Towards the practical dynamic

Dynamic error budgeting is a tool for designing high-precision systems. Its application, based on practical rules, to the specification and design of an accurate XY-θ stage is presented. It was concluded that all specifications of the stage could be met using this method.

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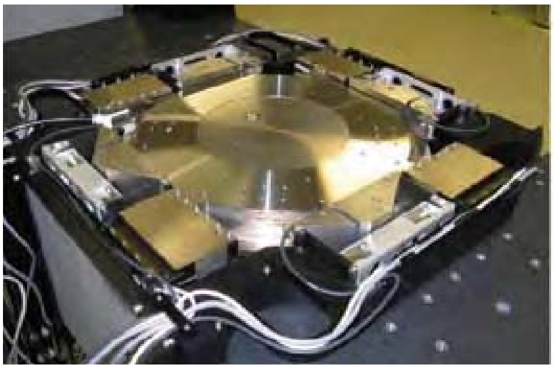
Dynamic error budgeting (DEB) [1] is a tool for designing high-precision systems. It is a first-time-right method, based on predicting disturbances and dynamics in the specification and design phase of a mechatronic system. During normal operation, systems will be subjected to many different disturbances. The power of the controller to eliminate the effects from such disturbances is generally limited and thus accuracy, as measured at the system sensors, is limited.
During the design of new systems, it is required to be able to predict the performance. To give such predictions, models of the system behaviour are made. Such models, when properly used, allow for the design of suitable control schemes. In many cases the design will be optimized to achieve a certain dynamic response or a certain error-correction capability as a function of frequency. For the user however, it is required to predict the position errors as a function of time under the influence of all potential disturbance sources.

Application

Dynamic error budgeting has been applied to the specification and design of an accurate XY-θ stage; see Figure 1. The required stage position error (noise) was 50 nm (3σ) on a VCC floor [3], a common standard for most lithography and inspection equipment to 1 μm detail size.

Modelling

The DEB method as introduced by J. van Eijk et al. in 2004 [2] is an approach that builds upon the use of Parseval's theorem linking frequency-domain and time-domain data; see Figure 2. In this method the different disturbance sources are identified during design. Suitable estimates of the magnitude and frequency content are determined and used to act upon the



application of error budgeting

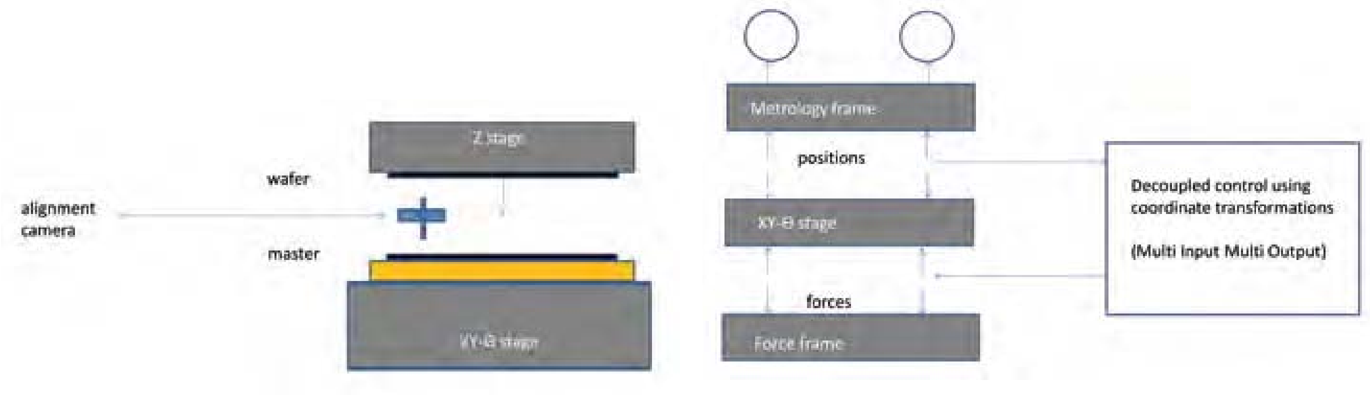


Figure 1. XY-θ stage (see also previous page) using air bearings, linear motors, linear encoders and a force frame.

model of the controlled system. The closed-loop frequency-domain transfer functions of the design are used to propagate each disturbance to the performance variable to obtain the power spectral density (PSD) of the performance. Based upon this information the total performance in the time domain can be calculated statistically. The individual contributions can be identified and the dominant dynamic effects can easily be seen in the cumulated power spectrum (CPS) over the relevant frequency range.

