Strategies to reduce the probability of a misleading signal

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The phenomenon of misleading signals

- The simultaneous use of two individual charts — one for the process mean μ and one for its variance σ^2 — provides a way to satisfy **Shewhart's dictum** that proper process control implies **monitoring** both **location** and **spread**.

- Since the process is deemed **out-of-control** whenever a **signal is observed on either individual chart**, the following **misleading signals** (MS) are likely to happen while using a simultaneous scheme for μ and σ^2:

Type of MS			
III	μ on-target	σ^2 off-target	**chart for μ is the first to signal**
IV	μ off-target	σ^2 on-target	**chart for σ^2 is the first to signal**

The phenomenon of misleading signals; existing work

- **MS can lead** the quality control operator/engineer **to misdiagnose assignable causes** and **deploy incorrect actions** while attempting to bring the process back to target.
- Awareness of the **phenomenon of MS** stretches back to the seminal work of **St. John and Bragg (1991)**.
- The **probability of a misleading signal** (PMS), proposed by **Morais and Pacheco (2000)** as a performance measure of simultaneous schemes for location and spread, has been already addressed for:
    - **i.i.d. Gaussian output** (Morais and Pacheco, 2000, 2006; Morais, 2002; Reynolds Jr. and Stoumbos, 2001, 2004);
    - **autocorrelated Gaussian output** (Antunes, 2009; Knoth, Morais, Pacheco and Schmid, 2009; Ramos, Morais, Pacheco and Schmid, 2012; Ramos, Morais and Pacheco, 2013);
    - **i.i.d. bivariate and multivariate normal output** (Ramos, Morais, Pacheco and Schmid, 2013a,b,c).

Existing work (cont'd)

Striking and instructive examples in the SPC literature show that:

- the ocurrence of **MS** should be a **cause of concern** in practice;
- **Shewhart-type** simultaneous **schemes compare unfavorably** to **EWMA-type**, in terms of the PMS;
- the fact that the **control statistics** of the individual charts for the **mean vector** ($\underline{\mu}$) are **based on quadratic forms aggravates** the **PMS**;
- when we deal with simultaneous schemes that falsely assume that the output is i.i.d. or with simultaneous schemes for $\underline{\mu}$ and $\underline{\Sigma}$, **PMS can take values exceeding** 50%.

What's ahead...

In this presentation we:

- discuss (necessary and) sufficient **conditions to achieve** $PMS \leq 50\%$;
- explore **strategies to reduce PMS**, namely, Shewhart-type alternatives to the $(\bar{X}, S^2)-$scheme.

AGENDA

1. A closer look at the PMS
2. A few strategies to reduce the PMS
3. Numerical results and final thoughts

1. A closer look at the PMS

$(\bar{X}, S^2)$ scheme

- i.i.d. Normal(μ, σ^2) output

In-control	Out-of-control	Control limits		Power function
μ_0	$\mu_0 + \delta \times \sigma_0/\sqrt{n},\ \delta \neq 0$	LCL_μ	UCL_μ	$\xi_\mu(\delta,\theta) = P_{\delta,\theta}(\bar{X} \notin [LCL_\mu, UCL_\mu])$
σ_0	$\theta \times \sigma_0,\ \theta > 1$	LCL_σ	UCL_σ	$\xi_\sigma(\theta) = P_\theta(S^2 \notin [LCL_\sigma, UCL_\sigma])$

- Run lengths (RL)

$$RL_\mu(\delta,\theta) \sim \text{Geometric}(\xi_\mu(\delta,\theta))$$
$$RL_\sigma(\theta) \sim \text{Geometric}(\xi_\sigma(\theta))$$

$$RL_{\mu,\sigma}(\delta,\theta) = \min\{RL_\mu(\delta,\theta), RL_\sigma(\theta)\} \sim \text{Geometric}(\xi_{\mu,\sigma}(\delta,\theta))$$

$\xi_{\mu,\sigma}(\delta,\theta) = \xi_\mu(\delta,\theta) + \xi_\sigma(\theta) - \xi_\mu(\delta,\theta) \times \xi_\sigma(\theta)$

$(\bar{X}, S^2)$ scheme (cont'd)

