Optimizing the Feedback Control of Galvo Scanners for Laser Manufacturing Systems

Theodore Mirtchev, Robert Weeks, Sergey Minko

Algonquin College, 1385 Woodroffe Avenue, Ottawa, ON K2G 1V8, Canada

weeksr@algonquincollege.com; phone: 1 613 727 4723 / 3480

ABSTRACT

This paper summarizes the factors that limit the performance of moving-magnet galvo scanners driven by closed-loop digital servo amplifiers: torsional resonances, drifts, nonlinearities, feedback noise and friction.

Then it describes a detailed Simulink® simulator that takes into account these factors and can be used to automatically tune the controller for best results with given galvo type and trajectory patterns. It allows for rapid testing of different control schemes, for instance combined position/velocity PID loops and displays the corresponding output in terms of torque, angular position and feedback sensor signal. The tool is configurable and can either use a dynamical state-space model of galvo's open-loop response, or can import the experimentally measured frequency domain transfer function.

Next a drive signal digital pre-filtering technique is discussed. By performing a real-time Fourier analysis of the raw command signal it can be pre-warped to minimize all harmonics around the torsional resonances while boosting other non-resonant high frequencies. The optimized waveform results in much smaller overshoot and better settling time. Similar performance gain cannot be extracted from the servo controller alone.

Keywords: laser drilling systems, galvo scanners, Simulink®, model-driven design and optimization

Introduction

Suppliers of high precision laser drilling/trimming equipment constantly search for ways to improve the performance of their system in order to match the demands of vast new application areas, such as drilling printed circuit boards for the automotive industry. High density interconnects printed wiring boards (PWBs) require drilling of hundreds of microvias per second with typical diameters of less than 50µm. One of the most critical modules of these step- and lase systems are the 2-axis galvo scanners. They include fast galvanometric actuators and the digital closed-loop servo controllers that drive them. Fine tuning of the feedback control for every specific application is always needed in order to increase performance and productivity.

The challenge is that new types of PWB's to be processed come with different sets of typical dimensions and via patterns. These translate into new typical laser beam trajectories. Therefore, the digital feedback control algorithms that drive the galvo subsystem have to be re-optimized with every major new product.

Ideally, increasing the speed and accuracy of galvo scanners by this re-tuning process should be automatic, fast and error-proof. This paper aims at creating a model-driven methodology and optimization tools that address this need.

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Limiting Factors

Optimal application-specific closed-loop control should be designed to minimize the main limitations. The performance of galvo scanners is limited by numerous factors summarized below [1,2]:

Torsional Resonances: At increased speeds the link between the galvo rotor and the mirror develops into a resonance at a frequency approximately given by:

$$\omega_r = \sqrt{\frac{K(J_R+J_M)}{J_R * J_M}} \quad (1)$$

, where J_R and J_M the two moments of inertia and K is the stiffness of the shaft. These resonances can be quite sharp, with gains > 20-30 dB. The presence of the torsional resonance severely limits the bandwidth that could be achieved by increasing the loop gain. Moving magnet scanners are especially sensitive because of their high torque, rigidity, and low inductance, which result in increased bandwidths. However, the highest harmonic in the drive signal or any other perturbing frequency should be kept well below ω_r. An optimized servo driver is needed to guarantee wide closed-loop bandwidths while mitigating the effect of the resonances.

Heat dissipation: A critical parameter is the thermal impedance of the drive coil that limits galvo's ability to dissipate the excess heat. The current drawn depends upon the size, speed, and repetition rate of typical beam motion patterns. Therefore the driving signals should be optimized for every particular application and galvo model in order to avoid thermal overload.

Drift: Thermal load causes short-term harmful variations of both electrical and mechanical parameters. Thermal drifts of the capacitive position sensor readings are particularly problematic for high accuracy systems. One solution is to counteract drift-related problems by including the experimentally measured drifts of the chosen galvo model in the control algorithm.

Nonlinearities: There a many potential sources of nonlinear response, for instance electrical, friction, mechanical misalignment in the angular sensor, etc. A digital controller should take these into account using lookup tables with experimental data.

Noise: Usually the feedback sensor system defines the noise floor of a closed-loop system. Noise accumulation will limit the achievable servo loop gain and thus the bandwidth. Many servo systems differentiate the position signal to generate a velocity feedback and provide damping. Digital differentiation is an inherently noisy operation and therefore a tradeoff between noise suppression and stability is needed.

