Implementation of one-layer gradient-based MPC+RTO of a propylene/propane splitter using dynamic simulation

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ABSTRACT – Here, the implementation of the gradient-based Economic MPC (Model Predictive Control) in an industrial distillation system is studied. The approach is an alternative to overcome the conflict between MPC and RTO (Real Time Optimization) layers in the conventional control structure. The study is based on the rigorous dynamic simulation software (SimSci Dynsim®) that reproduces the real system very closely and is able to communicate with Matlab where the control/optimization algorithm is implemented. The gradient of the economic function, which is required to the on-line execution of the extended control strategy, is obtained through the sensitivity tool of the real-time optimization package (SimSci ROMeo®). It is shown that the proposed integration approach leads to convergence and stability to the closed-loop system. In order to study the pros and cons of the new strategy, a propylene distillation system is simulated with both, the proposed approach (one-layer MPC+RTO) and the conventional two-layers hierarchical structure of control and optimization. The results show that, from the performance, stability and disturbance rejection viewpoint, the proposed gradient-based extended control method for this particular system is equivalent or better than the conventional approach.

1. INTRODUCTION

In the conventional industrial practice, Model Predictive Controllers (MPC) and Real Time Optimization (RTO) are implemented in a hierarchical control structure. The RTO is a model-based system, operated in closed loop, which implements the economic decision in real time, performing a static optimization, and providing the optimum operating point. It employs a stationary complex (nonlinear) model of the plant and for this reason it works on a timescale of hours or days. The optimization problem is Nonlinear Programming (NLP), whose solution provides optimizing set-points to the dynamic layer of the controller, usually a MPC. The MPC calculates the optimal control action to be sent to the plant, in order to regulate it as close as possible to the optimum point, taking into account a dynamic model of the plant, constraints, and stability requirements. The hierarchical control structure supposes a time-scale separation between the RTO and MPC layers. This separation represents a technical issue that may have serious consequences on the economic performance of the plant.
Recently, (Alamo et al., 2014) presented a MPC controller that integrates RTO in the MPC control problem, in such a way that the controller cost function includes the gradient of the economic objective cost. However, instead of applying to the system the optimal solution of the approximated problem, they propose to apply the convex combination of a previously known feasible solution and an approximated solution. This way, a sub-optimal MPC strategy that only requires a QP solver was obtained, and it is shown that the strategy ensures recursive feasibility and convergence to the optimal steady state in the economic sense.

2. ECONOMIC MODEL PREDICTIVE CONTROL (EMPC)

Consider a system described by a linear time-invariant discrete time model, which is subject to hard constraints on state and input:

\[ x(k+1) = Ax(k) + Bu(k) \quad \text{for all } k \geq 0, \text{ where } X \subseteq \mathbb{R}^n \text{ and } \Delta U \subseteq \mathbb{R}^m. \]  

Also, consider the following stationary economic optimization problem, in which the optimal steady state, \( x_s \), satisfies:

\[ x_s = \arg\min_x f_{eco}(x, p) \]

s.t. \( x \in X_s \)

\( f_{eco}(x, p) \) defines an economic cost function and \( p \) is a parameter vector that takes into account prices, costs and production goals.

Then, the controller cost function could be defined as:

\[ V_s(x, p; \Delta u) = V_{s\text{ss}}^\text{dyn}(x, \Delta u) + V_{s\text{ss}}(x_s, p) \]

Where,

\[ V_{s\text{ss}}^\text{dyn}(x, \Delta u) = \sum_{j=0}^{N-1} \| x - x_{ss} \|^2_R + \sum_{j=0}^{N-1} \| \Delta u \|^2_R \]

\( Q > 0 \) and \( R > 0 \) are penalization matrices of appropriate dimension and \( V_{s\text{ss}}(x_{ss}, p) = f_{eco}(x_{ss}, p) \).