- **PMS**

According to the definition of MS of types III and IV:

$$PMS_{III}(\theta) = P[RL_{\mu}(0,\theta) < RL_{\sigma}(\theta)], \quad \theta > 1; \tag{1}$$
$$PMS_{IV}(\delta) = P[RL_{\sigma}(1) < RL_{\mu}(\delta,1)], \quad \delta \neq 0. \tag{2}$$

Expressions simplify if the Shewhart-type simultaneous schemes are based on independent control statistics, such as $(\bar{X}, S^2)$:

$$PMS_{III}(\theta) = \frac{\xi_{\mu}(0,\theta) \times [1 - \xi_{\sigma}(\theta)]}{\xi_{\mu,\sigma}(0,\theta)}, \quad \theta > 1; \tag{3}$$
$$PMS_{IV}(\delta) = \frac{[1 - \xi_{\mu}(\delta,1)] \times \xi_{\sigma}(1)}{\xi_{\mu,\sigma}(\delta,1)}, \quad \delta \neq 0. \tag{4}$$

The **PMS** of Type III (resp. IV) can be interpreted as the **conditional probability** that the **chart for** μ (resp. σ^2) **signals** and the **chart for** σ^2 (resp. μ) **fails to do so**, given that the simultaneous scheme was responsible for an alarm.

$(\bar{X}, S^2)$ scheme (cont'd)

- **Conditions to achieve** $PMS \leq 50\%$

  If the individual charts of the simultaneous scheme for μ and σ^2 are of the Shewhart-type and are based on independent control statistics then:

$$PMS_{III}(\theta) \leq 50\% \quad \Leftrightarrow \quad ARL_{\mu}(0,\theta) + 1 \geq ARL_{\sigma}(\theta); \tag{5}$$

$$PMS_{IV}(\delta) \leq 50\% \quad \Leftrightarrow \quad ARL_{\sigma}(1) + 1 \geq ARL_{\mu}(\delta,1). \tag{6}$$

- **Sufficient conditions to achieve** $PMS \leq 50\%$

$$\xi_{\mu}(0,\theta) \leq \xi_{\sigma}(\theta) \quad \Rightarrow \quad PMS_{III}(\theta) \leq 50\%$$

$$\xi_{\sigma}(1) \leq \xi_{\mu}(\delta,1) \quad \Rightarrow \quad PMS_{IV}(\delta) \leq 50\%,$$

  i.e., if the chart for μ (resp. σ^2) triggers valid signals less or as frequently as the chart for σ^2 (resp. μ), when $\delta = 0$ and $\theta > 1$ (resp. $\delta \neq 0$ and $\theta = 1$), then the PMS of Type III (resp. IV) does not exceed 50%.

Comments

- Conditions are still valid for simultaneous Shewhart-type:
  - schemes for the control of the mean vector $\underline{\mu}$ and covariance matrix $\underline{\Sigma}$ of **multivariate normal output**;
  - residual schemes for the mean and variance of **autocorrelated output** (RL_σ depends on δ in this case).
- It is not easy to extend the conditions for the **PMS** of simultaneous **EWMA** schemes due to the Markovian character of the control statistics of the individual charts.
- Numerical results for the PMS for simultaneous EWMA-type schemes for $\underline{\mu}$ and $\underline{\Sigma}$ led to very few values of the $PMS_{III} > 50\%$, even though condition (5) was valid.

  (These values refer to a radical change in the joint behaviour of the quality characteristics: unitary variances increase and the correlation coefficients shift from 0 to a non null value.)

2. A few strategies to reduce the PMS

- **Matching in-control the individual charts for μ and σ^2**

  Setting $ARL_\mu(0,1) = ARL_\sigma(1)$ seems to lead to $PMS_{IV} \leq 50\%$.

  - If $ARL_\sigma \perp\!\!\!\perp \delta$ and $ARL_\mu(\delta,1) \downarrow \delta$ then $ARL_\sigma(1) \geq ARL_\mu(\delta,1) \;\Rightarrow\; PMS_{IV}(\delta) \leq 50\%$.
  - The $ARL_{\underline{\mu}}$ is often much more sensitive to changes in the covariance matrix than $ARL_{\underline{\Sigma}}$, leading to the violation of the rhs (5) and to $PMS_{III} > 50\%$, even if the individual charts were matched in-control.