Galvo Scanner Optimization Methodology

The galvo actuators are already highly optimized by the manufacturer and proprietary, so there are more options in tuning a customized feedback controller and drive signal generation. Some of the opportunities, considered in the present work are:

- Developing a detailed single-input multiple-output (SIMO) state-space model of the galvo that accounts for nonlinearities, noise and the other limitations.

- Model-driven optimization: including this model in an automatically optimizing Simulink® simulator of the full galvo encoder + feedback loop subsystem. Alternatively, the experimentally measured open-loop transfer function of the galvo can be used. Multi-variable optimization by simulation can predict the best tradeoff between speed and accuracy for every specific application.

- Spectral domain suppression of the torsional resonances while maximizing bandwidth. By performing a real-time Fourier analysis of the raw torque waveform it can be pre-warped to minimize harmonics in the vicinity of ω_r while boosting other non-resonant high frequencies.

Details of the proposed approaches are presented below.

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SIMO State-Space Model

A comprehensive state-space model of the dynamical response of a moving-magnet galvo scanner is expressed by the following equations [2]:

$$\frac{di}{dt} = -\frac{R}{L}i - \frac{T_i}{L}\frac{d\theta}{dt} + \frac{1}{L}(V_d + N)$$

$$\frac{d^2\theta}{dt^2} = \frac{T_i}{J_r}i - \frac{K_r}{J_r}\theta + \frac{K_r}{J_r}\varphi - \frac{B_r}{J_r}\frac{d\theta}{dt} \qquad (2)$$

$$\frac{d^2\varphi}{dt^2} == \frac{K_r}{J_m}\theta - \frac{K_r}{J_m}\varphi - \frac{B_m}{J_m}\frac{d\varphi}{dt}$$

The state vector is $x = |i, \theta, \varphi, \theta', \varphi'|$ where i the drive current, θ is the absolute angular position of the rotor, φ is the absolute angular position of the mirror and θ' and φ' are the corresponding angular velocities. The input is $= V_d + N$, where V_d is the applied drive coil voltage and N is an external source of noise which can be white and/or harmonic. The output vector is $y = |\varphi, V_s|$ where V_s is the angular sensor voltage $V_s = K_s\theta$ where K_s is the sensor constant in V/rad. The various coefficients are respectively T_i - the torque constant, L - the inductance of the coil, R - its resistance, K_r - the torsional stiffness of the element connecting the rotor to the mirror, J_r and J_m - the moments of inertia of the rotor and mirror and B_r and B_m - the friction coefficients. The first of these equations relates the drive voltage to the back emf, the coil inductive reaction, and the voltage drop in the coil. The other two equate the net drive torques to the inertial resistances and losses.

The model accounts for noise and experimentally calibrated nonlinearities and drifts, for example K_s can actually be the dependence $K_s(\theta)$.

For the initial design of the servo amplifier one needs the open-loop transfer function. From a simplified and linearized version of the SIMO model it can be derived in the form [2]:

$$\frac{\theta}{i} = \frac{T_i}{J_r}\frac{s^2+a}{(s^2+aJ_m/J_r)(s^2+a)-a^2J_m/J_r} \qquad (3)$$

, where $a = \omega_r^2 J_m/J_r$.

Automatically Optimizing Simulink® Tool

With this state-space model a Simulink® diagram of the scanner subsystem was built. Fig. 1 shows an outline of the multi-level hierarchy with the main modules: the PID position servo controller, the SIMO galvo actuator model and the driving waveform generator. It uses advanced features from various Matlab® / Simulink® toolboxes and blocksets [3]. A typical model-driven optimization process includes the following steps:

- When the specifications of a new PWB product are known the user enters the new typical x / y axis drive waveforms.
- Then, using a convenient Signal Constraint GUI shown in Fig. 2 he defines the new acceptable tolerances. For instance, upper limits on the rise time and overshoot after a step command can be defined.
- Next, the set of tunable parameters are selected. Normally, these are the coefficients of the PID controller, but any other feature can be included as well, for example digital filter bandwidths, feedback configuration, noise variance, etc.
- Then the automatic optimization procedure can be initiated. Using advanced multi-constraint numerical methods or genetic algorithms Simulink® will tune the selected parameters until the signals of interest satisfy the specifications.
- One final benefit of this tool is that by using Real-Time Workshop's [4] code generator one can directly output highly optimized low-level digital control code to be embedded in the servo, thus minimizing development and maintenance time.

