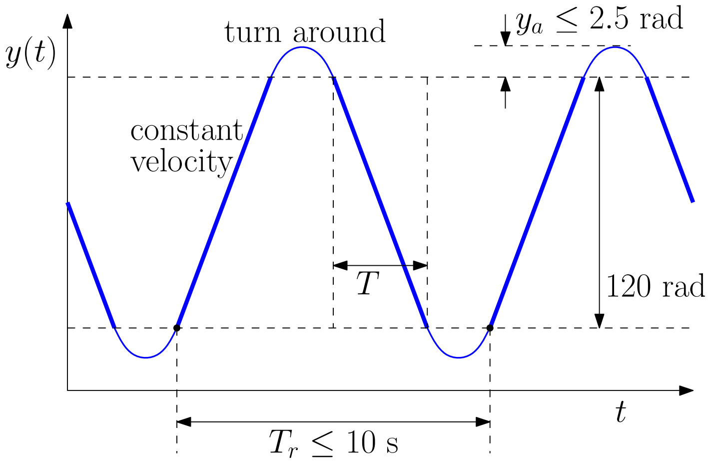

Figure X.3: Visualization of the constraints and requirements for the scanning motion of the non-collocated mass.

X.3 The final assignment

For the final assignment we assume that our 4th-order setup represents an actual industrial motion control application, where the goal is to accurately position the non-collocated mass along a certain trajectory. To be specific, we focus on a *bi-directional scanning* application, in which the load (the non-collocated mass) needs to move with a constant velocity over a certain distance or stroke (in this rotational case: the load needs to move a certain amount of rotations with a constant angular velocity), with a sufficiently small tracking error, both back and forth. Examples of such bi-directional scanning applications include print head motions of printers and plotters, reticle and wafer stages in lithography processes, and AFM imaging devices. The challenge is to make the scanning motion as fast as possible, i.e. to increase the constant scanning velocity while keeping the tracking error sufficiently low.

X.3.1 The numbers

In this assignment we assume that you are hired by an external customer to maximize the scanning performance of the system (supplied by the customer) using control engineering techniques. The customer thus wants you to achieve sufficiently small tracking errors, while minimizing the total time of the back and forth motion.

To this end there are a few strict application-driven constraints that *need* to be satisfied, which are further clarified in Figure X.3:

- The scanning stroke should be 120 rad, i.e. the constant velocity phase should cover (at least) 19.1 revolutions, both forwards and backwards.
- The total allowable stroke is only 125 rad, hence at the end of both forward and backward motion there is only 2.5 rad of stroke for a turn-around motion.
- Due to foreseen production variations and uncertainties, the modulus margin for the feedback loop should be at most 6 dB, i.e. $\max_\omega ||S(j\omega)|| < 6$ dB.
- The sampling rate of the control system is restricted to at most 4 kHz.

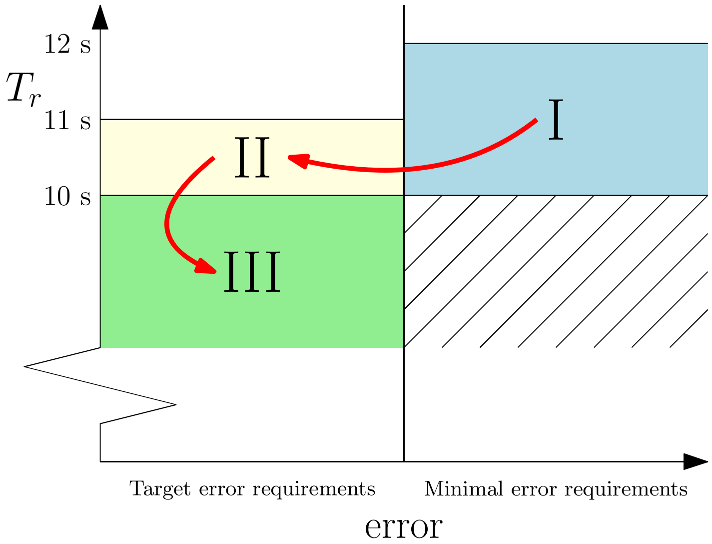

Figure X.4: Visualization of the relevant performance regions for the scanning application. Make sure to first demonstrate a region I performance, before trying to achieve a region II and/or region III performance.

Within these constraints, it is your job to maximize the scanning performance. The customer classifies this performance in three different regimes, illustrated in Figure X.4:

I. **Minimal performance region.**

- The total forward-backward motion takes 10 to 12 seconds (i.e. the period of the trajectory 10 s $\leq T_r \leq$ 12 s).
- The tracking error e during the 120 rad constant velocity phase satisfies
  - 6 mrad root-mean-square, i.e. $\frac{1}{T}\int_0^T e(t)^2\,dt < 6$ mrad;
  - 12 mrad peak, i.e. $\max\limits_{0\leq t\leq T} |e(t)| < 12$ mrad.

