Whitepaper

Model management for predictive accuracy

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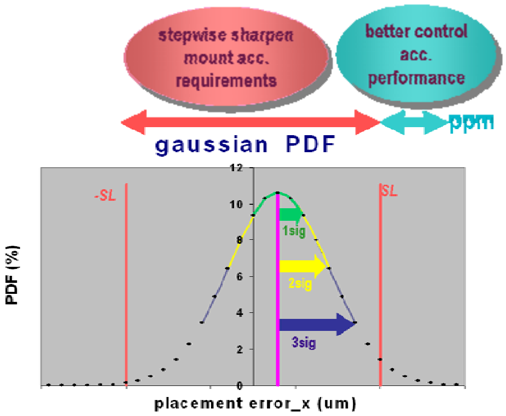
Abstract

Assembléon B.V. develops pick and place machines for microelectronic components. In order to control the accuracy performance of placement at printed circuit boards, empirical knowledge has been brought into fashion by the way of an accuracy management tool, in the form of Monte Carlo numerical simulations. This enables a better understanding and control of the AX machine precision performance.

Introduction

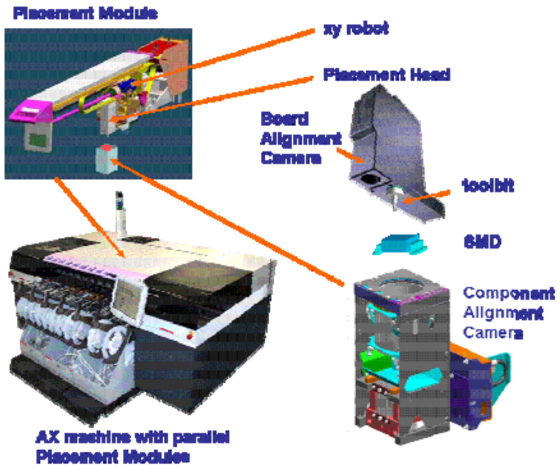
The current trend of miniaturization in products and substrates is expected to continue in most advanced electronic products. Telecommunication and computer applications typically need high density connection boards incorporating smaller passive components, finer pitch IC's and area array packages. The key factor in the technically successful evolution is the development of new interconnection processes, such as the use of conductive adhesive with very fine grained inter-connection materials. Consequence is that higher accuracy is required for placing Surface Mount Devices (SMD's) at the carrier footprints (Figure 1), to ensure together with high precision placed bonding material the required bond quality. Moreover, very high economical pressures are pushing production facilities to assemble products at very low cost. This requires a continuous reduction in the number of rejects through reliable and stable (in control) assembly processes without the need of inspection systems.

Figure 1 Typical trend in accuracy requirements for component placers is to lower both specification limits (SL) and reject levels (ppm = parts per million).
Note: PDF means "Probability Distribution Function"



Assembléon is market leader in providing high performances in both placement accuracy and output in the same machine. Its new AX placer (Figure 2) introduces the fine pitch component range capability into the parallel placement technology by the way of CCD component alignment cameras.

Figure 2: Schematic view of the AX machine and one if its parallel modules



It is able to place components on substrates with a precision of 50 µm ($\mu + 4\sigma$, Cpk=1.33) at a rate of 100k components per hour. Moreover, a process of continuous improvement has been installed exploiting new accuracy management methods.

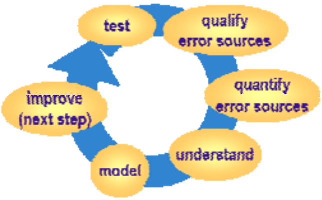
Accuracy management loop

Building accurate placement machines starts with selection of the right machine concept, including the modular architecture, related dimensions and mechanical interfaces. Adequate technologies must be selected when accuracy targets are tight. Motion, mechatronics and vision disciplines but also machine materials and constructions, manufacturing technology and tolerances, largely influence the inherent precision of the different machine modules. In addition, the end precision can only be guaranteed by separate module and system calibration.

In this complex puzzle about precision, the perception of the key playing pieces and interactions is vague. Though, this knowledge is very precious, as it is basic in initiating new development programs for better performance.