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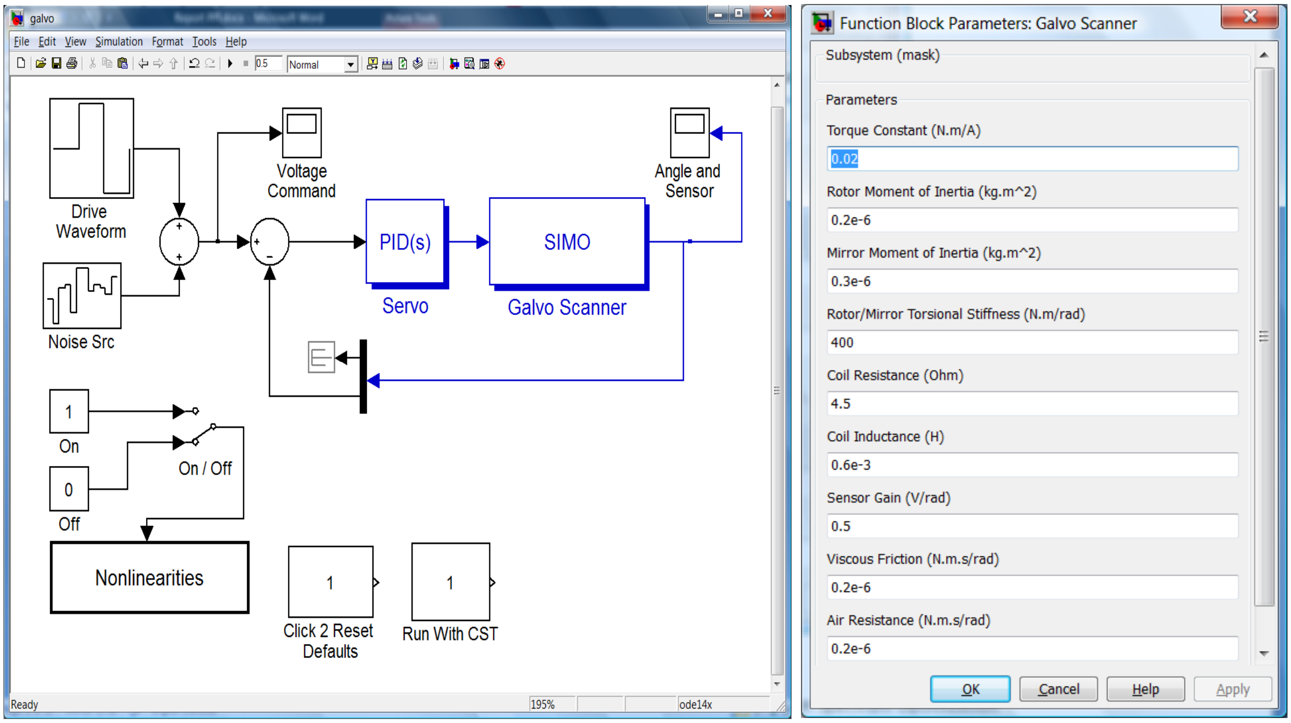

