Application of Set Membership Identification to Controller Design

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presented by

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Abstract

The topic of this thesis is the application of set membership identification to controller design. Set membership identification is a method for building a mathematical model of a dynamic system from experimental data. Based on the initially available information on the plant that is being identified, the knowledge of a bound on the disturbance signal that affects the obtained measurements and the measurements themselves, it provides a set of all possible plant models that are consistent with the available data. The resulting uncertainty model obtained when set membership identification is used is deterministic in contrast to the probability density function which represents the identification uncertainty when probabilistic identification is used. The assumptions made by set membership identification are often less restrictive than the assumptions made by probabilistic identification. In addition, the deterministic uncertainty description can be very useful when used for robust controller design or in control design tasks in which constraint satisfaction is required. Furthermore, in direct controller design, where the controller is directly designed from experimental data, the deterministic uncertainty set obtained when the set membership identification is used can be exploited in order to provide stability and performance guarantees for the designed controller.

However, set membership identification is less used in controller design compared to the probabilistic identification. The main reason for this lies in the fact that the set membership identification received less research attention than the probabilistic identification and is hence not so well known and understood by control engineers. Therefore, in order to enable greater exploitation of all the benefits that the use of set membership identification can bring to controller design, further research is required. As a contribution to these research efforts, three topics related to set membership identification and its application to controller design are considered in this thesis.

The first contribution presents new theoretical results related to the worst-case identification experiment design in the set membership context for constrained linear systems with multiple inputs. The presented results can be seen as a generalization of the theory related to experiment design for set membership identification that already exists in the literature to the case of constrained systems with multiple inputs. Based on the presented theoretical derivations, a computationally tractable algorithm for experiment design that is based on convex optimization is proposed. This algorithm calculates the input sequence that is guaranteed to satisfy the input constraints and at the same time minimizes a measure of the worst-case identification uncertainty that can be obtained in any particular experiment. The effectiveness of the proposed approach is demonstrated by a numerical case study which shows that there are clear advantages of using the proposed scheme with respect to more traditional experiment design methods that are based on generating random signals. Therefore, the proposed methodology could be used to systematically design identification experiments that lead to small identification
uncertainty when set membership identification is used and hence better performance of
the controllers designed on the basis of such models.

The second contribution is an adaptive model predictive control algorithm for con-
strained, multiple input, multiple output linear systems that is based on set membership
identification. This algorithm relies on recursive set membership identification in order
to update the set of all plant models that are consistent with initial assumptions on the
system and available measurements at each time step. The controller then enforces the
constraints for all the models in this set and hence also for the actual plant. In addition
to the base algorithm, several extensions that can be used in order to reduce computa-
tional complexity of the overall adaptive approach, introduce exploring property in order
to facilitate faster identification and introduce forgetting of old information in order to
apply the algorithm to time varying systems are presented. The proposed approach is
experimentally tested on a quad-tank laboratory setup in various operating conditions
which include a non-minimum phase behavior and the presence of non-negligible non-
linearity. In addition, the possibility for its use in building climate control is considered
and illustrated by a simulation case study. Experiments and simulations show that, for
the sake of constraint satisfaction, it is more beneficial to use the proposed adaptive
scheme than to use a non-adaptive or a certainty equivalence adaptive model predictive
control algorithm that uses least squares.

The third contribution of the thesis is a novel on-line direct controller design method
for nonlinear systems that uses set membership identification. The technique does not
derive explicitly a model of the system, rather it delivers directly the feedback controller
by combining an on-line and an off-line scheme. Like in other on-line algorithms, the
measurements collected in closed-loop operation are exploited to modify the controller
in order to improve the tracking performance over time. At the same time, a predictable
closed-loop behavior is guaranteed by making use of a batch of available data, which is a
characteristic of off-line algorithms. The feedback controller is parameterized with kernel
functions and the design approach exploits results in set membership identification and
learning by projections in order to provide guarantees on the stability and reference
tracking performance of the designed controller. In addition to theoretical analysis of its
properties, the tuning of the algorithm is discussed in detail and a method to adapt some
of the tuning parameters on-line while retaining the stability guarantees is presented.
The experiments done on a water tank system show that the controller obtained when
the proposed on-line design scheme is used exhibits better reference tracking performance
than a nonlinear controller obtained by an off-line direct design procedure and a well
tuned linear controller.
Zusammenfassung


