VOLUME I OF III
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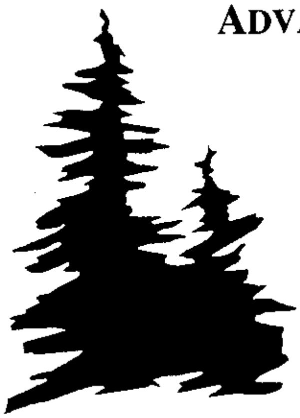
ADVANCED EQUIPMENT CONTROL / ADVANCED PROCESS CONTROL
PROCEEDINGS VOLUME I



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The Set-Valued Run-to-Run Controller With Ellipsoid Approximation

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Motivations

- Robustness. Traditional run-to-run (RtR) control methods neglect the importance of robustness due to the estimation methods they use. We want to find a new RtR controller which can identify the process model in the feasible parameter set which is insensitive to noises, therefore the controller can be robust.
- Fast convergence. The new RtR controller should be able to track the changing process quickly.
- Noises discerning ability. It can discern different noises such as shifts (step disturbances) or drifts.

Introduction of the Set-valued Method

- Due to the existence of noises, it is difficult to accurately estimate the process models, what we can be sure is a set that the model parameters reside in.
- We want to find a "good" and "safe" estimate of the process model within this set.
  - "Good" means that the estimated model is close to the underlying real model in mean square sense;
  - "Safe" means that the estimated model is insensitive to noises.
- Applications: Optimal control, image processing, system identification, and spectral estimation, etc.

Why Ellipsoid

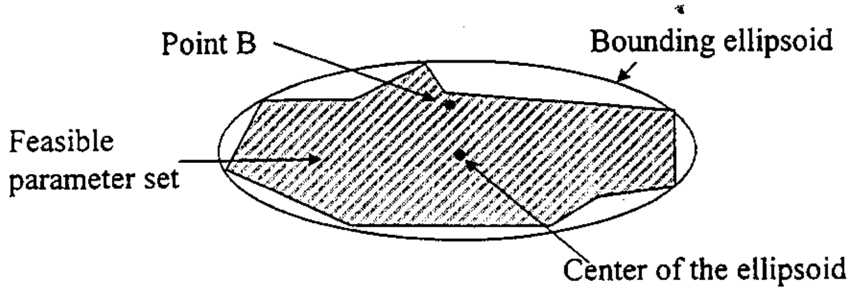
- The main difficulties of the set-valued method lie in:
  - The excessive computational time required to calculate the feasible sets. It is hard to describe these sets with explicit formulas, because they can be very irregular.
  - Solving the optimization problem within these sets.
- It is nature to use ellipsoids to approximate these sets.
- Advantages of the ellipsoid approximation:
  - An ellipsoid is characterized by a vector center and a matrix, which is easy to calculate;
  - For convex or almost convex regions, ellipsoids can be used to obtain a satisfactory approximation;
  - Linear transformations map ellipsoids into ellipsoids.

Find the Minimum Ellipsoid

- The minimum ellipsoid bounding the feasible parameter sets is desired.
- Two main ellipsoid schemes available:
  - The Optimal Volume Ellipsoid (OVE) algorithm by M. F. Cheung, etc in 1991 [1].
  - The Optimal Bounding Ellipsoid (OBE) algorithm by Fogel and Huang in 1982 [2].
- Differences between the two ellipsoid schemes:
  - The derivation of the OVE algorithm is based on a geometrical point of view.
  - The OBE algorithm uses a recursive least square type scheme to update the ellipsoid.

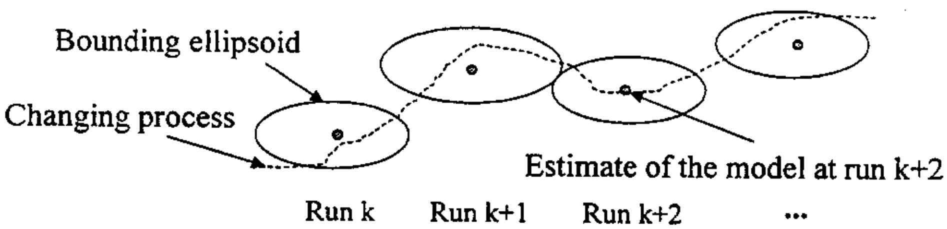
Estimate the Model within the Ellipsoid

- The center of the ellipsoid is a good and safe estimate of the process model in general (Shown in the figure).
- Point B is not a good estimate, since it can easily fall out of the feasible parameter set.
- There are some other schemes to estimate the process model parameters like the worst-case approach [3].



