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# Dynamics and Control of Integrated Microchemical Systems

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**Abstract:** Microchemical systems are a new generation of miniature chemical systems that carry out chemical reactions and separations in precisely fabricated three dimensional microreactor configurations in the size range of a few microns to a few hundred microns. Typical microchemical systems combine fluid handling and reaction capabilities with electronic sensing and actuation, are fabricated using integrated circuit (IC) manufacturing techniques and use silicon and related IC industry materials, polymers, ceramics, glass or quartz as their material of construction. The use of such systems for in-situ and on-demand chemical production is gaining increasing importance as the field of microreaction engineering transitions from a theoretical concept to a technology with significant industrial applications. In this paper, we provide an overview of the issues involved in modeling, design and control of microchemical systems and as examples, demonstrate some of these concepts with our work on modeling and control of microreformers for hydrogen delivery systems in micro-fuel cells. The paper concludes by suggesting possible areas of future research.

Keywords: Microreactors, microchemical systems, micro-reformers, integrated system-on-chip, embedded control, micro-fuel cells

## 1. INTRODUCTION

The use of micro-scale chemical handling and analysis dates back to the spring of 1935 during the 89th meeting of the American Chemical Society in New York City. During this meeting, based on discussions on chemical microscopy, the American Microchemical Society was established in 1935 (www.microchem.org). However, Microchemistry was not a new discipline even at that time. Friedrich Emich from Graz, Austria is recognized as the founder of classical microchemistry for his work on the development of techniques for various sections of the field in the early 1920s, specifically for inorganic microanalysis. Fritz Pregl, also from Graz, concentrated on procedures for organic chemistry microanalysis, for which he received the Nobel Prize in chemistry in 1923.

The origins of microchemical systems are clearly deeply rooted in microchemistry, as evidenced by the following definition of microchemistry (see the American Microchemical Society web page www.microchem.org) which is also applicable to modern day microchemical systems:

*Microchemistry "deals with the development, correlation, and systematization of the methods for handling small quantities of materials, and for the observation of their properties. . . . the upper limits of the size is reasonably defined by the statement that the quantity of material taken should be so small as to prevent the use of traditional methods of working. The lower limit is determined by the progress in microtechnique . . ." (ca. 1930) Sabine [1969].*

For a long time, however, the miniaturization techniques available for fabrication of true integrated microchemical systems were rather limited, and efforts were mainly concentrated on the development of microscopic and microanalytical techniques relating to chemical processes rather than the development of complete integrated chemical processing microreactors. This has changed over the last two decades as rapid advances in the microelectronics industry have led to the search for novel applications of miniaturization to all aspects of engineering. Early efforts beginning in the mid-1970s led to the use of silicon (at that time used mainly for making integrated electronic circuits) as a material for making micro-scale mechanical devices (Petersen [1982]). This subsequently resulted in the field of micro electro mechanical systems (MEMS) with demonstrated applications ranging from motion sensors such as accelerometers for airbag deployment in automobiles to complete micro scale turbines and engines (Fu et al. [2001]), developed primarily for research purposes. Judy [2001] provides an excellent review of the developments in MEMS. More recently, soft lithography and patterning methods have emerged as cost effective alternatives to these IC-based fabrication.

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The first reference to miniaturized chemical handling components can be traced back to as early as 1979, when researchers at Stanford University in the United States reported one of the first examples of an analytical device on a chip- a complete gas chromatography (GC) system on a silicon wafer (Terry et al. [1979]) . There were some attempts to commercialize the design as it showed considerable promise at that time, but it is only relatively recently that microengineered components have begun to appear in modern GCs. The early demonstration of the micro GC on a chip, however, generated significant activity in the area of miniature chemical handling systems. A major area of interest in this quest for miniaturization has also been the development of miniature chemical reactors on microchips for portable applications. The ease of startup and shutdown of the miniature reactors and their ability to handle small amounts of hazardous chemicals with high degree of safety are some of the key advantages of this technology. Micro-scale reaction systems also provide significantly higher surface area to volume ratios of the reaction chambers compared to conventional reactors and this can be effectively used to facilitate novel reaction pathways by suppressing unwanted homogeneous-phase side reactions, not previously possible in the conventional scale reactors. The possibility of integrating these miniature reactors with sensors, actuators and control electronics on a single chip to create a highly reliable chemical processing microplant has thus generated a lot of interest in this field. Terms such as lab-on-a-chip and plant-on-a-chip have been coined and adopted, and these concepts are no longer merely theoretical ideas but real-world technologies with significant industrial applications. The large amount of interest in this field has led to the establishment of a dedicated series of annual conferences, the International Conferences on Microreaction Technology (IMRET), beginning in 1997. The first IMRET was held in Frankfurt in Germany, organized by Dechema e. V. Since then, the conference has been organized every year alternately in Europe by DECHEMA and in North America by AIChE (Ehrfeld [1997], Ehrfeld et al. [1998], Renken et al. [2003]).