The control of accuracy starts in fact with empirical data of separate modules (robots, cameras,…). Members of interdisciplinary module teams are in charge of the continuous update of a parametric partition of the accuracy budget at modular level. Submitting the modules to different boundary conditions, the root causes of inaccuracy must be identified. Measurement methods must be defined to quantify the related inaccuracy contributions. The acquired knowledge is then reflected and fixed in tested models. Extending these practices into the integrated machine system creates the foundation for controlled machine precision (Figure 3).

Figure 2: Accuracy management loop

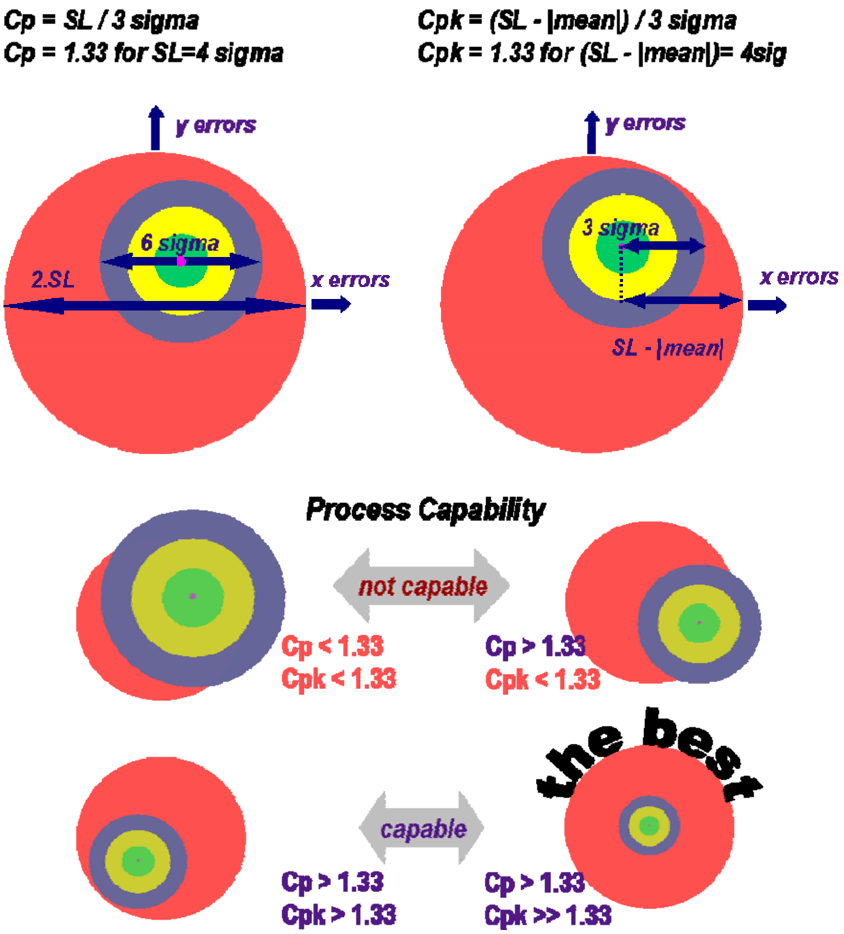


It is well known that the causes of placement deviations are classified in two groups: deterministic and stochastic errors. Deterministic errors are considered as emanating from dimensional static imperfections (manufacturing and mechanical interface tolerances, imprecise calibrations) and quasi-static inaccuracies (e.g. wear and temperatures varying slowly in time). Stochastic errors are for their parts related to dynamic variables in the placement process (vibrations, friction, spindle errors, quantization processes in the CCD cameras, scattering of placement coordinates and variations in material characteristics like circuit dimensional stability, component colour and geometries).

Deterministic errors have the same values when placing components of different type, with the same machine modules, at different footprint positions and orientations, on different substrates. Stochastic errors have different values for each component placement, even repeating placement of the same component on the same placement coordinate of the same board, and are often called process errors because most of them are specific to the physics of the placement "process".

Stochastic accuracy (4σ) is the dominant part of the AX placer accuracy, which makes the control of accuracy very hard and decreases the profit of eventual feedback loops. Statistics is therefore crucial in standards about Surface Mount Equipment Characterizations, like the IPC-9850 (1). With regards to the statistical treatment of placement deviation data, deviations are assumed to follow normal (Gaussian) distributions characterized by an offset 'μ' (a mean deviation of deterministic errors) and a spread 'σ' (the standard deviation of the stochastic errors). Both specifications and quantification values are expressed in terms of capability index values (Cp and Cpk) according to the capability to place components within some tolerance limits. These 'technical Specification Limits (SL)' are given in Figure 4 (e.g. 50 um with Cpk>1.33).