Modify the OVE Algorithm

- The OVE algorithm can not track fast changing processes.
- The Modified OVE (MOVE) algorithm works for fast changing processes. The procedure is shown by the following figure.
- The MOVE algorithm can deal with various disturbances including large step disturbance, drifts, etc.
- We will focus on the MOVE algorithm later on.



Formulation of the MOVE Algorithm

- Given a linear-in-parameter system, we can rewrite it as:

$$y_k = X_k^T \theta_k + \eta_k \qquad (1)$$

- For example:

$$y_k = c_{1,k} + c_{2,k}u_{1,k} + c_{3,k}u_{2,k} + c_{4,k}u_{3,k} + c_{5,k}u_{1,k}u_{2,k} + c_{6,k}u_{3,k}^2 + \eta_k$$

  can be rewritten as the form of equation (1), with

$$X_k = \left[1, u_{1,k}, u_{2,k}, u_{3,k}, u_{1,k}u_{2,k}, u_{3,k}^2\right]^T, \quad \theta_k = [c_{1,k}, c_{2,k}, c_{3,k}, c_{4,k}, c_{5,k}, c_{6,k}]^T$$

- Let the noise bound be γ, the feasible parameter set is:

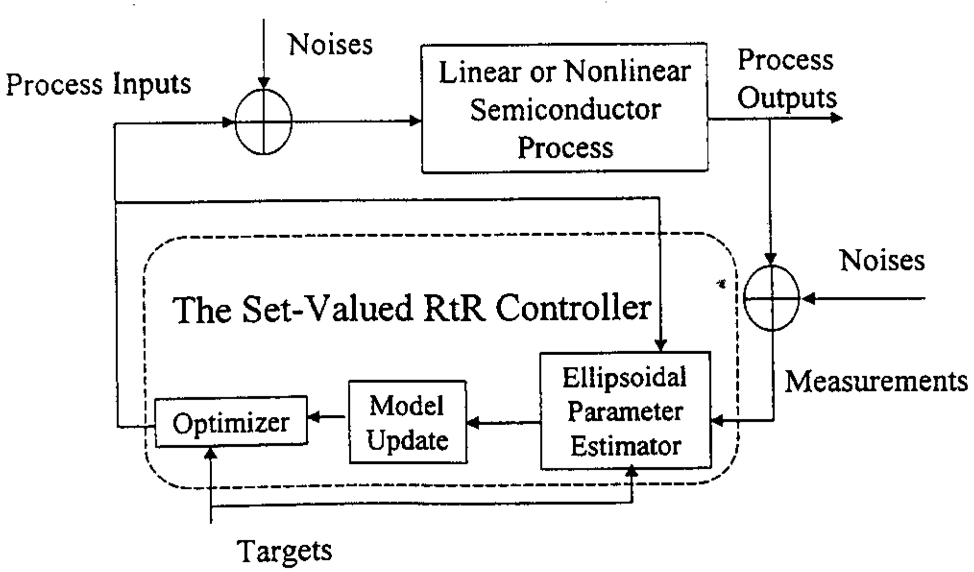
$$F_k = \{\theta_k : \left| y_k - X_k^T \theta_k \right| < \gamma\}$$

The MOVE Algorithm

- The MOVE algorithm calculates the ellipsoid E_k:
  $$E_k = \min\{vol(E)\}, \text{s.t. } E \supset F_k$$
- If the disturbance exceeds certain threshold, then the ellipsoid center θ_k and size P_k are updated.
- For detail of the MOVE algorithm, please refer to [4].
- An expanding matrix F is added in the MOVE algorithm. It is used to track fast changing processes.