Design

Design choices such as bandwidth, frequency of vibration isolation, and use of force frames have been made on basis of DEB results and applied to the model of the stage and the disturbances; see Figure 3.

Verification

Comparing measured 3σ values to calculated 3σ values, it can be seen that results on a typical clean room floor are significantly better than the specification; see Figure 4. The actual noise level from the floor is less than specified. Applying the actual floor disturbances to the models results in the cumulated amplitude spectrum (CAS) of Figure 5. It shows a model accuracy of 1.2 nm. The small deviation might be due to the air bearings and measurement accuracy. The main disturbance is from floor vibrations

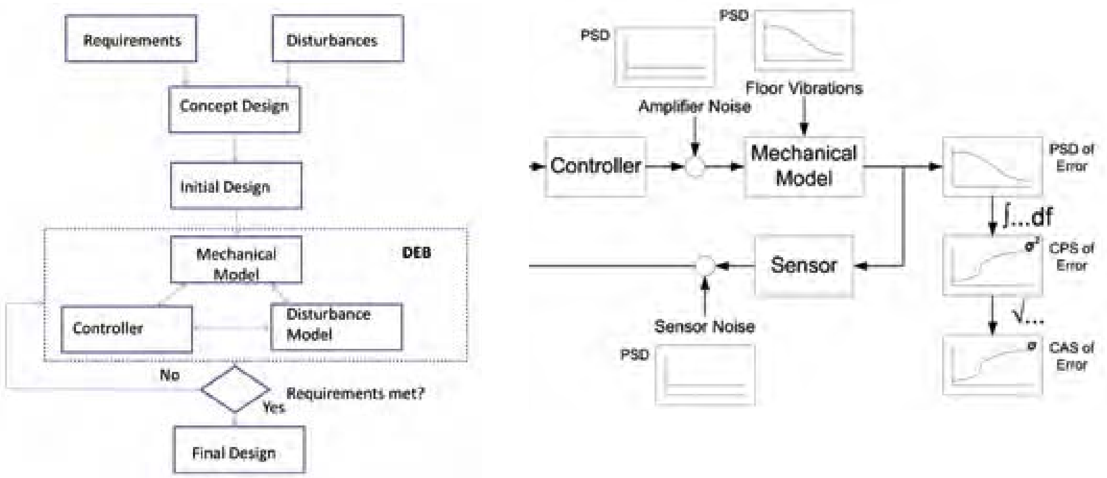


Figure 2. Design method and modeling.