Der erste Beitrag besteht darin, neue theoretische Resultate bezüglich worst-case Identifikationsexperimente mittels SMIM für begrenzte linear System mit mehreren Eingängen zu präsentieren. Die vorgestellten Resultate sind eine Verallgemeinerung der bereits existierenden Resultate für begrenzte Systeme mit mehreren Eingängen. Basierend auf diesen neuen Erkenntnisse wird ein computationally tractable Algorithmus vorgestellt, der auf convex Optimierung basiert. Dieser Algorithmus berechnet eine Eingangssequenz, welche garantiert die Eingangs begrenzungen erfüllt und gleichzeitig die schlimmstmögliche Identifikationsunsicherheit minimiert, welche ein beliebiges Experiment generieren kann. Die Wirksamkeit der vorgeschlagenen Methode wird anhand eines numerischen Experiment gezeigt, auch im Vergleich zu herkömmlichen Methoden, welche auf zufällig generierte Signale basieren. Daraus lässt sich schliessen, dass die auf die SMIM basierte Methode systematisch für den Entwurf von Identifikationsexperimenten gebraucht werden kann, um kleine Identifikationsfehler zu generieren, welches wiederum eine bessere Regelgüte erlaubt.

Der zweite Beitrag dieser Arbeit ist ein adaptiver Model Predictive Control Algorithmus für begrenzte System mit mehreren Ein- und Ausgängen. Der Algorithmus basiert auf die rekursive Set Membership Identification, welche die Menge aller möglichen Systemmodelle, welche konsistent sind mit den gemachten Annahmen bezüglich der Systeme und den verfügbaren Messungen, aktualisiert. Der Regler ist dann so gewählt, dass er die Systembegrenzungen für alle Modelle innerhalb dieser Menge einhält. Zusätzlich zum regulären Algorithmus gibt es verschiedene Erweiterungen, welche gebraucht werden
können, um die Rechenkomplexität des adaptiven Prozesses zu minimieren, oder um ver-
gangene Informationen zu vergessen, oder für zeitvariante Systeme. Die vorgeschlagene
Methode wurde an einem Vier-Tank Laborversuch, ein nicht-minimalphasiges System
mit nicht vernachlässigbarer Nichtlinearität, unter verschiedenen Zuständen getestet.
Zusätzlich wenden wir die Methode an einem Gebäuderegelungsproblem in Simulation
an. Experimente und Simulationen zeigen, dass es vorteilhaft ist, die vorgeschlagene
adaptive Methode zu gebrauchen als ein nicht-adaptiver oder certainty-equivalent Model
Predictive Control Regler mit least squares.

Der dritte Beitrag dieser Arbeit ist ein neuer on-line direct controller Designmethode für
nicht lineare System mittels der SMIM. Diese Methode leitet nicht explizit ein System-
modell her, sondern retourniert direkt das Regelsignal, basierend auf eine Kombination
von on-line und off-line Methoden. Ähnlich wie in anderen on-line Algorithmen, werden
die Messdaten in closed-loop Einsatz benutzt und der Regler so modifiziert, dass die
Trackinggüte verbessert wird mit der Zeit. Gleichzeitig ist ein vorhersagbares closed-
loop Verhalten garantiert, mittels des Gebrauchs von vorhandenen Daten, welches eine
Charakteristik von off-line Algorithmen ist. Der Regler ist parametrisiert durch Kernel-
funktionen und die Designmethode benutzt Resultate der Set Membership Identification
Theorie und learning by projections, um Stabilität und Güte von Referenztracking zu
garantieren. Zusätzlich zu den theoretischen Aspekten wird das Tunen des Algorithmus
diskutiert, und eine Methode zum on-line Tunen von Parametern vorgestellt. Die Wirks-
samkeit des vorgeschlagenen Algorithmus wird anhand eines Wassertanksystems gezeigt.
Die Experimente zeigen, dass die vorgeschlagene on-line Methode einem Referenzsignal
besser folgt als nicht-lineare Regler mit off-line direct control sowie ein gut getunter
linear Regler.