II. **Improved tracking performance region.**

- The total forward-backward motion takes 10 to 11 seconds (i.e. the period of the trajectory 10 s $\leq T_r \leq$ 11 s).
- The tracking error e during the 120 rad constant velocity phase satisfies
  - 3 mrad root-mean-square, i.e. $\frac{1}{T}\int_0^T e(t)^2\,dt < 3$ mrad;
  - 6.3 mrad peak, i.e. $\max\limits_{0\leq t\leq T} |e(t)| < 6.3$ mrad.

III. **Faster performance region.**

- The total forward-backward motion takes less than 10 seconds (i.e. the period of the trajectory $T_r <$ 10 s).
- The tracking error e during the 120 rad constant velocity phase satisfies the same stringent requirements as in region II.

The customer wants you to achieve *at least* a region I performance; however, he will pay you extra when a region II performance is achieved, simply because this performance has significantly more commercial value. For region III the customer will pay you even more; he will double the price for every second faster than 10 s.

X.3.2 The assignment

It is your task to analyze and control this system for the above described application. To this end, design a suitable trajectory and feedback controller (and possibly feedforward controller), such that the above constraints are met. Your customer wants at least a region I performance, but you are stimulated to further improve the tracking error (region II) and possibly also the scanning time T_r (region III); in all cases still satisfying all other constraints.

It is up to you to decide how to achieve this, but one decision will be made for you: the customer needs full knowledge and control over the point-of-interest (PoI), which is the the non-collocated sensor; as such, you will have to apply *load feedback*. Other than that, *you* decide what to do with it, which measurements to take, which controller to design, which iterations to make, whether to include feedforward, etc. Remember to always motivate your decisions!

Realize that although all setups look the same, they don't fully behave the same. Hence, some setups will be able to achieve better performances than others. Your grade will therefore *not* depend on the exact performance region you achieve, **but rather on how well you can show to have optimized it for your specific setup and the way you got there**. Stated otherwise, if you happen to work with a smooth setup, you are expected to be able to push the performance further than your colleagues with a less smooth setup. In the end, it's about convincing your customer that you've pushed your specific system to its limits. In your reporting, make sure to demonstrate why your achieved performance is the best possible for your specific setup, well-motivated by data and figures.

X.3.3 Preparation

Your time is limited, hence, you should prepare your sessions as good as possible. Make sure to carry out all experimental exercises of section X.2 first. Moreover, it is advised to document your preparation in a measurement plan, containing e.g.

- a rough prediction of the dynamics you expect to encounter;
- a description of the FRF measurements (and settings) you want to carry out;
- a proposed control strategy (feedforward or not, motor or load feedback, etc);
- a way of working for how to check the constraints and evaluate the performance (tracking error and T_r);
- an approach to tune the controller(s) and evaluate their tracking performance.

Needless to say, the purpose of your measurement plan should be that you know which data to take in which order, and that you have prepared the m-scripts to do so.

X.3.4 Execution

Document the execution of your measurements in a solid experimental report (to be handed in at the end of the quartile). In this report, show your intermediate results, validate your predictions, describe your lessons learned, demonstrate the system performance you have achieved and the way you got there. Show the appropriate **Bode diagrams**, **Nyquist plots**, **time traces** and **spectral analyses**, e.g. to prove your achieved bandwidth, margins and feedback error, but also to demonstrate that your design meets the constraints, and is near-optimal in terms of minimizing first the tracking error, and then T_r. Let your scientific results convince your client that you've done the absolute best.

X.3.5 Some last suggestions...

- Remember that you have access to both encoders, both yielding different dynamics, which you can use when validating your predicted dynamics or performing your first closed-loop FRF measurements.

- The SPERTE real-time control implementation can sometimes give short error spikes if not properly used. To limit these spikes to a minimum, take care not to make your Simulink scheme more complicated than necessary, and scope as little signals as possible (typically not more than 3), using **only** the real-time scope in the provided template. If these spikes remain, try **lowering the sample rate** to e.g. 3.5 or 3 kHz (you should do so in the Simulink file via Property Inspector → Properties → Callbacks → InitFcn). If, after these precautions, you still see distinct unexplainable error spikes (i.e. not correlating with your reference in any way), you can ignore them for the performance assessment, as long as you clearly defend this in the report.

- The current amplifier has a thermal safety; if by improper operation it is heating up too much, the amplifier will stop functioning until it cools down again. If this happens to you, just wait for it to come alive again (about half an hour); and in the meantime, think about what you should do differently to prevent it from happening again.

- Although the "Ref3" GUI is provided in the Simulink template to help you design your reference, you are free to design the reference in any other way you please, as long as it satisfies the constraints of the exercise. Note that its correct implementation will be your own responsibility in that case (tip: use `set_param.m` in that case).

- Use the time between different guided sessions to process your data, design controllers, determine a way forward and modify your plan. It is unlikely that you can use the exact same setup in different sessions, so use the first session mainly to get acquainted with the system and the challenge, and use the second session to tailor your final approach on your final setup to achieve your final performance.

- In case you need more time than the scheduled experiments, you can always borrow a setup at ProtoZone and work on it *in your own time* (i.e. without supervision). Visit ProtoZone for up-to-date information on their opening hours, which can be limited!