Fig. 1. The GUI of the optimizing simulator

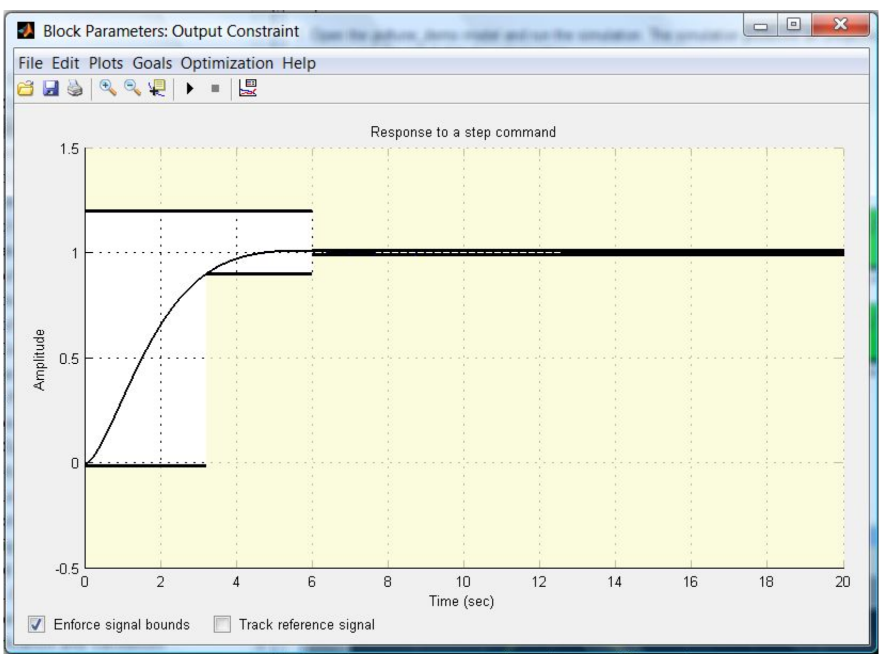

Fig. 2. The Signal Constraint GUI. By dragging the black limits upper and/or lower limits on various signal characteristics can be easily defined. The dark areas are "forbidden zones". Simulink® will then automatically tune the controller coefficients until the signal of interest satisfies the specifications, as shown here.

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Real-Time Drive Waveform Spectrum Optimization

This technique requires knowledge of the closed-loop transfer function of the scanner. The transfer function can either be:

- Approximated using eq. 3 above, or
- Experimentally measured with a dynamic signal and system analyzer, for instance SigLab 50-21 from Spectral Dynamics, Inc, http://www.spectraldynamics.com/

Than a digital pre-filter can be synthesized that will suppress drive waveform harmonics in the vicinity of the resonances, while pre-amplifying weaker high frequencies that are non-resonant. Fig 3 illustrates the Bode magnitude of an under-damped scanner and the transmission spectrum of one of the possible matching pre-filters. The galvo subsystem in this example uses a simple proportional feedback controller.

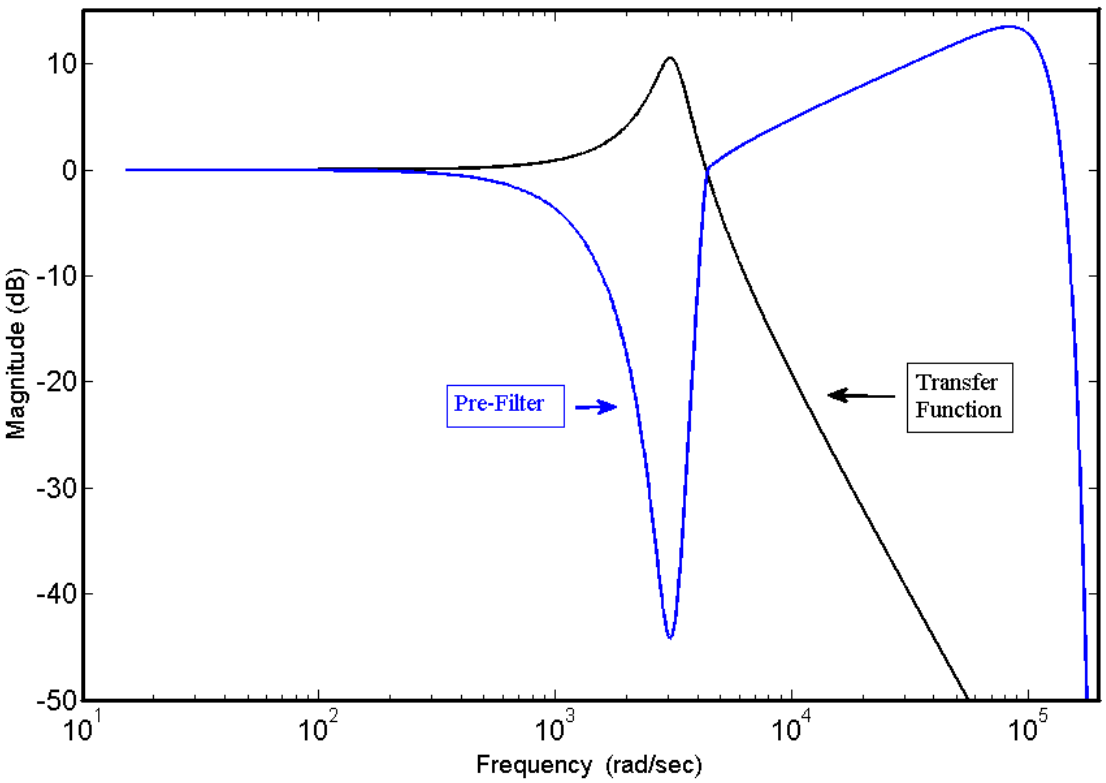

Fig. 3. Bode plot of a typical galvo scanner transfer function and the transmission spectrum of a matching pre-filter.

Fig 4 compares the dynamical responses of an under-damped galvo scanner in two cases: when it is driven by a simple step command (left) and with the pre-warped command waveform (right). The solid lines show the angular positions, while the dashed lines show the command waveforms.