Finally, the optimization problem to be solved by this MPC with extended cost function is given by:

\[ \min_{\Delta u} V_s(x, p; \Delta u) \]

s.t. \( x_j = x \)

\( x_{ss} = Ax + Bu, \quad j = 0, \ldots, N-1 \)

\( x_j \in X, \Delta u_j \in \Delta U \quad j = 0, \ldots, N-1 \)

\( x_{ss} \in X_s \)

The idea consists in considering the gradient of the economic cost, \( f_{eco} \), instead of the cost itself, to produce an approximated cost \( V_{s\text{ss}}^{app} \). The approximated optimal solution is then obtained through the solution to the following problem (Alamo et al., 2014):

\[ \min_{\Delta u} V_{s\text{ss}}^{app}(x, p; \Delta u) \]

s.t. \( x_j = x \)

\( x_{ss} = Ax + B\Delta u, \quad j = 0, \ldots, N-1 \)

\( x_j \in X, \Delta u_j \in \Delta U \quad j = 0, \ldots, N-1 \)

\( x_{ss} \in X_s \)

Where, the approximated cost is given by:

\[ V_{s\text{ss}}^{app}(x, p; \Delta u) = V_{s\text{ss}}^{app}(x; \Delta u) + \nabla V_{s\text{ss}}(\hat{x}_s, p)[x_{ss} - \hat{x}_s] \]

and \( \nabla V_{s\text{ss}}(\hat{x}_s, p) \) represents the gradient of \( V_{s\text{ss}} \) w.r.t. \( x \), evaluated at a certain point \( \hat{x}_s \).
Consider a parameterized family of feasible solutions, given by the convex combination of
the feasible solution \( \hat{u} \Delta \) and the approximated optimal solution \( u^* \Delta \):
\[
\Delta u(\lambda) = \{ (1-\lambda)\hat{u}_\Delta + \lambda u^* \Delta, \ldots, (1-\lambda)\hat{u}_{\Delta N} + \lambda u^*_{\Delta N} \} = (1-\lambda)\Delta \hat{u} + \lambda \Delta u^*
\]
\[
x(\lambda) = \{ (1-\lambda)x^*_\Delta + \lambda x^*_{\Delta}, \ldots, (1-\lambda)x^*_{\Delta N} + \lambda x^*_{\Delta N} \} = (1-\lambda)x^* + \lambda x^*
\]
\[\lambda \in [0,1]\]

Finally, the obtained solution by the convex combination is implemented into the system.

3. SIMULATION RESULTS

In this section, simulation tests are presented to evaluate the performance of the proposed
one-layer gradient-based approach when compared with the two-layer conventional structure
presented in (Hinojosa and Odloak, 2013; 2014) considering the dynamic simulation as a virtual
plant. To study the implementation of the economic advanced control strategy, which was
developed in MATLAB, and the gradient calculation, which was based on the rigorous steadystate
optimization commercial package ROMeo integrated to the dynamic simulation that
represents the true plant, it was necessary to integrate the various software components with
a real-time data communication. For this purpose, it was included a communication interface
based on OPC technology that allows the real-time data transfer between Dynsim, MATLAB
and ROMeo. The output zones, input constraints, tuning parameters, simulation conditions
and transfer function model are proposed in (Hinojosa and Odloak, 2013, 2014). There were
performed two simulation experiments, the first one with controlled variables outside their
control zone and the second one introducing a feed composition disturbance in the
Propylene/Propane (PP) splitter.

Both simulation experiments are presented in Fig. 1 that shows the outputs of the PP
splitter outputs for the two-layer MPC + RTO alongside the responses for the one-layer
gradient-based EMPC. Fig. 2 compares the control inputs for the two strategies and it also
shows the optimizing input targets calculated by ROMeo for the two-layer strategy. In Fig. 3
the instantaneous economic function for both strategies is presented in order to compare the
economic benefit and efficiency in each simulation experiment.

![Figure 1](image1.png)

**First experiment**

**Second experiment**

**Figure 1 – Controlled outputs, EMPC (—), two-layers approach (— —), control zone (— —)**
First experiment

Second experiment

Figure 2 –Manipulated inputs, EMPC ( ), two-layers approach ( ), economic target ( )

First experiment

Second experiment

Figure 3 –Economic function, EMPC ( ), two-layers approach ( ),

4. CONCLUSIONS

In this work, the gradient-based EMPC, which is a MPC+RTO integration approach, was studied and implemented in the PP splitter. The study was performed through simulation of an existing Propylene/Propane separation unit of an oil refinery using the commercial dynamic simulation software (Dynsim) associated with a real-time optimizer (ROMeo) and the real-time facilities of Matlab. It was shown that the proposed approach has an equivalent or better performance when compared with the two-layer hierarchical structure. This representative example shows that the proposed approach can be implemented in the real system and extended to other real applications.

5. REFERENCES

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