Judging by the increased research activity in this area across different parts of the world and the growth in the number of proposed applications, it can be expected that microchemical systems may soon pave the way for integrated portable microplants with unlimited domestic and industrial applications in quite the same way that computers are used today in more ways than could have been imagined a few years ago.

## 2. TECHNOLOGICAL PROGRESS

Various micromachining techniques have been used and perfected over the years for fabricating miniature chemical reactors, chief among them being the use of photolithography, thin film deposition, deep reactive ion etching (DRIE) (Larmer and Schilp [1994]) and wafer bonding (Klaassen et al. [1996], Albaugh and Rasmussen [1988]) for micromachining silicon and other IC industry materials. Apart from using these standard microfabrication techniques, there has also been a lot of activity in the development of fabrication methods and concepts specific to the microchemical and microfluidics area. These include the development of microfluidic interconnection techniques (Gray et al. [1999], Puntambekar and Ahn [2002], Tsai and Lin [2001], Pattekar and Kothare [2003]) and techniques for the formation of microfluidic channels that are either coated with catalyst (Pfeifer et al. [1999], Pattekar et al. [2001]) or those that incorporate filtering structures for trapping catalyst microparticles inside etched microchannels (Ajmera et al. [2001], Losey et al. [2001], Pattekar and Kothare [2004]). There have also been significant developments in research on various miniaturized fluidic handling components that will eventually form an integral part of these microchemical systems- fluidic actuators such as micropumps (Benard et al. [1998]) and microvalves (Vandelli et al. [1998]), which have brought the concept of micro scale integrated chemical systems closer to reality. For mass production of miniature chemical systems, microfabrication techniques such as LIGA (acronym formed by the initial letters of the German words lithographie (lithography), galvanoformung (plating) and abformung (molding) have also been developed and used (IMM). Several non-traditional microfabrication techniques such as micromilling, punching, electrodischarge machining (EDM) have also been employed for fabricating microchemical systems. More recently, soft lithography methods have greatly extended the fabrication capabilities while containing cost.

The theoretical modeling and analysis of micro scale chemical systems has also evolved considerably over the years and forms an integral part of the research effort (Hsing [1998], Senturia et al. [1992], Pattekar and Kothare [2002], Alfadhel and Kothare [2005a,b]). Certain fundamental differences between conventional chemical processes and microreaction systems call for significantly novel approaches to the modeling of this new class of chemical systems. It has been found that rigorous partial differential equation (PDE) based modeling for mass, momentum and energy balances (Hsing [1998], Alfadhel and Kothare [2005a,b]) is better suited for these systems than the empirical approaches that are often employed for the modeling of conventional large-scale chemical processes. One of the main reasons is that while many empirical relations that have been developed for conventional chemical systems can break down at the micro-scale due to the high surface area to volume ratios characteristic of microreactors, the fundamental balance relations still apply, and these can be used, with some modification (Alfadhel and Kothare [2005a]), for systems operating in continuum transport regimes (where the characteristic reactor dimensions are much higher than the mean free path of the species molecules). At the same time, the precision with which these systems can be fabricated using techniques similar to IC manufacturing ensures accuracy in modeling the geometries of the microreaction chambers thereby obviating the need for empirical modeling by reducing the uncertainties involved (Pattekar and Kothare [2002]).