- **Choice of control statistics**
  - Replacing $(\bar{X}, S^2)$ scheme with its EWMA counterpart can considerably reduce the PMS of types III and IV.
  - However, since some quality control practitioners are still reluctant to use EWMA charts, we explore the **impact on PMS** of the two **alternative** Shewhart-type **statistics** proposed by **Walsh (1952)** for the location and the spread of i.i.d. univariate normal output.

Comparison study

Scheme i	Control statistics $(T^{(i)}, U^{(i)})$	Control limits $LCL_\mu^{(i)},\ UCL_\mu^{(i)}$	$UCL_\sigma^{(i)}$
1	$\left(\bar{X},\ S^2\right)$	$\mu_0 \pm \gamma_\mu^{(1)} \times \frac{\sigma_0}{\sqrt{n}}$	$\gamma_\sigma^{(1)} \times \frac{\sigma_0^2}{n-1}$
2	$\left(\frac{\bar{X}-\mu_0}{S/\sqrt{n}},\ S^2\right)$	$\pm\gamma_\mu^{(2)}$	$\gamma_\sigma^{(2)} \times \frac{\sigma_0^2}{n-1}$
3	$\left(\bar{X},\ \frac{1}{n}\sum_{i=1}^n (X_i - \mu_0)^2\right)$	$\mu_0 \pm \gamma_\mu^{(3)} \times \frac{\sigma_0}{\sqrt{n}}$	$\gamma_\sigma^{(3)} \times \frac{\sigma_0^2}{n}$

- Critical points: $\gamma_\mu^{(i)} = \Phi^{-1}(1-\beta^{(i)}),\ i = 1, 3;\ \ \gamma_\mu^{(2)} = F^{-1}_{t_{(n-1)}}(1-\beta^{(2)})$;
  $\gamma_\sigma^{(i)} = F^{-1}_{\chi^2_{(n-1)}}(1-2\beta^{(i)}),\ i = 1, 2;\ \ \gamma_\sigma^{(3)} = F^{-1}_{\chi^2_{(n)}}(1-2\beta^{(3)})$.
- $\beta^{(i)}$: $ARL_{\mu,\sigma}^{(i)}(0,1) = \alpha^{-1}$;
  $ARL_\mu^{(i)}(0,1) = ARL_\sigma^{(i)}(0,1) = [2\beta^{(i)}]^{-1}$ (indiv. charts are matched in-control).

- **PMS**

  The 2nd. and 3rd. pairs of alternative control statistics are **dependent**; the corresponding **PMS** have **different expressions** than the ones in equations (3) and (4):

  - $PMS^{(i)}_{III}(\theta) = \frac{P_{0,\theta}\left(T^{(i)} \notin [LCL^{(i)}_{\mu}, UCL^{(i)}_{\mu}],\, U^{(i)} \in [0, UCL^{(i)}_{\sigma}]\right)}{1 - P_{0,\theta}\left(T^{(i)} \in [LCL^{(i)}_{\mu}, UCL^{(i)}_{\mu}],\, U^{(i)} \in [0, UCL^{(i)}_{\sigma}]\right)},\ \theta > 1;$
  - $PMS^{(i)}_{IV}(\delta) = \frac{P_{\delta,1}\left(T^{(i)} \in [LCL^{(i)}_{\mu}, UCL^{(i)}_{\mu}],\, U^{(i)} \notin [0, UCL^{(i)}_{\sigma}]\right)}{1 - P_{\delta,1}\left(T^{(i)} \in [LCL^{(i)}_{\mu}, UCL^{(i)}_{\mu}],\, U^{(i)} \in [0, UCL^{(i)}_{\sigma}]\right)},\ \delta \neq 0.$

  (closed expressions in the appendix!).