$$P_k := P_k + F = P_k + \begin{bmatrix} F(1,1) & 0 & 0 & \cdots & 0 \\ 0 & F(2,2) & 0 & \cdots & 0 \\ 0 & 0 & \ddots & 0 & \vdots \\ \vdots & \vdots & 0 & \ddots & 0 \\ 0 & \cdots & \cdots & 0 & F(n,n) \end{bmatrix}$$

Structure of a Set-valued RtR Controller with Ellipsoid Approximation



Procedures of the SVR-MOVE Controller

- The set-valued RtR controller using the MOVE algorithm will be called the SVR-MOVE controller.
- Procedures:
  - Step 1: Initialize model, cost function & recipes;
  - Step 2: Setting targets & constraints;
  - Step 3: Setting the controller parameters;
  - Step 4: Generating recipes by the process model to minimize the cost function;
  - Step 5: Measure outputs, update process model if necessary;
  - Step 6: Go to Step 4.

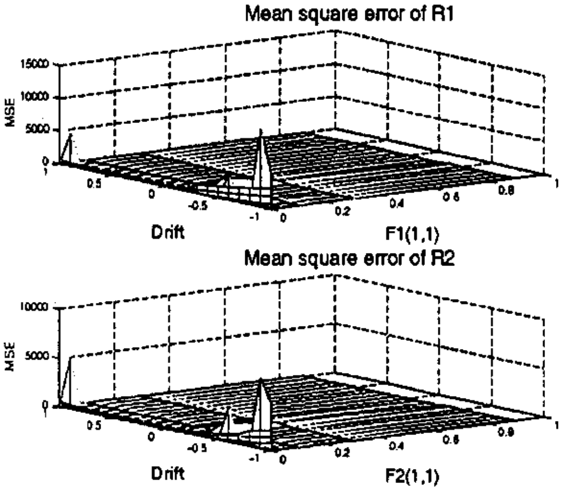
Parameter Selection of the SVR-MOVE Controller

- The threshold for judging drifts and shifts. It is usually equal to 3 times of the estimate of the noise variance.

- The expanding matrix F. The most important parameter of F is F(1,1). It is related to the drift disturbance directly.

- The noise bound γ. It should be set a small value. Usually the range [0.01-0.05] is good.

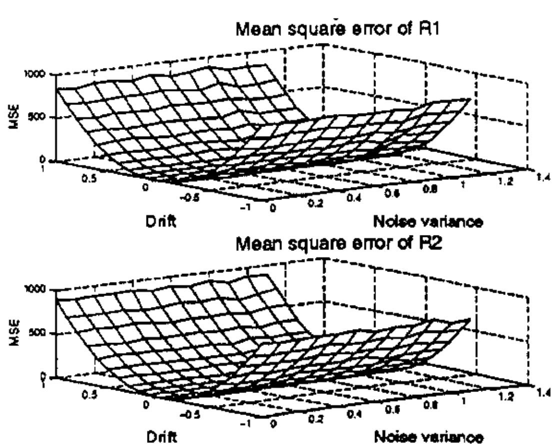
Mean Square Errors (MSEs) with Respect to F(1,1)s



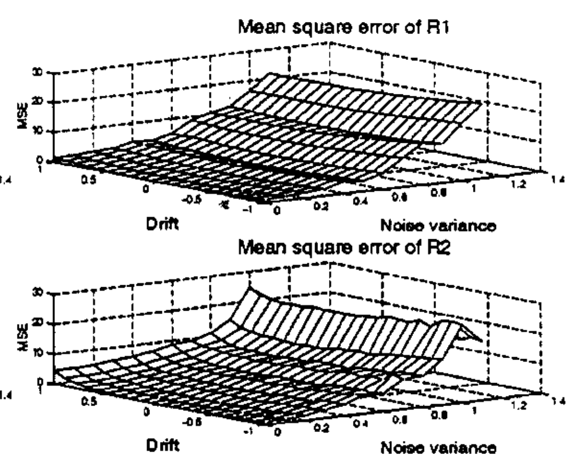
- The figures are based on simulation of low pressure chemical vapor deposition (LPCVD) furnace process.
- Two targets R_1 and R_2 are controlled.
- No other noises.
- Small F(1,1)s will have large MSEs.