Figure 3: Cp and Cpk capability indices:



Set-up of numerical models

It is a real challenge to build models estimating placement accuracy since they have to deal with both analytical and statistical formulations. The approach presented in this paper has been developed in cooperation with Philips/CFT/Mechatronics (2).

<u>The analytical model</u>

The aim of the analytical model is to catch the complete AX pick and place process in a series of homogeneous transforms following the practice in robotics as implemented in the control SW of Code/Cimetrix (3), and to express results in substrate coordinates.

Modelling the new AX capability of handling large IC’s with Component Alignment (CA) CCD camera’s, the following analytical processing sequence is followed:

- First measuring the board position w.r.t. the xy robot,
- Then, measuring the component position in the frame of the Placement Head System, and w.r.t. the toolbit centre of rotation (COR),
- Solving the “corrected” xy & φz placement coordinate in the xy robot and Phi-Z unit frames (inverse kinematics), and

- “Placing” the component at corrected coordinate,
- Finally, measuring the placement deviations w.r.t. the footprints in the board CAD frame, as should be measured by Coordinate Measuring Machines (CMM’s).

The model uses the defined machine nodes: Cartesian (X,Y,Z) frames assigned by geometrical drawings or by calibrations to the separate machine modules. The planar character of the substrates is exploited to restrict transforms to 5 degrees-of-freedom in a 2D-dimensional world, which is very useful in limiting the complexity at this stage of modelling. Variables concerned are rotation around the Z axis, translations in x and in y, and anisotropic stretch in x and in y.

$$F = \begin{pmatrix} x' \\ y' \\ 1 \end{pmatrix} = T.v = transl(Tx, Ty, 0).rot(0,0,\theta z).strecth(sx, sy, 0).v(x, y, 1) = \begin{pmatrix} sx.\cos\theta z & -sy.\sin\theta z & Tx \\ sx.\sin\theta z & sy.\cos\theta z & Ty \\ 0 & 0 & 1 \end{pmatrix} . \begin{pmatrix} x \\ y \\ 1 \end{pmatrix}$$

Each processing step is modelled as kinematic chain of such transforms, which solution consists in the value of 1 or 2 transforms required to solve the next analytical step (Table 1).

Table 1: Summary of sequential analytical equations

	Analytical equations	searched transform solution	Delivered transforms *
1	Board alignment	board alignment transform	robotTcad (T,R,S)
2	Component alignment	Component position in the PHS w.r.t. COR and w.r.t head frame	corTcomp (T,R) & headTcomp (T,R)
3	Correction: inverse kinematics	“corrected” xy and φz to use for placement	robotThead (T) headTcor (R)
4	Motion: forwards placement kinematic chain	reached “placement” coordinate in cad frame	cadTcomp (T,R)
5	Placement error equation	difference between cad coordinates of footprint and of placed component	Plerr matrix (T,R)

**) aaaTbbb transform gives the coordinates of object bbb in the aaa Cartesian frame. Transform parts with non zero nominal values are indicated as follows: T =Translation; R = rotation; S = stretch*

The kinematic transform chains have been programmed in MATLAB® (4). Realistic “nominal values” of the variables, that is what is really achieved by mechanics and calibrations, are selected to solve the analytical formulas.

Calibration concepts impact fundamentally the kinematic chains basic to the models (and related errors). Small HW changes can be solved by adapting accuracy budget values, while maintaining the same list of accuracy errors.