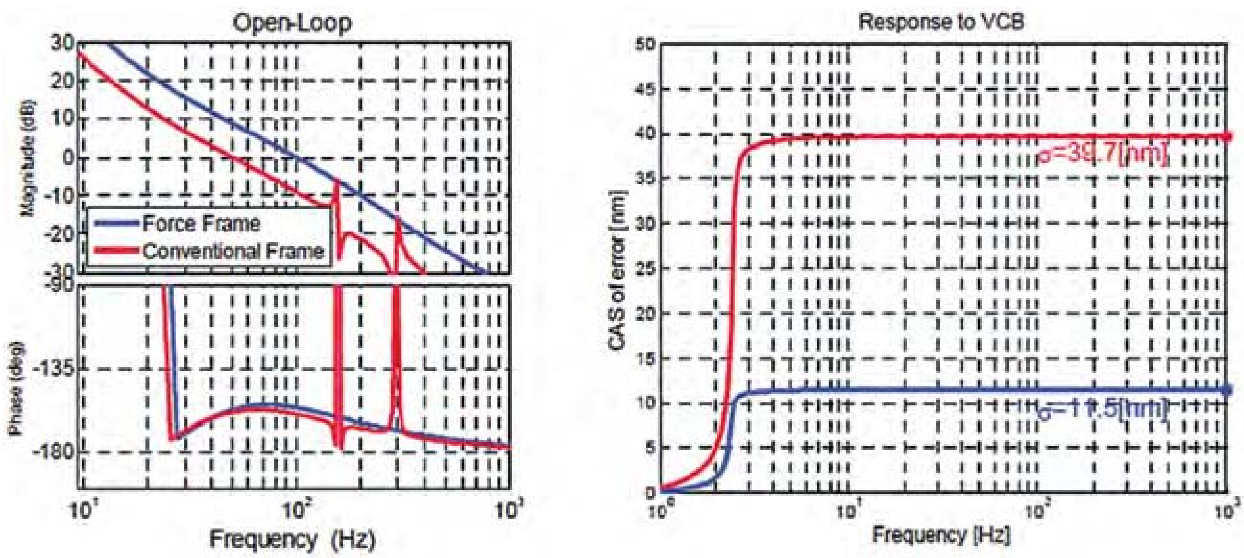


Figure 3. Influence of force frame on accuracy, and summary of design choices (see table below).

Options	Colin Gordon floor		Force frame		High base suspension	
	VCB	VCC	50 Hz servo bandwidth	100 Hz servo bandwidth	2.5 Hz vibration isolation (air mounts)	5 Hz vibration isolation (rubbers)
1	x		x			x
2		x	x			x
3	x		x		x	
4	x			x		x
5	x			x	x	
6		x		x		x

Amplifier noise

To drive the linear motor, the NYCe4000 motion controller from Bosch Rexroth was used. The Pulse Width Modulated amplifiers have a smaller error contribution (2 nm) than expected (5 nm); see Figure 6. The error due to the modulation frequency of 96 kHz can be neglected. The 2 nm contribution to the end result is mainly caused by the analogue-to-digital conversion and noise in the current feedback loop.

Practical application rules

Figure 7 shows the principle of the DEB method. In blue practical rules for successful application have added. The validated model can also be used to check the original theoretical Gordon VCC specification; see Figure 8. Its value is 43.1 nm.

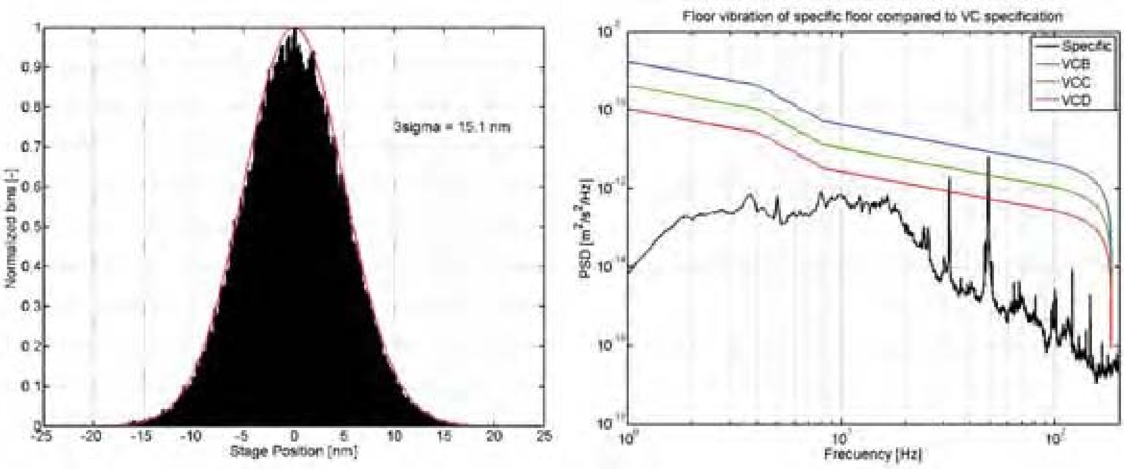


Figure 4. Repeatability error distribution (on the left), and noise from floor and position noise.