MSEs When F(1,1)s are Fixed, White Noises are Added

F1(1,1)=F2(1,1)=10^{-6}



F1(1,1)=F2(1,1)=0.05



Comments about Value Selection of the Expanding Matrix F

- Trade-off in the selection of values of F(1,1).
  - The larger the F(1,1), the stronger the ability to compensate the drift disturbance.
  - However, since F expands the ellipsoid at each run, it increases the size of the ellipsoid, which affects the estimation quality.
- It is safe to let the other parameters F(i,i), i=2,..., in F to be infinite small compared to F(1,1), since they are related to higher order terms.
- When no drifts exist, it is nature to let F=0.

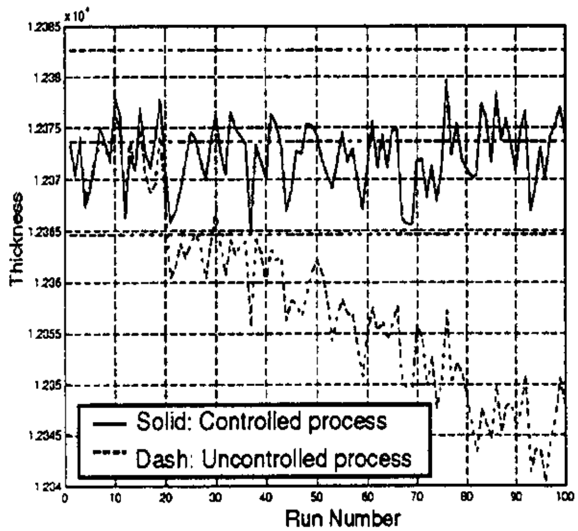
Simulation 1. An Almost Linear Photoresist Process I

The process model [5] is:

$$T = -13814 + \frac{2.54 \cdot 10^6}{\sqrt{SPS}} + \frac{1.95 \cdot 10^7}{BTE\sqrt{SPS}} - 3.78BTI - 0.28SPT - \frac{6.16 \cdot 10^7}{SPS} + d \cdot k + w$$

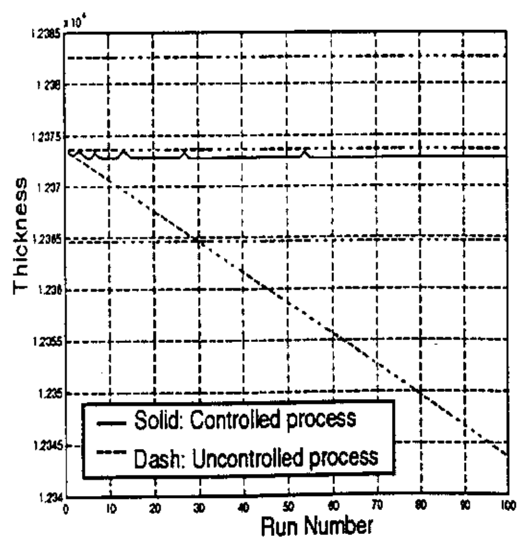
- Inputs: SPS is the spin speed, SPT the spin time, BTI the baking time, and BTE the baking temperature. They are constrained to: 4500<SPS<4700; 15<SPT<90; 105<BTE<135; 20<BTI<100 respectively.
- Output: T, the resist thickness.
- Noises: d is equal to -0.3, w is Gaussian with variance 9.
- K: Run number

Photoresist Process I Controlled by the SVR-MOVE Controller



- The target is 12373.621.
- The three straight dashed lines in the figure are the +3σ, target and -3σ lines respectively.
- The uncontrolled process diverges
- The controlled process stays in the 3σ region satisfactorily.

Photoresist Process I without White Noises



- Only drift noise exists.
- The uncontrolled process diverges as a straight line.
- The controlled stays very close to the target.
- It proves the effectiveness of the controller to deal with drift.