Set-up of accuracy budgets

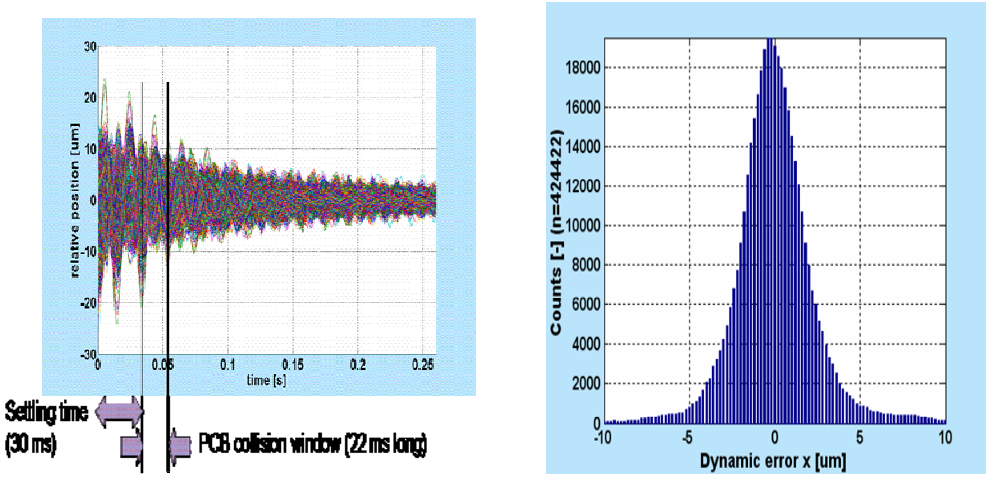
It is important to make the list of accuracy errors complete. In the AX machine, about 50 errors have been identified with either x,y and/or variable. As already told, each error type should be allocated to a module, its related process, interface or system boundary working conditions, since it makes the responsibilities between the development groups clear. In addition, it gives the possibility to distribute the accuracy budget in a specification stage.

Accuracy budgeting aims at reducing the list of errors into a list of statistically independent variables (as much as possible): the cross correlation between them is zero. Moreover, all errors are distributed following different partitions, like that of deterministic (“mod”) or stochastic (“proc”), and like that of the machine modules. This allows us to do a sensitivity analysis on the output of the model, quantifying the contribution of each input error measured at module level, or group of input errors following a selected partition, to the end placement error. Note that linking these non-correlated variables with analytical formulae can introduce some correlation in the end dx,dy and dphi accuracy results.

The accuracy budget is finalized when the type of Probability Distribution Function (PDF) is identified, and when the related variables are quantified. Since most errors are of the normal type N(μ, σ), quantification of both repeatability (σ) and maximum fixed deviations from target values (mean, μ) are required. Typical examples are:

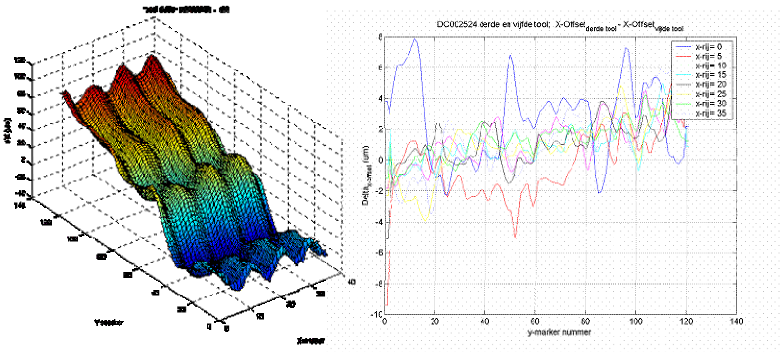
- The error from the settling behaviour of the toolbit for different robot types, accelerations, setpoints and path lengths Figure 6),

Figure 6: Distribution of dynamical error-x in a 22ms substrate collision window (195.3 us/sample) after correction into zero end position: [μ=0; 3σ=7/5μm at 30/55ms settle time]



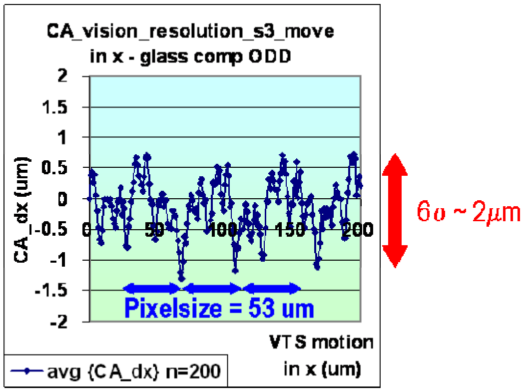
- The repeatability in calibrating the work area of the xy robot at the robot manufacturer, making use of a lithographic glass marker plate (Figure 5).