3. Numerical results and final thoughts

Example

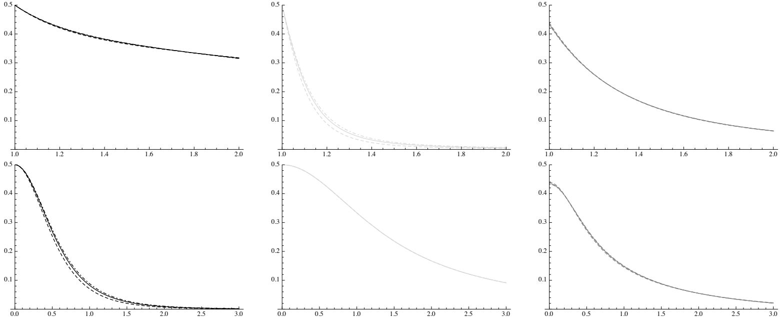
- $n = 3, 5, 7; \quad \mu_0 = 0, \sigma_0 = 1;$
- $\beta^{(i)} : ARL^{(i}_{\mu,\sigma}(0,1) = \alpha^{-1} = 500$ (and also for 370.4 and 1000),
  $ARL^{(i)}_{\mu}(0,1) = ARL^{(i)}_{\sigma}(0,1) = [2\beta^{(i)}]^{-1};$

n	Statistics	i	$\beta^{(i)}$	$\gamma^{(i)}_{\mu}$	$\gamma^{(i)}_{\sigma}$	$ARL^{(i)}_{\mu,\sigma}(0,1)$
3	$(\bar{X},\ S^2)$	1	0.000500	3.290386	13.814510	500.0
	$(\sqrt{n}(\bar{X}-\mu_0)/S,\ S^2)$	2	0.000500	31.599055	13.815511	
	$(\bar{X},\ \sum_{i=1}^{n}(X_i-\mu_0)^2/n)$	3	0.000566	3.255733	16.005584	
5			0.000500	3.290386	18.465718	
			0.000500	8.610302	18.466827	
			0.000535	3.271520	20.359516	
7			0.000500	3.290386	22.456550	
			0.000500	5.958816	22.457744	
			0.000524	3.277483	24.207792	

- values of PMS of types III and IV, namely for $\theta = 1.02, 1.1, 1.2, 2$ and $\delta = 0.05, 0.5, 1, 2;$
- plots of PMS have been added to make the comparison between the three simultaneous schemes possible.

Example (cont.)

Plots of $PMS^{(i)}_{III}(\theta)$ (top) and $PMS^{(i)}_{IV}(\delta)$ (bottom), for scheme $i = 1, 2, 3$ (in black, light grey, grey; left to right, resp.), $\alpha = 1/1000, 1/500, 1/370.4$ (dashed, solid and dot dashed lines, resp.) and $n = 3$.



- The graphs of **PMS of types III and IV** for all three simultaneous schemes, sample sizes ($n = 3, 5, 7$) and significance levels ($\alpha = 1/1000, 1/500, 1/370.4$) are **somewhat insensitive to** $ARL^{(i)}_{\mu,\sigma}(0, 1) = \alpha^{-1}$.

Example (cont.)

$PMS_{III}^{(i)}(\theta)$ and $PMS_{IV}^{(i)}(\delta)$ for simultaneous Shewhart-type schemes for μ and σ^2 ($\alpha = 1/500$ and $n = 3, 5, 7$).

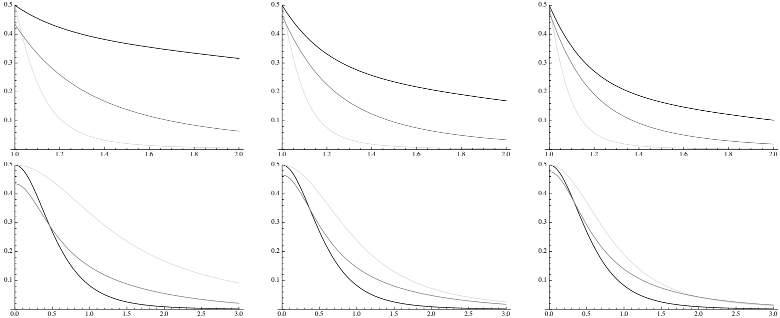
		$PMS_{III}^{(i)}(\theta)$				$PMS_{IV}^{(i)}(\delta)$		
		n				n		
i	θ	3	5	7	δ	3	5	7
1	1.02	0.489460	0.475799	0.465561	0.05	**0.496112**	**0.496112**	**0.496112**
2		0.433340	0.419974	0.410012		0.499377	0.498806	0.498367
3		0.411395	0.431322	0.433766		0.431778	0.462197	0.473257
	1.1	0.454931	0.397725	0.357110	0.5	**0.269291**	**0.269291**	**0.269291**
		0.231677	0.192758	0.167371		0.444525	0.400651	0.370967
		0.332637	0.319955	0.297960		0.276739	0.289937	0.292367
	1.2	0.423132	0.331381	0.271748	1	**0.082472**	**0.082472**	**0.082472**
		0.108061	0.075944	0.058490		0.333556	0.238787	0.189438
		0.259552	0.225470	0.193665		0.148157	0.144792	0.139310
	2	0.315981	0.169326	0.102093	2	**0.009078**	**0.009078**	**0.009078**
		0.005592	0.003031	0.002133		0.167056	0.072439	0.043153
		0.064100	0.034090	0.019236		0.054896	0.047982	0.042719

