

# Model Predictive Control: History and Development

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**Abstract**— This paper traces the development of model predictive control technology over the years. An approximate genealogy of linear MPC algorithms has been explained.

**Keywords**— DMC, History of MPC, IDCOM, Model Predictive Control.

## I. INTRODUCTION

Model Predictive Control was originally developed for chemical applications to control the transients of dynamic systems with hundreds of inputs and outputs, subject to constraints [1]. It is a form of control in which current control action is computed by solving on-line, at each sampling instant, a finite horizon open-loop optimal control problem, using current state of plant as initial state. The optimization yields an optimal control sequence, the first control of which is applied to the plant.

In last two decades the MPC landscape has changed drastically. There has been a large increase in the number of reported applications and significant improvements in the technical capability. The purpose of this paper is to provide an overview of history of the industrial MPC followed by a very brief look into the industrial applications of MPC.

## II. A BRIEF HISTORY OF MPC

This section presents a brief history of industrial MPC technology. Fig. 1 shows an evolutionary tree for the most significant industrial MPC algorithms.

The development of modern control concept can be traced back to the work of Kalman in the early 1960's who sought to determine when a linear control system can be said to be optimal [2], [3]. A linear quadratic regulator (LQR) was designed to minimize an unconstrained quadratic objective function of states and inputs. The LQR algorithm had powerful stabilizing properties because of the infinite horizon. But it had little impact on the control technology development in the process industries. The reason for this was that there were no constraints in its formulation and the nonlinearities of the real system.

Various applications of MPC were reported in the process industry in the late 1970's. The important ones were by Richalet *et.al* which presented Model Predictive Heuristic Control (MPHC) and by Cutler and Ramaker which presented Dynamic Matrix Control [4], [5]. Model Predictive Heuristic Control was later called Model Algorithmic Control (MAC). The underlying theme of both the theories was to use a dynamic model of the process to predict the effect of future control actions, which were determined by minimizing the predicted error subject to operational restrictions. The optimization is repeated at each sampling instant with updated information from the process. These algorithms were algorithmic as well as heuristic and took advantage of the development of digital computers. The initial versions of MPC were not automatically stabilizing. However, if stable plants are considered and a horizon is chosen large enough compared with the settling time of the plant, stability is achieved.

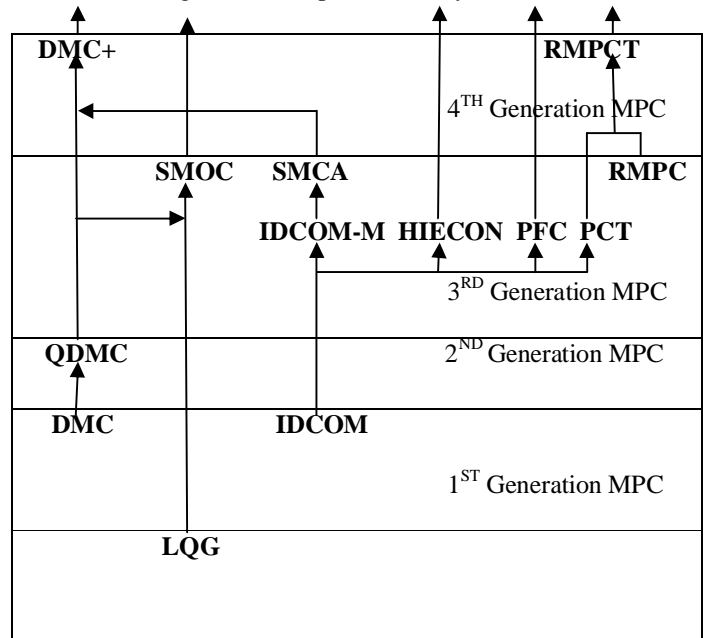


Fig 1 Genealogy of MPC algorithms

The solution software to MPHC was referred to as IDCOM, an acronym for Identification and Command [6]. In this approach, impulse response model and a quadratic

objective function over a finite prediction horizon was used. Optimal inputs were computed using a heuristic iterative algorithm, interpreted as the dual of identification.