Efforts at MIT in the early 1990s led to the development of a dedicated set of design and simulation software tools for MEMS applications, MEMCAD (Senturia et al. [1992]), specifically suited for mechanical design and lab-on-a-chip system analysis. Another tool that has been used for rigorous modeling of microchemical systems (Pattekar and Kothare [2002], Bleris and Kothare [2005c,a]) is FEMLAB (FEMLAB [2001]), a general-purpose modeling and simulation package for 3D geometries that uses core MATLAB

functions for numerical integration of systems of coupled partial differential equations. It also provides the ability to export entire or reduced-order models of any system to SIMULINK in MATLAB, thereby allowing for rigorous controller design and dynamic simulations of the system to study controller performance (Bleris and Kothare [2005c]).

## 3. KEY APPLICATION AREAS

Microreactors are well suited in applications where the cost of developing and building these miniature systems for handling miniature amounts of chemicals is justified by reasons of safety, portability and speed of analysis and applications where there is a large enough demand for these micro-scale reactors to make mass fabrication of the devices economically feasible. One major area of interest continues to be the development of chip-scale DNA sequencing and other biological analysis systems which can greatly reduce the time and cost associated with carrying out these analyses manually using conventional laboratory equipment. This has spurred the research activity on lab-on-a-chip systems, leading to the establishment of an entire industry in the United States based on this technology (LaO).

The use of microreactors for processing chemicals is also well suited for a number of applications. Microreactors have been demonstrated for handling and production of small amounts of hazardous chemicals, such as for Phosgene synthesis (Ajmera et al. [2001]). Various research groups have developed microreactors for a range of chemical processes such as partial oxidation of ammonia (Srinivasan et al. [1997]), nitration (Antes et al. [2000]), and chemical detection (Floyd et al. [2000]). Another area of interest for the use of micro-scale chemical systems involves portable applications, since the miniaturized chemical handling components can be readily integrated into a portable unit. One example is hand held analysis systems such as the portable GC using miniaturized components mentioned earlier. There has also been a lot of activity in the development of a number of portable analysis systems for detection of hazardous chemicals in air and water. These systems form a broad range of testing equipment collectively referred to as micro total analysis systems ($\mu$ TAS) (van den Berg and Bergveld [1995]).

## 4. DYNAMIC MODELING AND CONTROL OF MICROCHEMICAL SYSTEMS

For the purpose of this paper, following Fedkiw et al. [1999], we define a microchemical system as having the following characteristics:

(1) it carries out chemical transformations (reactions) and/or separations;
(2) it is fabricated using MEMS microfabrication methods;
(3) it uses silicon and related integrated circuit (IC) industry materials but can include other materials such as polymers, ceramics, glass, quartz, etc.;
(4) it contains microfluidic and non-electronic feature sizes in the range of sub-microns to a few hundred microns;
(5) it integrates non-electronic features with at least one electronic feature, e.g., a resistive heater;
(6) its main function is chemical or electrochemical *synthesis* as opposed to *analysis* or sensing.

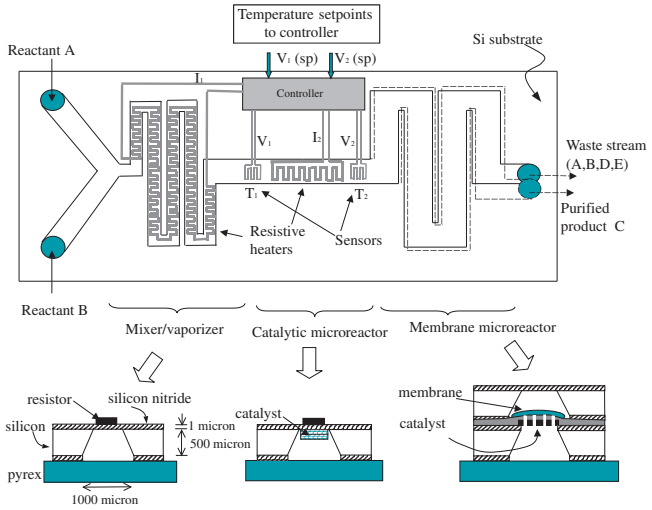


Fig. 1. A prototypical integrated microchemical system.

