Adaptive Parameter Tuning of PID Controllers using Structured H_∞-Synthesis

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In industrial automation, mechatronic systems like industrial robots and electrical drives are frequently supplied with predefined controller architectures, which are strictly dictated by the robot control unit. These controllers are typically pre-tuned by the manufacturer for one specific, nominal operating point. However, when these systems have to fulfill dynamic tasks with changing physical conditions, the standard controllers often fail to deliver optimal results, as the assumption of a single nominal operating point is no longer valid. The physical mismatch forces the standard controller into a continuous state of overcompensation, resulting in high-frequency oscillations in the control signal, aggressive torque chattering, imprecise trajectory tracking, increased energy consumption, and accelerated mechanical wear.

Adapting the controller to specific application needs is particularly challenging because the internal architecture of most industrial servo drives cannot be structurally modified. Given the constraints of existing hardware, structured H_∞-synthesis emerges as a highly suitable approach to address this limitation [1], as it allows the direct optimization of predefined controller parameters without requiring full access to the control loop structure. The methodology is applied to a cascaded control loop, a structure commonly implemented in industrial robot controllers. The control objectives are formulated as a mixed-sensitivity problem in the frequency domain. By applying weights to the sensitivity and complementary sensitivity functions, the design enforces steady-state accuracy, ensures fast reference tracking, and suppresses high-frequency measurement noise [2].

To handle the parameter uncertainty introduced by varying physical loads, an interval-based adaptive control strategy is developed [3]. The continuous range of possible inertias is discretized into overlapping logarithmic intervals (see Figure 1). For each interval, a dedicated robust controller is synthesized offline using the `hinfstruct` command from the MATLAB Robust Control Toolbox [4]. This approach ensures that, regardless of the physical load, a stabilizing and highly optimized parameter set is calculated in an offline phase, which is then available for the current operating condition in the online phase.

The methodology is validated on a single-joint permanent magnet synchronous motor test system, where inertia is systematically varied by mounting metal disks directly onto the spindle. A digital twin architecture-combining TwinCAT [5] for real-time control and Virtuos [6] for process monitoring-injects the offline-calculated parameters into the servo drive via Servo over EtherCAT. Finally, the synthesized interval-based controllers are compared against the factory-default standard.

The results confirm the superiority of the structured H_∞-synthesis approach, particularly under challenging dynamic conditions such as abrupt position steps. Under maximum load conditions during such large step-wise position commands, the standard controller

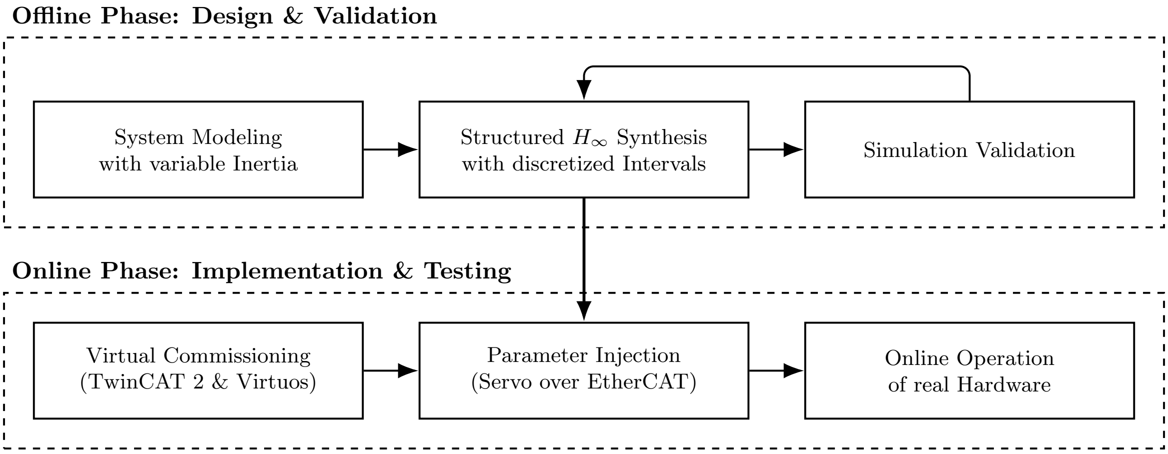

Figure 1: Schematic overview of the proposed methodology.

exhibits severe oscillations upon braking and fails to reach the target position precisely, resulting in a steady-state error of approximately 10.69°. In contrast, the synthesized controllers maintain high trajectory precision and stable settling behavior across all load cases, reducing the torque Integral Squared Error (ISE) by approximately 80% compared to the standard controller. Ultimately, structured H_∞-synthesis proves to be a highly effective tool for optimizing industrial control systems with fixed structural constraints. By pre-calculating robust parameter sets for discrete operational intervals, control performance and hardware lifespan can be substantially improved, offering immediately accessible potential for optimizing complex manufacturing processes in modern industrial environments.

References

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