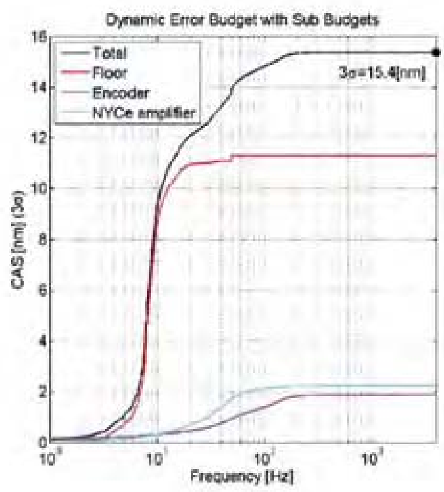


Figure 5. Simulated error budget using actual noise from floor.

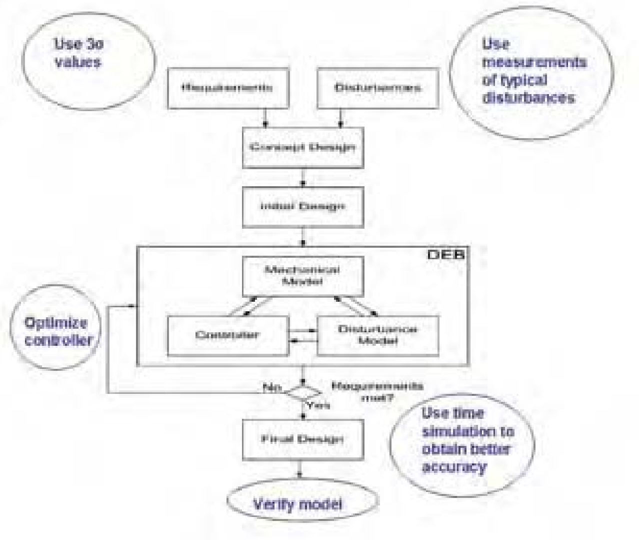


Figure 7. DEB design method and practical application rules (see table below).

Use 3σ values Gaussian	For specific purposes 3σ values, indicating 99.75% of a signal is within specification, are recommended to use and agree upon at the start.
Use measurement of typical disturbances	Colin Gordon floor specification is a theoretical method to indicate the floor disturbances. In practice the disturbances have different patterns. This results in a conservative value for the design and hence risk of over-engineering.
Optimise controller	Both mechanical concept and controller scheme including its parameters should be evaluated. In this case, the integrator value has a significant impact on suppressing the low-frequency disturbances.
Use time-domain simulation to obtain better accuracy	The DEB method is based on independent disturbances. By use of a closed-loop system some disturbances will be correlated. In a time-domain simulation these become visible, resulting in more accurate values. In this case the results are better.
Verify model	Do not only verify the results versus specifications, but also validate the model with the measurement. In this case, the amplifier noise of the NYCe4000 controller and the floor noise were measured separately. The resulting validated model can be used for further optimisation without changing the system and using its operation time.

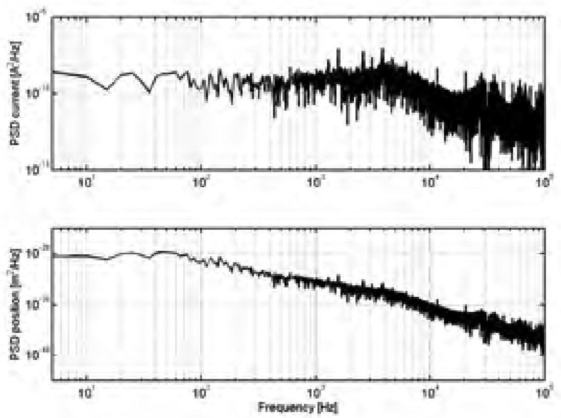


Figure 6. The power spectrum density (PSD) of the PWM amplifier of the NYCe4000 motion controller.