Figure 5: Calibration data given at left, and differences between these data for the same robot calibrated at 2 calibration tools [μ = 0; 3σ = 12μm]



- The uncertainty in the SMD position returned by the component alignment camera for sub-pixel movements of the component w.r.t. Component Alignment CCD camera (Figure 7).

Figure 7: Sub-pixel resolution moving with a Vision Test System (VTS) a component detected with 40 edges over CCD pixels [μ=0; 3σ=1μm]



- The uncertainty of board marker positions for varying illumination conditions fulfilling each the image quality required to be processed (Figure 8).

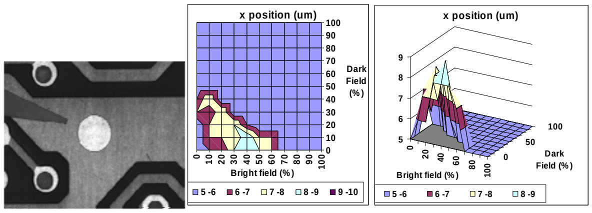


Figure 4: Variations in board marker position for all illumination settings teachable to the board alignment camera. Consequence is a stochastic error [μ=0, 3σ=3μm] in the case of artwork recognition (using a lot of board markers to assemble all components) or a deterministic error [μ a value of N(0,σ=1μm), 3σ=0μm] in the case of global fiducial recognition (using only 2 or 3 markers).

<u>The statistical model</u>

The impact of the statistical errors could be treated applying the theory of propagation of errors to the formulations of the analytical model (5) . Unfortunately, this method introduces an unnecessary high complexity in the analytical formulations by the way of covariance terms. In the simple example of kinematic chain T = F1.F2.F3, where the Fi's can introduce correlation between the x and y errors by the way of rotation terms, each element k of the transform T has its error written in terms of the variances σ^2_x and σ^2_y, and of the covariance σ_{xy}:

$$\sigma^2\, T_k = (\partial\, T_k/\partial\, x)_\mu^{\,2} \,.\, \sigma^2_x + (\partial\, T_k/\partial\, y)_\mu^{\,2} . \sigma^2_y + 2.\,(\partial\, T_k/\partial\, x)_\mu \,.\, \sigma_{xy} .\, (\partial\, T_k/\partial\, y)_\mu$$

Moreover, quantification of these covariance terms is often error prone.

However, not dealing with such correlations in a series of transforms can lead to considerable errors. This is e.g. the case if angular errors induce x, y errors on end-points of critical positioning devices. Statistical numerical methods have therefore been given preference to the theory of propagation of errors.

The error sources of the accuracy budget are mapped onto the appropriate variables in the analytical transforms (Table 2). These errors are shaped as vectors with a length of n~10000 numerical “Monte Carlo” realizations, random samples of the respective Normal distributions.

The “pr_position” of footprints is added in the list of statistical input variables. It is not an inaccuracy source, but generates just a random selection of n footprints in the robot frame. This variable has a uniform PDF.

Only few board markers positions have been programmed in the model to simulate the effect of board alignment using maximum 3 markers for hundreds of component placements.

Table 2: Kinematic chain about fiducial coordinates in the xy-robot Cartesian frame (robotTfiducial). Nominal variable values are given together with the applicable error.

robotThead	headTbam	bamTmarker
Nominal values in mm and mrad		
(x,y)a= (95,225) *) φa=1	(x,y)b= (0.15,0.15) φb= 35 mrad	(x,y)i=(1.5,1.5)**) φi=-15 mrad
Errors ***) (with n Monte Carlo realizations) added		
To the translation variables		
Pr_dynamic Pr_crosstalk Pr_reproduction Pr_calibration_residu Pr_temperature Pr_temperature_alinear	Ph_calib_bam_to_head	Ba_pixelsize Ba_vision_resolution Ba_light Ba_skew
To the rotation variables		
Pr_calibration_residu Pr_interface_temperature Pr_interface_calibration Ph_mechanical_calibration Ph_mechanical_interface-reproduction		

**) expected marker coordinate in xy robot frame*
***) nominal marker values in the Board Alignment camera (from board transport)*
****) Abbreviations used:*
Ba(m) = Board Alignment (Module): a CCD camera
Pr = Placement xy robot
Ph = Placement head (integrating Phi-Z unit and Bam)

The placement accuracy is then calculated statistically from a n samples large population of x,y and phi errors, added to the nominal values, identical for each of the n Monte Carlo realizations. This means that the equations of Table 1 are solved n times to simulate n component placements, each characterized by other incidental errors, but also other machine modules and other footprint cad positions.