It is easy to see that the scanner reacts to the optimized waveform (right, dashed line) with:

- Much smaller overshoot, and
- More than two times better settling time.

Note that similar improvement would be impossible to implement with classical PID techniques or in hardware, for example by bandwidth increase, because this will also increase noise sensitivity and may lead to instability.

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It is straightforward to add an implementation of this filtering technique to the optimizing simulator and tune parameters of the matching filter, foe instance the dB transmission of the notch feature under the resonance.

Further studies are needed to test the benefits of this technique when applied to more sophisticated controllers.

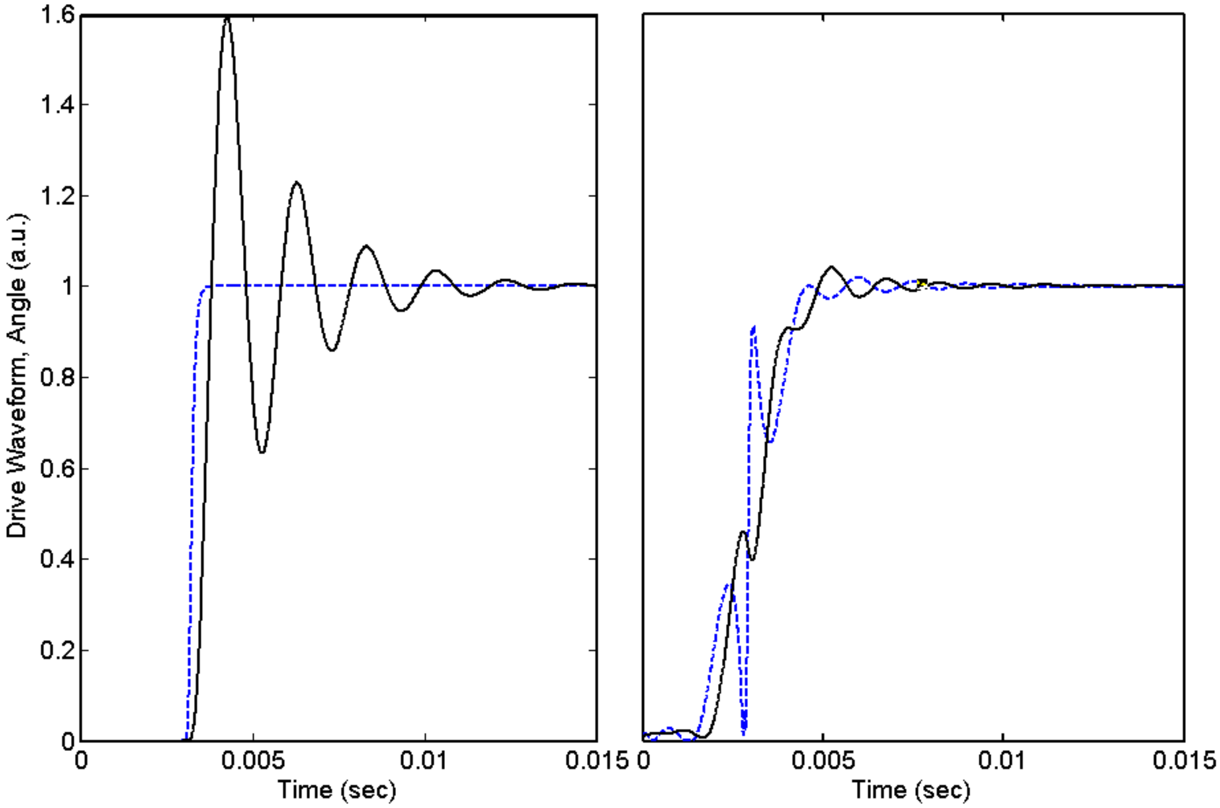

Fig. 4. Galvo response to a simple step waveform (left) and to a filtered drive waveform left.

Conclusion

We described a model-driven methodology that facilitates the re-tuning and the constant re-optimization of the galvo scanner feedback control algorithms used in high performance laser drilling systems. For every major new PWB product the user enters into an advanced diagram simulator the new typical beam movement patterns and the new acceptable tolerances. In essence, executable specifications are thus created. Simulink® can then automatically optimize a set of key parameters of the galvo/servo subsystem, for instance the PID controller gains, or digital filter bandwidths. Finally, tested re-optimized control code can be generated and downloaded to the processor embedded in the real controller. The procedure is simple, fast and automatic.

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