- **PMS of Type IV** is **independent of** the sample size n, when we use the $(\bar{X}, S^2)-$ **scheme**...

  By incorporating the sample size in $\delta = \sqrt{n}(\mu - \mu_0)/\sigma_0$, we get $\xi_\mu(\delta, 1)$ independent of n; fixing the in-control ARL of the simultaneous scheme and demanding that both individual charts have the same in-control ARL, leads to $\xi_\mu(\delta, 1) = 2\beta^{(1)} = \xi_\sigma(1)$ also independent of n.

Example (cont.)

Plots of $PMS_{III}^{(i)}(\theta)$ (top) and $PMS_{IV}^{(i)}(\delta)$ (bottom), for $i = 1, 2, 3$ (in black, light grey, grey, resp.), $\alpha = 1/500$ and $n = 3, 5, 7$ (left to right).



- $(\sqrt{n}(\bar{X} - \mu_0)/S,\ S^2)-$**scheme** (light grey) tends to be **superior** (resp. inferior) to the $(\bar{X},\ S^2)-$ or $(\bar{X},\ \frac{1}{n}\sum_{i=1}^{n}(X_i - \mu_0)^2)-$schemes, **in terms of PMS_{III}** (resp. PMS_{IV}).
- **None** of the two **alternative** simultaneous schemes are able to **reduce both** the **PMS** of Type III and Type IV of the $(\bar{X},\ S^2)-$scheme.

Final thoughts

Directions for future work on simultaneous schemes for the process location and spread include:

- exploring the adoption of **alternative control statistics** in order to decrease the PMS in a **multivariate setting** (Tang and Barnett, 1996a,b).
- assessing the impact of **falsely assuming a simpler model** than the one of the output on PMS (for example, applying a residual scheme designed for an AR(1) model when the output follows an AR(2) or an ARMA(1,1) model);
- extending the analysis of the **impact of autocorrelation** on the PMS for **multivariate output** (Garthoff *et al.*, 2012);
- studying **other MS related phenomena** such as the probability of an *unambiguous signal* suggested by Hawkins and Maboudou-Tchao (2008).

Appendix

- $P_{\delta,\theta}\left(T^{(i)} \in [LCL_\mu^{(i)}, UCL_\mu^{(i)}],\ U^{(i)} \in [0, UCL_\sigma^{(i)}]\right)$ equals

$$\begin{cases} \left[\Phi\left(\frac{\gamma_\mu^{(1)}}{\theta} - \frac{\delta}{\theta}\right) - \Phi\left(-\frac{\gamma_\mu^{(1)}}{\theta} - \frac{\delta}{\theta}\right)\right] \times F_{\chi^2_{(n-1)}}\left(\frac{\gamma_\sigma^{(1)}}{\theta^2}\right), & i = 1 \\ \int_0^{\frac{\gamma_\sigma^{(2)}}{\theta^2}} \left[\Phi\left(\frac{\gamma_\mu^{(2)}}{\sqrt{n-1}}\sqrt{x} - \frac{\delta}{\theta}\right) - \Phi\left(-\frac{\gamma_\mu^{(2)}}{\sqrt{n-1}}\sqrt{x} - \frac{\delta}{\theta}\right)\right] \times f_{\chi^2_{(n-1)}}(x)\, dx, & i = 2 \\ \int_{-\frac{\gamma_\mu^{(3)}}{\theta} - \frac{\delta}{\theta}}^{\frac{\gamma_\mu^{(3)}}{\theta} - \frac{\delta}{\theta}} \phi(z) \times F_{\chi^2_{(n)}}\left(\max\left\{0, \gamma_\sigma^{(3)}/\theta^2 - (z + \delta/\theta)^2\right\}\right) dz, & i = 3. \end{cases}$$

