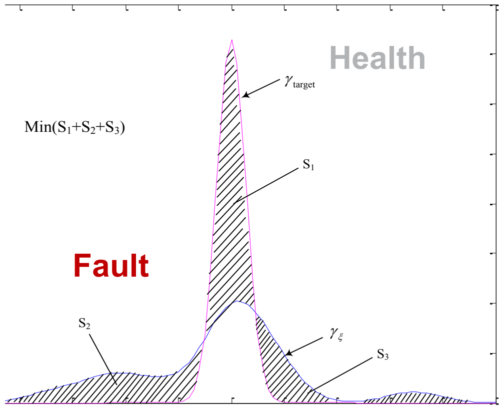
Important production features





Moisture set-point fault and dying section actuator faults:
Different grades have been over/less dried by an average of 0.31%

Case IV: Collaborative Fault Tolerant Control for Papermaking

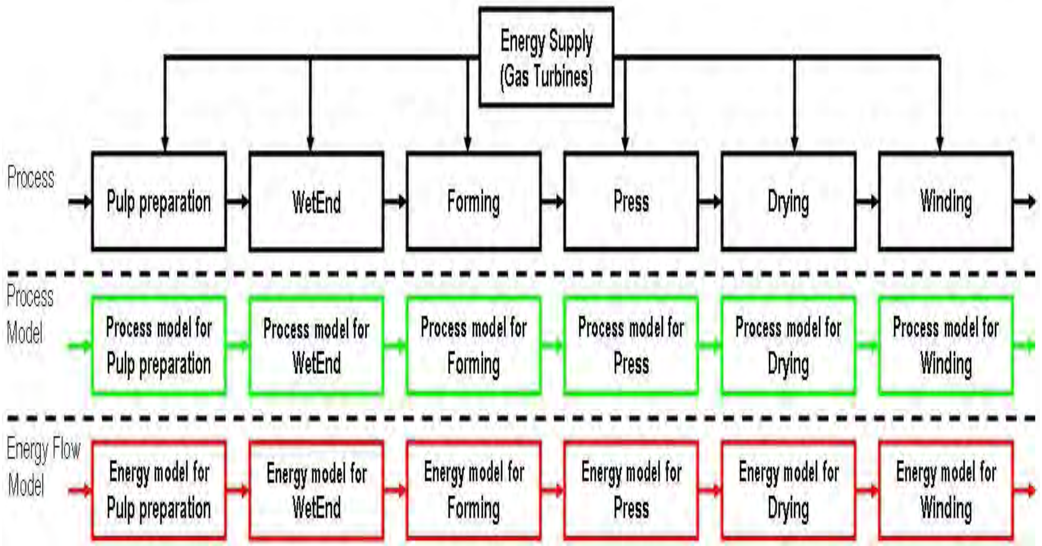


$$X_n \oplus U_n[t_n, t_{n+1}] \oplus F_n \Rightarrow X_{n+1}, (n = 1,2,\dots K)$$

$$\gamma_{j+1}(z, U_k^{j+1}) \sim \{\gamma_j(z, U_k^j), \dots, \gamma_1(z, U_k^1)\}$$

Proposed methods:

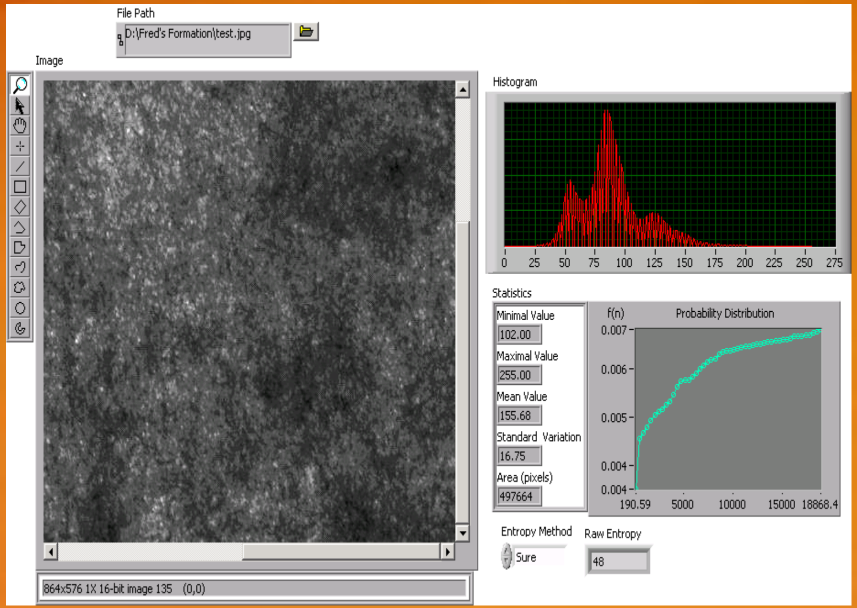
1) Use of variation transformation,
2) Entropy transformation
3) Probability density function of quality data

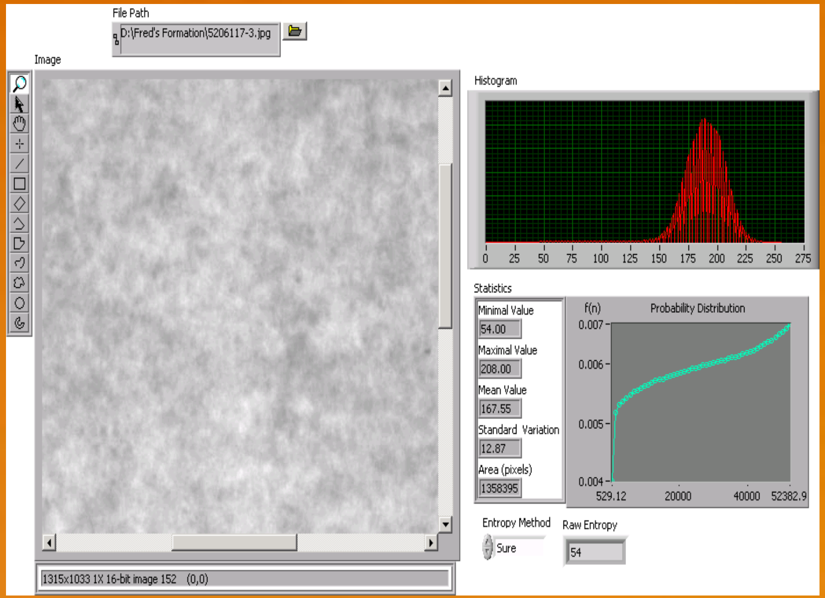


Process Model and Energy Flow Model

Fault tolerant control effect before and after faults in drying section

- ❑ Forming/press section control: PID for vacuum power systems
- ❑ Drying section control: Model Predictive Control for steam flows
- ❑ Grey image as a measure with their Probabiity Density Functions





Fault in drying section: moisture too high

Fault tolerant control effect with set-point tuning in forming section

Conclusions and future issues

- ❑ Collaborative fault tolerant control has been summarized, where simultaneously operated and sequentially operated systems are considered with case studies

Take Aways (Further research)

- ❑ Handling communications faults among all sub-systems
- ❑ Arranging subsequent sub-systems in a fault tolerant way requires capacity optimization for each sub-systems
- ❑ Fault tolerant rerequires finite-time control
- ❑ Fault prognosis in a collaborative way

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Thank you all for your attention

Questions?