Linear Robust Control of a Nonlinear and Time-varying Process: A Two-step Approach to the Multi-objective Synthesis of Fixed-order Controllers

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For Leonie

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ABSTRACT

Our approach to the development of linear control concepts for nonlinear uncertain processes emerged from the challenge to control a pilot-scale reactive distillation column for the semi-batch synthesis of methyl acetate. Methyl acetate synthesis by reactive distillation is well-known. Several linear control concepts have been suggested and have been tested with nonlinear simulation models. To date, however, publications where these control concepts have been tested in experiments on real plants are sparse, motivating the experiments conducted during this thesis. For the reactive distillation process, but for other processes as well, linear control is complicated by pronounced nonlinearities, slow time variations, considerable time delays, measurement as well as actuator uncertainties, and the fact that reliable control models are difficult to obtain.

To overcome these difficulties, our approach is characterised by the following central steps: first, a suitable control structure that enables an economic process operation is determined, employing a basic nonlinear process model that can be obtained relatively straightforwardly. Then, experiments are conducted to obtain a locally more accurate linear model and to compute a description of the mismatch between the linear model and the nonlinear process which are used to compute an optimal controller. A multi-objective synthesis procedure facilitates the formulation of all relevant control performance criteria, in particular robustness of the controller to the computed model uncertainties. To obtain a fixed-order controller that is practically applicable, the order of the optimal multi-objective high-order controller is reduced, paying particular attention to the conservation of robustness. The integrated approach is applied to the methyl acetate synthesis process, finally leading to a relatively simple multivariate PI controller so that the results can be transferred to industrial practice. The validity of the control concept is demonstrated in a series of control experiments that were performed at the real reactive distillation column.

Control-theoretic contributions of this thesis are the formulations of the multi-objective controller synthesis and the reduction step as convex linear-matrix-inequality (LMI) optimisation problems. As a central result, a new numeric optimisation method to efficiently solve these optimisation problems by a sequential solution of simpler quadratic programs is proposed. Convergence is proved and benchmark examples indicate significant improvements relative to current LMI solvers. To decrease the possibly limiting impact of the uncertainty description, another theoretic contribution deals with the computation of tight uncertainty bounds that are consistent with measured data. The formulation leads to a nonconvex optimisation problem that is solved by first computing a conservative solution by means of LMI techniques and then using the result as a starting point for a gradient-based local search.

KURZFASSUNG

Unser Ansatz zur Entwicklung von linearen Regelungen für nichtlineare und ungenau bekannte Prozesse entstand aus der Herausforderung eine semi-kontinuierliche Pilotreaktivrektifikationskolonne zur Synthese von Methylacetat zu regeln. Der Einsatz von Reaktivdestillation zur Methylacetatsynthese ist wohlbekannt: mehrere lineare Regelungskonzepte wurden vorgeschlagen und in rigorosen Modellen validiert. Bis heute gibt es jedoch kaum Veröffentlichungen, in denen diese Regelkonzepte in Experimenten belegt wurden. Aus diesem Grund bilden experimentelle Untersuchungen, sowohl zur Modellbildung als auch zur Validierung des Regelungskonzeptes, einen Schwerpunkt der vorliegenden Arbeit. Die lineare Regelung des Reaktivrektifikationsprozesses und anderer Prozesse im realen Anlagenbetrieb wird durch hervorgehobene Nichtlinearitäten, langsam zeitveränderliches Verhalten, beträchtliche Totzeiten, Ungenauigkeiten der Mess- und Stelleinrichtungen und durch die oft mangelnde Verfügbarkeit eines zuverlässigen Regelungsmodells erschwert.
Zur Bewältigung dieser realen Herausforderungen wird ein schrittweiser Ansatz verfolgt: zuerst wird, anhand eines einfachen, nichtlinearen Prozessmodells, eine geeignete Regelungsstruktur ausgewählt, die einen ökonomisch sinnvollen Betrieb ermöglicht. Um ein lokal genaueres dynamisches lineares Modell zu finden und um verbleibende Abweichungen des linearen Modells vom tatsächlichen nichtlinearen Prozess zu beschreiben, werden Experimente durchgeführt. Das lineare Modell sowie die Unsicherheitsbeschreibung werden zur Berechnung eines optimalen linearen Reglers eingesetzt. Die Formulierung aller praktisch relevanten Regelgütekriterien wird durch einen multikriteriellen Ansatz vereinfacht, der die Formulierung von Robustheitsnebenbedingungen zulässt. Um einen anwendbaren Regler vorgegebener Ordnung zu erhalten, wird der Optimalregler reduziert, wobei die Einhaltung der harten Regelgütekriterien berücksichtigt wird. Der integrierte Ansatz wird auf die Reaktivrektifikationskolonne angewendet und führt auf einen einfachen, industriell anwendbaren Mehrgrößen-PI-Regler, dessen Regelgüte in einer Reihe von Experimenten gezeigt wird.
Ein regelungstheoretischer Beitrag dieser Arbeit ist die Formulierung des multikriteriellen Syntheseproblems als konvexes LMI-Optimierungsproblem. Als zentrales Resultat wird ein neuer Ansatz vorgeschlagen, der das LMI-Optimierungsproblem durch eine Sequenz von numerisch einfacheren quadratischen Optimierungsproblemen löst. Die Konvergenz des Ansatzes wird bewiesen und numerische Experimente zeigen signifikante Vorteile im Vergleich zu aktuellen LMI-Optimierungsverfahren. Ein weiterer Beitrag handelt von der Berechnung von minimal konservativen Unsicherheitsschranken, die mit gemessenen Daten konsistent sind. Das resultierende nichtkonvexe Optimierungsproblem wird gelöst, indem zunächst eine konservative LMI-Optimierung durchgeführt wird, die einen Startpunkt für eine gradientenbasierte lokale Optimierung liefert.

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