- $P_{\delta,\theta}\left(T^{(i)} \notin [LCL_\mu^{(i)}, UCL_\mu^{(i)}],\ U^{(i)} \in [0, UCL_\sigma^{(i)}]\right)$ is given by

$$\begin{cases} \left\{1 - \left[\Phi\left(\frac{\gamma_\mu^{(1)}}{\theta} - \frac{\delta}{\theta}\right) - \Phi\left(-\frac{\gamma_\mu^{(1)}}{\theta} - \frac{\delta}{\theta}\right)\right]\right\} \times F_{\chi^2_{(n-1)}}\left(\frac{\gamma_\sigma^{(1)}}{\theta^2}\right), & i = 1 \\ \int_0^{\frac{\gamma_\sigma^{(2)}}{\theta^2}} \left\{1 - \left[\Phi\left(\frac{\gamma_\mu^{(2)}}{\sqrt{n-1}}\sqrt{x} - \frac{\delta}{\theta}\right) - \Phi\left(-\frac{\gamma_\mu^{(2)}}{\sqrt{n-1}}\sqrt{x} - \frac{\delta}{\theta}\right)\right]\right\} \times f_{\chi^2_{(n-1)}}(x)\, dx, & i = 2 \\ \int_{-\infty}^{-\frac{\gamma_\mu^{(3)}}{\theta} - \frac{\delta}{\theta}} \phi(z) \times F_{\chi^2_{(n-1)}}\left(\max\{0, \gamma_\sigma^{(3)}/\theta^2 - (z - \delta/\theta)^2\}\right) dz & \\ \quad + \int_{\frac{\gamma_\mu^{(3)}}{\theta} - \frac{\delta}{\theta}}^{+\infty} \phi(z) \times F_{\chi^2_{(n)}}\left(\max\left\{0, \gamma_\sigma^{(3)}/\theta^2 - (z + \delta/\theta)^2\right\}\right) dz, & i = 3. \end{cases}$$

Appendix (cont'd)

- $P_{\delta,\theta}\left(T^{(i)} \in [LCL_{\mu}^{(i)}, UCL_{\mu}^{(i)}],\ U^{(i)} \notin [0, UCL_{\sigma}^{(i)}]\right)$ is equal to

$$
\begin{cases}
\left[\Phi\left(\frac{\gamma_{\mu}^{(1)}}{\theta} - \frac{\delta}{\theta}\right) - \Phi\left(-\frac{\gamma_{\mu}^{(1)}}{\theta} - \frac{\delta}{\theta}\right)\right] \times \left[1 - F_{\chi^2_{(n-1)}}\left(\frac{\gamma_{\sigma}^{(1)}}{\theta^2}\right)\right], & i = 1 \\
\int_{\frac{\gamma_{\sigma}^{(2)}}{\theta^2}}^{+\infty} \left[\Phi\left(\frac{\gamma_{\mu}^{(2)}}{\sqrt{n-1}}\sqrt{x} - \frac{\delta}{\theta}\right) - \Phi\left(-\frac{\gamma_{\mu}^{(2)}}{\sqrt{n-1}}\sqrt{x} - \frac{\delta}{\theta}\right)\right] \times f_{\chi^2_{(n-1)}}(x)\,dx, & i = 2 \\
\int_{-\frac{\gamma_{\mu}^{(3)}}{\theta} - \frac{\delta}{\theta}}^{\frac{\gamma_{\mu}^{(3)}}{\theta} - \frac{\delta}{\theta}} \phi(z) \times \left[1 - F_{\chi^2_{(n)}}\left(\max\left\{0, \gamma_{\sigma}^{(3)}/\theta^2 - (z + \delta/\theta)^2\right\}\right)\right] dz, & i = 3.
\end{cases}
$$

The derivation of $P_{\delta,\theta}(T^{(i)} \in [LCL_{\mu}^{(i)}, UCL_{\mu}^{(i)}],\ U^{(i)} \in [0, UCL_{\sigma}^{(i)}])$ follows closely Walsh (1952); the one of the remaining probabilities follows in a straightforward manner.

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