Effective Analysis of VMAT QA Generated Trajectory Log Files for Medical Accelerator Predictive Maintenance

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Objective

To determine the effectiveness of SPC analysis for a model predictive maintenance process that uses accelerator generated parameter and performance data contained in trajectory log files.

Methods

I/MR charts are the most sensitive in identifying changes in parameters. Our hybrid method for calculating the chart limits and chart analysis rules will determine how effective we can predict when maintenance intervention is necessary. Our experience has shown that the use of traditional SPC chart limits (±3 standard deviation from the grand mean) can result in an unacceptable rate of false positive signals (1,2). Using information on system specifications from the manufacturer, consulting the literature for recent studies on quality control of complex treatment delivery (IMRT, VMAT, SBRT, etc) and white papers on quality assurance of linear accelerators (3) we introduce a hybrid approach to calculating the control chart limits that includes a factor (S_p) that fractionally increases the limits based on the operational parameter specification and/or performance criteria.

Individual grand mean ($\bar{I}$), moving range (MR) and grand mean (I/MR) chart values are determined as follows:

$$\bar{I} = \frac{[\sum I_{t_{t=1\dots T}}]}{T} \tag{1}$$

$$MR_t = |I_t - I_{t+1}| \tag{2}$$

$$\overline{MR} = [(\sum MR_t)_{t=1\dots T-1}]/(T-1) \tag{3}$$

where T = 20 and I_t is the individual value of the component. Control limits are then calculated.

For Individual control limits:

$$[\bar{I} \pm (E_2\overline{MR})] \pm S_p \tag{4}$$

For Moving Range control limits:

$$UCL = [D_4\overline{MR}] + S_p \tag{5}$$

$$LCL = D_3\overline{MR} = 0 \tag{6}$$

where factors (D_3, D_4, E_2) are determined when n = 2.

The effect of using our hybrid approach is to increase the variance and reduce the kurtosis of the parameter probability density function. This is illustrated in Figure 1 for MLC speed.

Individual chart warnings and alarms are determined by:

a) Alarms: 2 of 3 or 3 of 5 consecutive data points exceeding the upper or lower control limits;
b) Warnings: 2 of 3 or 3 of 5 consecutive data points exceeding ±2 standard deviations from the mean.

Moving Range chart warnings and alarms are determined by:

a) Alarms: 3 of 5 consecutive data points exceeding the upper control limit;
b) Warnings: 3 of 5 consecutive data points exceeding +2 standard deviations from the mean.

Synthetic Errors Introduced

Synthetic errors were introduced to determine the initial effectiveness of the I/MR charts in detecting relevant changes in all 525 operating parameters being monitored.

Dashboard Interface Development and Layout

The MatLab programming environment was used to develop the predictive maintenance dashboard. The dashboard provides a means for visualization of the I/MR chart analysis.

Results

The synthetic errors introduced were detected in 99.4% (522 out of 525) of I/MR charts. Synthetic positional errors of 2mm for collimator jaw and MLC carriage exceeded the chart limits. Simulated Gantry speed error (0.2 deg/sec) and MLC speed error (0.1 cm/sec) exceeded the speed chart limits. Gantry position error of 0.2 deg was detected by the CC maximum value charts. The MLC position error of 0.1 cm was detected by the CC maximum value location charts for every MLC.