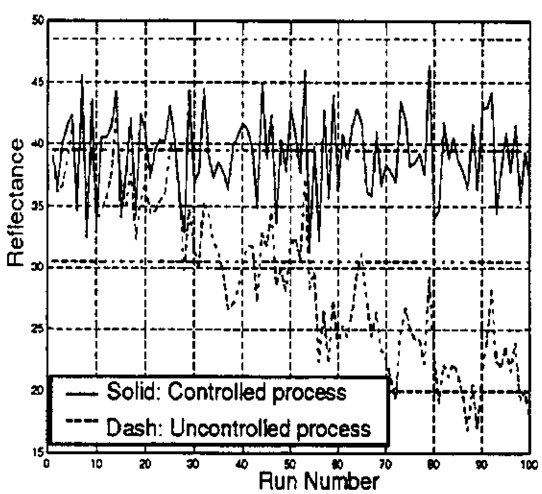
Simulation 2. A full Second-order Nonlinear Photoresist Process II

The process model [5] is:

$$\begin{aligned} R = {} & 1344 - 0.046SPS + 0.32SPT - 0.17BTE + 0.023BTI - 4.34 \cdot 10^{-5} \cdot SPS \cdot SPT \\ & + 5.19 \cdot 10^{-5} \cdot SPS \cdot BTE - 1.07 \cdot 10^{-3} SPT \cdot BTE + 5.15 \cdot 10^{-6} \cdot (SPS)^2 \\ & - 4.11 \cdot 10^{-4} \cdot SPT \cdot BTI + d \cdot k + w \end{aligned}$$

- Inputs: Same as in photoresist process I.
- Output: R, the reflectance in percentage.
- Noises: Same as in photoresist process I.
- The target is fixed at 39.4967%.

Photoresist Process II Controlled by the SVR-MOVE Controller



- The uncontrolled process diverges.
- Most of the time the controlled process stays in the $\pm 3\sigma$ area.
- It shows the ability of the SVR-MOVE controller to control non-linear processes.

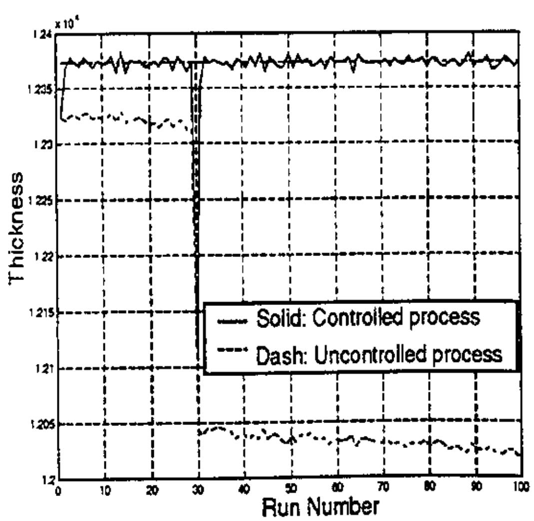
Simulation 3. Photoresist Process I with Large Model Error

- The process model is:

$$y_k = -13814 + \frac{2.54 \cdot 10^6}{\sqrt{SPS}} + \frac{1.95 \cdot 10^7}{BTE\sqrt{SPS}} - 3.78BTI - 0.28SPT - \frac{6.16 \cdot 10^7}{SPS} + d \cdot k + v_2 + v_3 + v_3 \times v_4$$

- Inputs: Same as before.
- Output: y_k.
- Noises.
  - d is defined the same as before.
  - v_2 is the product of two Gaussian random variables.
  - v_3 is a random variable with uniform distribution.
  - v_4 is a Gaussian variable too.

Photoresist Process I with Large Model Error



- There is a large model error at the beginning.
- A large step disturbance occurs at run 30.
- The output still stays close to the target.
- It shows the ability of the controller to deal with large model errors, large disturbance and multiple noises.

Summary

- The set-valued RtR controller with ellipsoid approximation gives a safe and good estimate of the process model in a minimum volume ellipsoid, which bounds the feasible parameter set.
- The SVR-MOVE controller is easily applicable to various semiconductor processes.
- The SVR-MOVE controller is robust, and it can deal with large model errors, large disturbance and multiple noises.
- In the parameter selection of the SVR-MOVE controller, further theoretical analysis is still needed.

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