DMC was presented by Cutler and Ramaker at the 1979 AIChE meeting [7], and at the 1980 Joint Automatic Control Conference [5]. In this approach, linear step response model for the plant and quadratic objective function over a finite horizon was used. The optimal inputs were computed as the solution to a least squares problem.

Prett and Gillette described an application of DMC to FCCU reactor/ regenerator in which the algorithm was modified to handle nonlinearities and constraints [8].

The initial IDCOM and DMC algorithms represent the *first generation* of MPC technology. Later on a *second generation* of MPC such as quadratic dynamic matrix control (QDMC) came into picture.

Cutler et. al. first described the QDMC algorithm in a 1983 AIChE conference paper [9]. Garcia and Morshedi presented a more comprehensive description some years later [10]. QDMC approach used quadratic programming to solve the constrained open-loop optimal control problem where the system is linear, objective function is quadratic and the constraints are defined by linear inequalities. Although QDMC algorithm provided a systematic approach to incorporate input and output constraints, but there was no clear way to handle an infeasible solution.

To tackle this issue, engineers at Shell, Adersa, Setpoint, Inc. developed new versions of MPC algorithms. IDCOM-M controller was first described in a paper by Grosdidier, Froisy, and Hammann in 1988 [11]. Another paper presented by Froisy and Matsko in 1990 described an application of IDCOM-M to a Shell fundamental control problem [12]. The main difference from the previous algorithms is the use of two separate objective functions, one for the outputs and then, if there are extra degrees of freedom, one for the inputs. A quadratic output objective function is minimized first subject to input constraints. Each output is driven as closely as possible to a desired value at a single point in time known as the coincidence point. The desired output value comes from a first order reference trajectory that starts at the current measured value and leads smoothly to the set-point.

In the late 1980's engineers at Shell Research in France developed the Shell Multivariable Optimizing Controller

(SMOC) [13]. It was described as a bridge between state-space and MPC algorithms. This approach uses state space models so that full range of linear dynamics can be represented. A kalman filter is used to estimate the plant states and unmeasured disturbances from output measurements. A distinction is introduced between controlled variables appearing in the control objective and feedback variables that are used for state estimation.

The IDCOM-M and SMOC represent the *third generation* of MPC technology. This generation distinguishes between several levels of constraints and provides some mechanism to recover from infeasible solution. There were other algorithms belonging to this generation such as hierarchical constraint control (HIECON), PCT algorithm sold by Profimatics and RMPC algorithm sold by Honeywell.

In the late 1995, RMPC algorithm offered by Honeywell was merged with the Profimatics PCT controller to create RMPCT, robust model predictive control technology. In 1998, SMCA and DMC technologies were merged to create DMC-plus. RMPCT and DMC-plus are representative of *fourth generation* of MPC technology. This generation is sold today with features such as, windows based graphical user interface, multiple optimization levels to address prioritized control objectives, improved identification technology based on prediction error method.

### III. STABILITY

For those working with predictive control, stability has always been an important issue. Due to the finite horizon, stability is not guaranteed and is achieved by tuning the weights and horizons. Mohtadi proved specific stability theorems of GPC using state-space relationships and studied the influence of filter polynomials on robustness improvement [14]. However a general stability property for predictive controllers, in general, with finite horizons was still lacking. This led researchers to pursue new predictive control methods with guaranteed stability in the 1990s. With that purpose a number of design modifications have been proposed since then including the use of terminal constraints by Kwon *et al.*, the introduction of dual-mode designs by Mayne and Michalska and the use of infinite prediction horizons by Rawlings and Muske, among others [15], [16], [17]. Clarke and Scattolini and Mosca *et al.* independently developed stable predictive controllers by imposing end-point equality constraints on the output after a finite horizon [18], [19]. Kouvaritakis *et al.* presented a stable formulation for GPC by stabilizing the process prior

to the minimization of the objective function [20]. Many of these techniques are specialized for state-space representations of the controlled plant, and achieve stability at the expense of introducing additional constraints and modifying the structure of the design.

Practitioners, however, avoid changing the structure of the problem and prefer to achieve stability by tuning the controller. For that a good doses of heuristics is used.

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