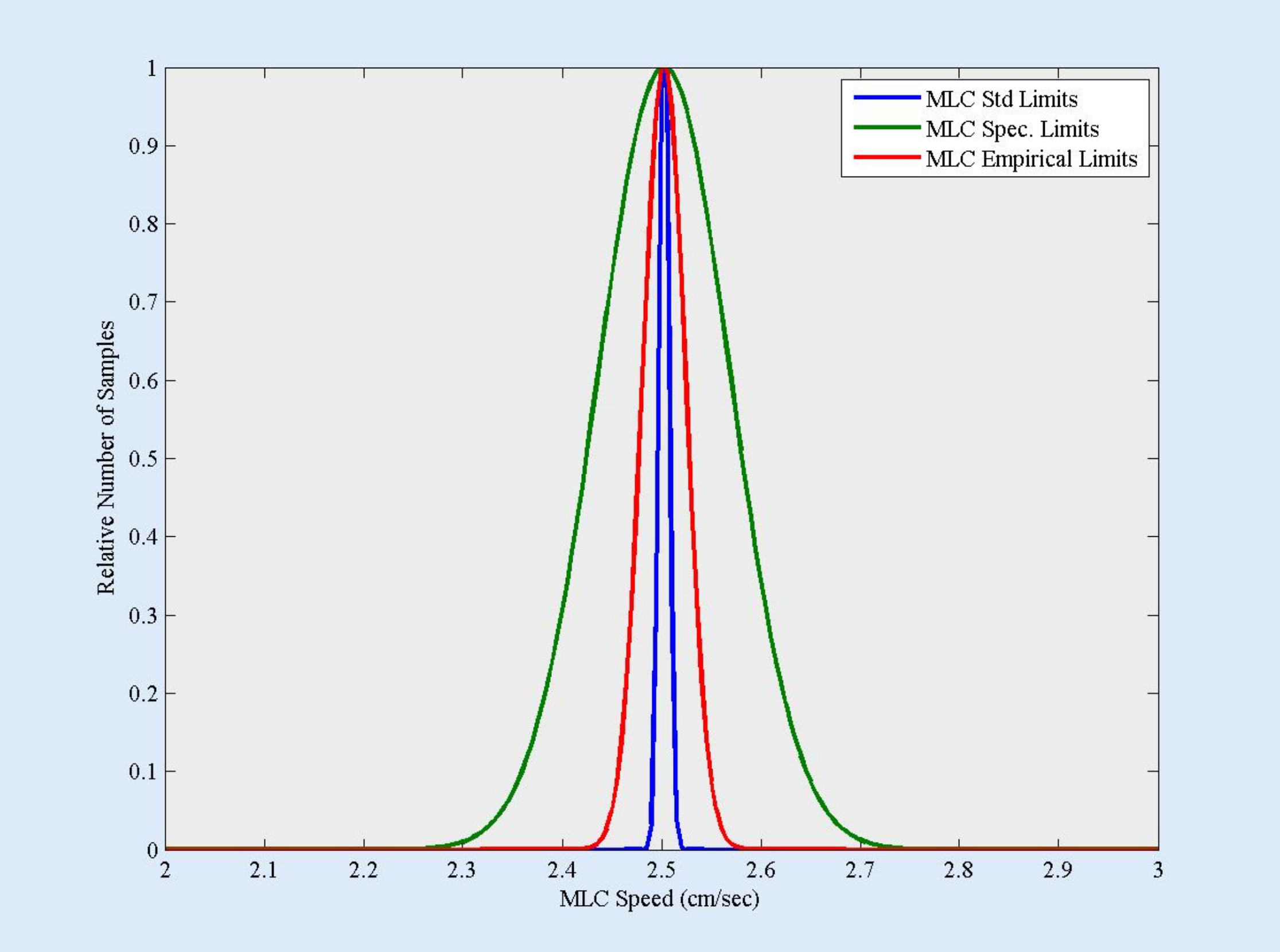


Figure 1. Normal probability density functions representing three I chart limit calculation methods for MLC leaf speed (traditional/standard SPC, MLC manufacturer specification (±2 mm), and our empirical method).