Further improvements using DEB

Based on the verified model further improvements of the accuracy can be shown. The integrator frequency can be increased to 20 Hz without losing too much phase margin. This could improve the performance from 15 nm to 9 nm. Decreasing the suspension eigenfrequency of the vibration isolators from the original 8 Hz to 4 Hz improves the accuracy to 7 nm at a higher cost price of the stage.

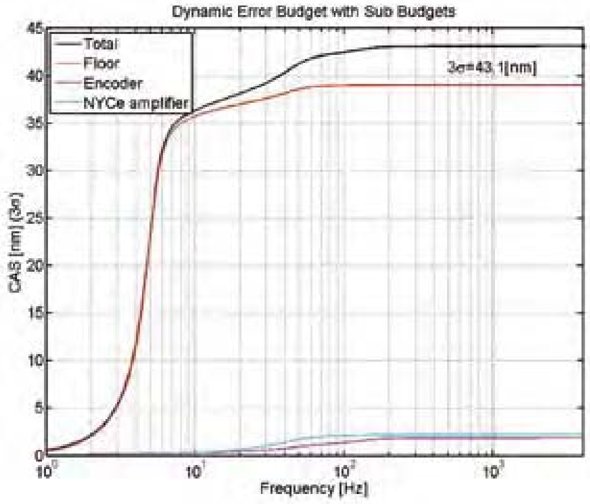


Figure 8. Cumulated amplitude spectrum on VCC floor (suspension frequency 5Hz).

Conclusions

All specifications of the XY-θ stage were met using dynamic error budgeting. The Colin Gordon floor classification [3] is a conservative value for predicting performance; it is more accurate to measure characteristic floors. DEB results should be analysed with care. The DEB tool is based on uncorrelated disturbance sources. It can be proven that most common disturbance sources, i.e. encoder resolution, are not uncorrelated. Therefore, time-domain simulations can provide more accurate results, since correlation of the disturbances is taken into account.

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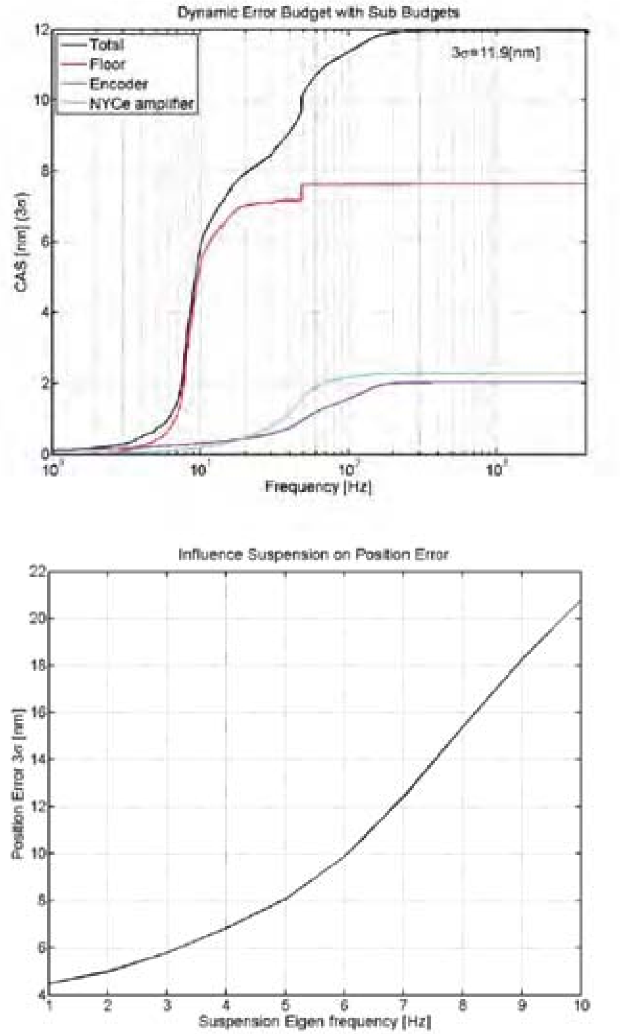

Figure 9. Error budget with optimised integrator value in controller; below, frequency of vibration isolation versus accuracy.

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