The resulting end-placement is a n-long matrix calculated as the difference between the transforms of “placed” components and related footprints in the cad frame.

Placement_error = cadTcomponentplaced – cadTfootprint

Results

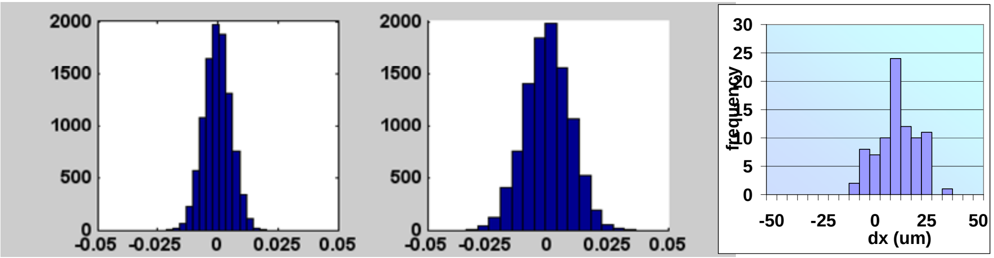
Statistics is successively applied on the collected n sample values of the placement error matrix translation x & y and rotation □ variables, and n samples combination of them at the component's lead tips (where □ error induces x & y components). Typical results generated with these data are:

- The Specification / Cpk1.33 of the accuracy performance of a single placement module tested following the IPC-9850 standard (1) (Table 3 & Figure 9). The selection of one single module means that the contribution of the group of deterministic errors is taken as worst case (accepting 2% reject after production)

Specification of Worst case Placement Module placing QFP80's (16.8 mm size, pitch 0.65 mm)	x (um)	y (um)	phi (mrad)
maximum allowed offset	13	7	0.2
maximum allowed repeatability (1 sigma)	9	9	0.4
accuracy specification limit (Cpk=1.33)	50	42	1.8
maximum Lead Tip Error specification limit (Cpk=1.33)	54	44	n.a.

Placement Module Measured placing QFP80's (16.8 mm size, pitch 0.65 mm)	x (um)	y (um)	phi (mrad)
offset	9	3	0.3
repeatability (1 sigma)	10	5	0.4
accuracy (offset + 4 sigma)	48	24	2.1
maximum Lead Tip Error specification limit (Cpk=1.33)	53	31	n.a.

Table 3: Comparison between model results and one of the first AX placement modules with CA camera measured. Measured Y data are better than estimations from model since most y robots perform better than their specification



a) b) c)

Figure 9: Histograms of QFP80 (pitch 0.65mm) placement deviations
a) results of model (n=10000 samples): distribution of deterministic deviations over the placement modules
b) results of model (n=10000 samples): distribution of stochastic deviations per placement modules
c) measurement of one single module with very low statistics (n=85) (the average error should be one random selection of distribution a)

- The Specification (Cpk1.33) of the accuracy performance of a large number of single placement modules assembled in several AX machines in series and tested following the IPC-9850 standard (1) (Figure 10). The deterministic errors add statistically to the stochastic ones, which brings the offset to zero.

Table 4: Specification of AX machines integrating more than 25 placement modules.

Specification of AX machines with several Placement Modules placing QFP80's (16.8 mm size, pitch 0.65 mm)			
	x	**y**	**phi**
	(um)	**(um)**	**(mrad)**
maximum allowed offset	0	0	0.0
maximum allowed repeatability (1 sigma)	11	10	0.4
accuracy specification limit (Cpk=1.33)	44	38	1.6
maximum Lead Tip Error specification limit (Cpk=1.33)	47	36	n.a.