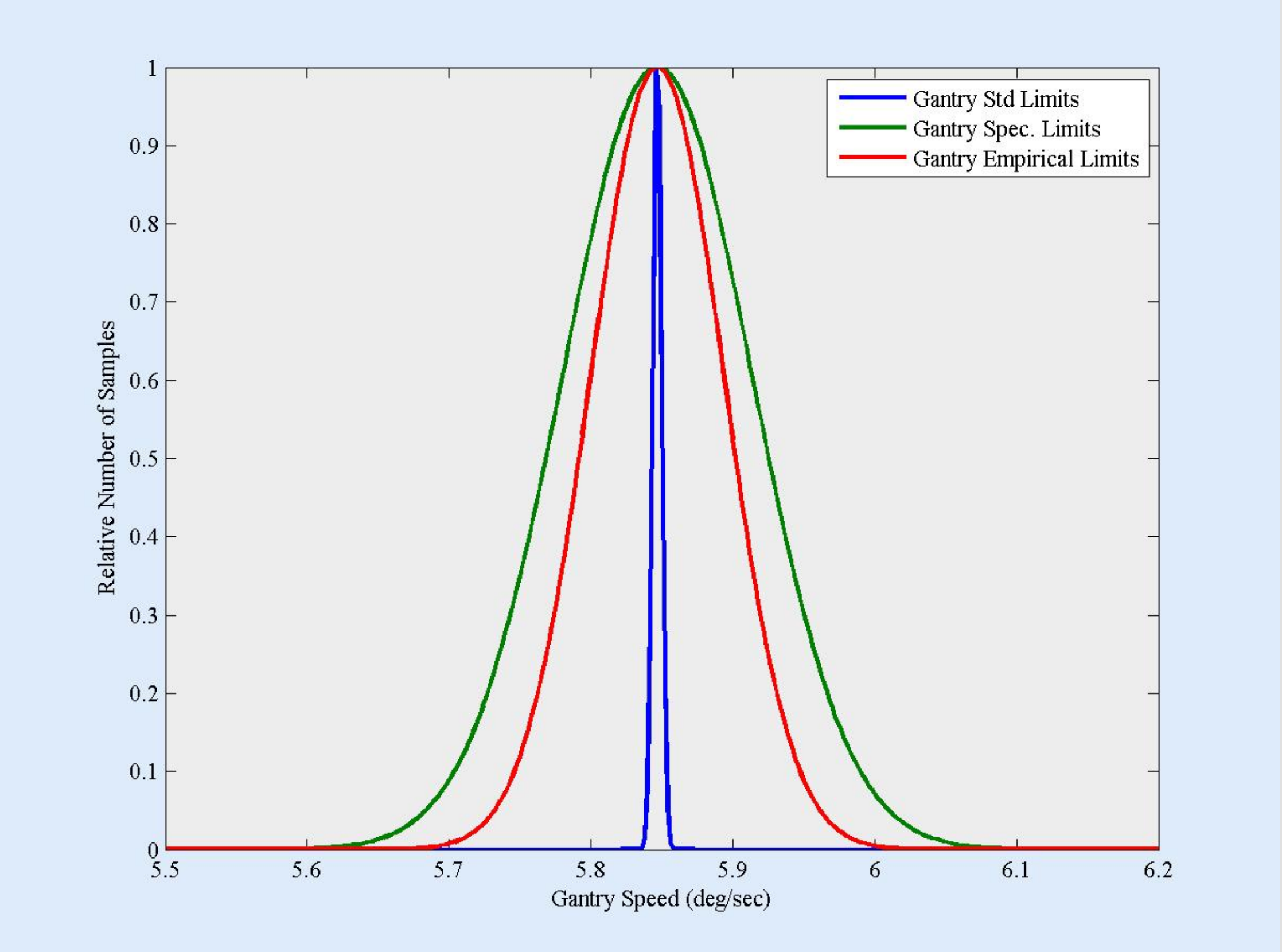
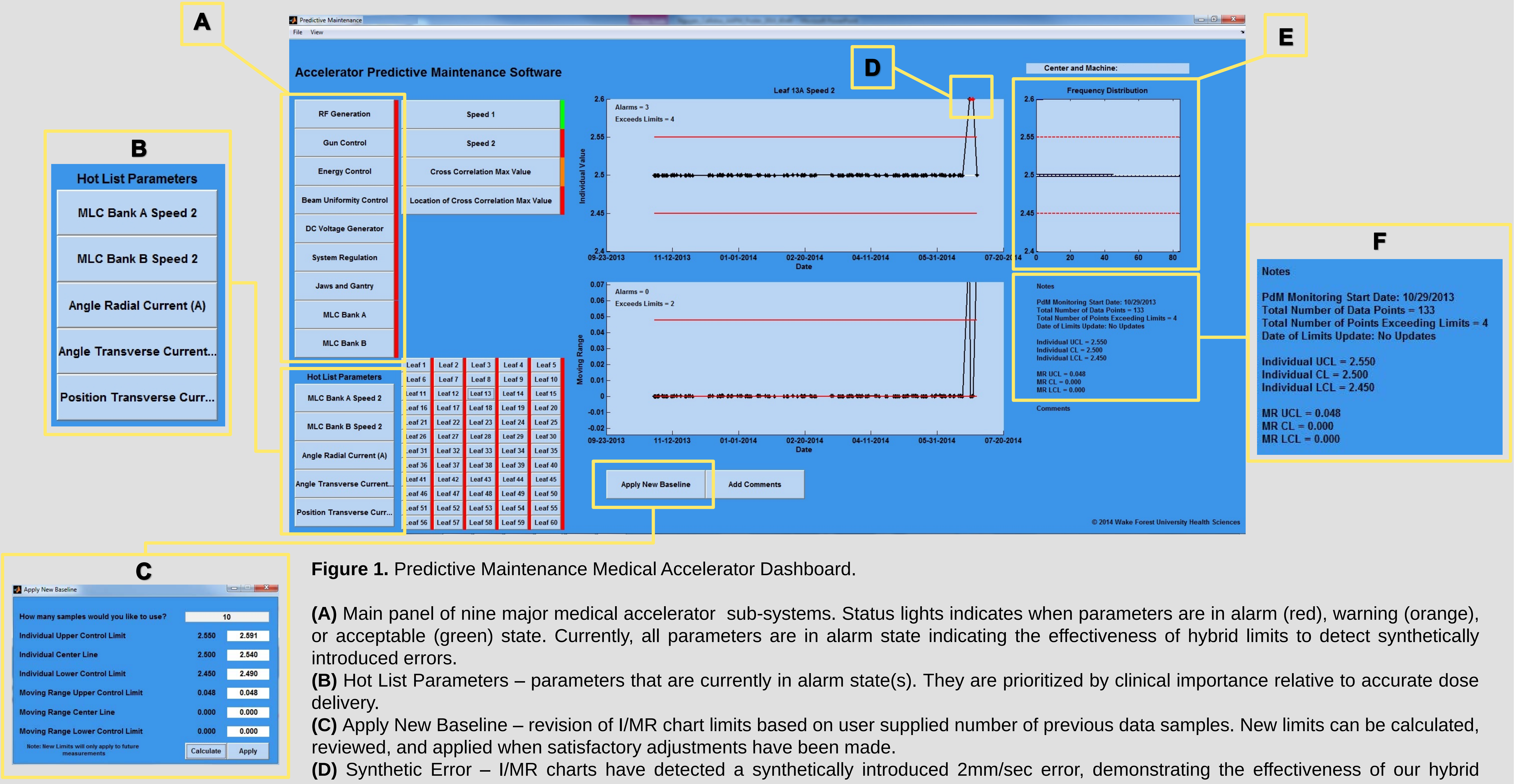


Figure 2. Normal probability density functions representing three I chart limit calculation methods for Gantry speed (traditional/standard SPC, Gantry manufacturer specification (±0.2 deg), and our empirical method).



Apply New Baseline

How many samples would you like to use? 10

Individual Upper Control Limit	2.550	2.591
Individual Center Line	2.500	2.540
Individual Lower Control Limit	2.450	2.490
Moving Range Upper Control Limit	0.048	0.048
Moving Range Center Line	0.000	0.000
Moving Range Lower Control Limit	0.000	0.000

Note: New Limits will only apply to future measurements

Notes

PdM Monitoring Start Date: 10/29/2013
Total Number of Data Points = 133
Total Number of Points Exceeding Limits = 4
Date of Limits Update: No Updates

Individual UCL = 2.550
Individual CL = 2.500
Individual LCL = 2.450

MR UCL = 0.048
MR CL = 0.000
MR LCL = 0.000

Figure 1. Predictive Maintenance Medical Accelerator Dashboard.

(A) Main panel of nine major medical accelerator sub-systems. Status lights indicates when parameters are in alarm (red), warning (orange), or acceptable (green) state. Currently, all parameters are in alarm state indicating the effectiveness of hybrid limits to detect synthetically introduced errors.
(B) Hot List Parameters – parameters that are currently in alarm state(s). They are prioritized by clinical importance relative to accurate dose delivery.
(C) Apply New Baseline – revision of I/MR chart limits based on user supplied number of previous data samples. New limits can be calculated, reviewed, and applied when satisfactory adjustments have been made.
(D) Synthetic Error – I/MR charts have detected a synthetically introduced 2mm/sec error, demonstrating the effectiveness of our hybrid method of calculating chart limits.
(E) Frequency Distribution – horizontal histogram distribution of "Individual" data samples.
(F) Notes – standard summary of parameter history and I/MR chart statistics

Conclusions

SPC I/MR evaluation of trajectory log file parameters may be effective in providing an early warning of performance degradation or component failure for medical accelerator systems.

Acknowledgements

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