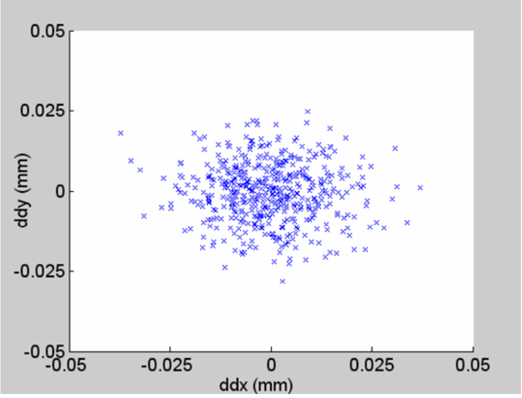


Figure 10: Correlation plots of AX machines integrating more than 25 placement modules

- The ranking of the partition groups w.r.t. their contribution to the end placement accuracy in terms of partial standard deviations (Figure 11).

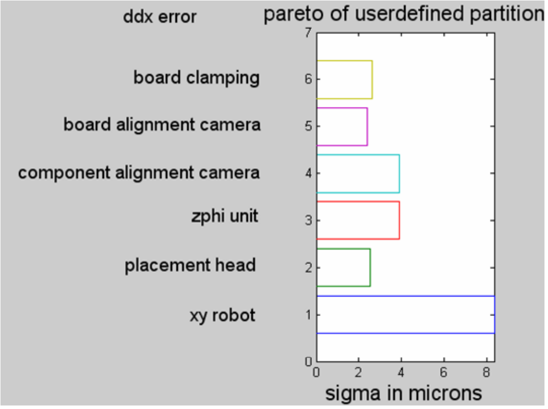


Figure 11: Pareto of partial sigma values for the different modules in a AX machine using several placement modules.

- The local accuracy character originated from the AX board alignment algorithm (Figure 12). This knowledge is explicitly used in the product preparation SW to select appropriate artwork features guaranteeing each separate component a specific required accuracy.

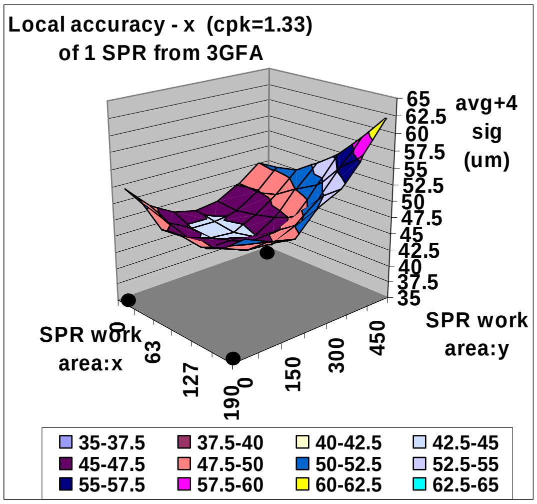


Figure 12: The local accuracy distribution in the work area of the robot is a function of the board alignment algorithm selected, the number of substrate markers used and their positions (black circles in the figure), and the anisotropy in relative stretch of the xy robot w.r.t. the susbtrate.

Conclusions

The management model presented in this paper is a powerful tool during the early development phase of a new machine. Conception of new machines, correctness of measurement, calibration and correction methods, distribution of accuracy budgets over the modules and resulting accuracy performance can be exercised and estimated. Succeeding improvement steps, planning new technologies, HW/SW upgrades of separate modules or system calibrations, can be selected from the pareto of partial sigma values of the module partition group, or even of a partition group using all separate error sources. The same pareto can be used in value engineering to indicate over-specified module elements in the budget.

References

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2) Sensitivity Analysis for Machine Accuracy, Internal Philips report,CFT note, CTB593-00-5112, D.Vangheluwe, 8 aug 2000

3) Cimetrix Incorporated, headquartered in Salt Lake City, Utah, developer of software products for motion intensive applications. CODE™ (Cimetrix Open Development Environment for machine control) is one of their core product (see www.cimetrix.com/codefamily.cfm)

4) MATLAB® is a core product of The MathWorks, Inc., provider of technical computing and Model-Based Design software, Headquartered in Natick, Massachusetts (USA); The Mathworks, BV (Benelux), Postbus 280, 2800 AG Gouda.

5) FCM II 6.1 NT, Calibration and Correction Model QCLC and BVM FoV Update, APEX 2002 Project, Piotr J. Meyer, Philips CFT North America, Department Mechatronics, 2001_06_15