To facilitate the discussion, we consider the schematic of a prototypical integrated microchemical system shown in Figure 1. The microplant integrates classical chemical unit operations at a micro-scale: a mixing/heating unit, a catalytic microreactor and a membrane microreactor/microseparator. The overall goal of this microplant is to produce high purity product C from liquid phase reactants A and B. The vaporizer serves to perform phase transformation and homogenization of A and B. The catalytic microreactor serves as the central unit for carrying out the heterogeneous gas phase reaction of A and B to produce product C and an undesirable and possibly hazardous byproduct D. The membrane microreactor serves to convert hazardous product D to a more benign waste product E while simultaneously separating the desired product C from unreacted A, B and byproducts D, E. Integrated resistive temperature sensors measure inlet and outlet temperatures of the microreactor and feedback a voltage signal to the controller module. The controller in turn sends appropriate currents to the resistive heaters which provide heat input to the vaporizer and the microreactor to control the two temperatures.

The cross-sections of the individual micro-units, shown in Figure 1, indicate that the entire microplant is housed in microchannels fabricated in a silicon substrate and capped with an appropriate base plate. These structures are fabricated using standard surface and bulk micromachining techniques Madou [2002] such as photolithography, pattern transfer, sputtering, chemical vapor deposition, alkaline etching and plasma etching. While microfabrication of such a microchemical system prototype is a research problem in its own right, our emphasis will be primarily on the dynamical analysis of the fabricated microsystem.

The prototype shown in Figure 1 is abstract and captures the essence of a realistic microchemical system, as defined above, while serving as a test-bed for formulating a number of relevant system theoretic problems in a general microchemical system. Furthermore, it generalizes a number of potential reaction/separation/purification schemes from classical chemical engineering as well as electrochemical reactions schemes involving fuels and oxidants which can be tested in a microchemical setting. Examples include

the classical hydrocarbon reforming-shift reforming reaction sequence with or without membranes Pattekar and Kothare [2004, 2005], Karnik et al. [2003], Franz et al. [1999], Wilhite et al. [2004], methanol dehydrogenation to formaldehyde Maurer et al. [2000] and dehydrogenation of cyclohexane to benzene Cui et al. [2000].

The operational goals of the prototype may be considered to be one or more of the following:
(1) stabilization of the overall microplant at the chosen operating conditions;
(2) maximization of the microsystem throughput;
(3) maximization of conversion of the reactants to the desired product C;
(4) minimization of the amount of hazardous byproduct D in the waste stream;
(5) satisfaction of constraints on key process variables to ensure integrity of the microsystem material.

Inherent in such a problem formulation is the need to (a) understand the impact of the microsystem design (shape, size, length of microchannels, micro-unit topology) on its performance; (b) develop and analyze models that can be used as the basis for microreactor design, operational optimization and multi-unit feedback controller synthesis; and (c) study robustness of operation, i.e., understand the effect of microfabrication errors (M'Closkey et al. [2000], Grayver and M'Closkey [2001]), imperfections in microreactor geometry (Stone and Kim [2001]) and structural/parametric model uncertainty on closed-loop controller performance. It is worth noting that the aforementioned set of problems is independent of the specific microsystem geometry, configuration and reaction kinetics and therefore, is not limited to the specific prototype shown in Figure 1.

Our goal is to consider generic issues that arise when dealing with control problems for such microsystems.

## 5. ISSUES IN CONTROL OF MICROSYSTEMS

The study of the dynamical properties and feedback control of microreactors poses unique challenges. These challenges stem from the unique characteristics of microsystems, namely, their small size, high surface area to volume ratios implying higher heat and mass transfer rates, low thermal inertial, fast transients, and small available physical space for building and incorporating the controller implementation with the microreactor system.

A variety of heuristics from macro-scale systems that allow considerabe decoupling of control loops become inapplicable in the context of microreactors due to very strong integration of various unit operations fabricated in close proximity of each other on a common substrate. Similarly, the notion of controller "implementation", which is typically relegated to "computer" control for macrosystems with appropriate data acquisition and feedback signal transfer, is no longer simple for microchemical systems since an integrated microchemical system must also integrate a "small" controller within the micro-scale space constraints available. In other words, one simply cannot control a microreactor system with a computer, but the control alsgorithm must be "embedded" with the microreactor substrate. And finally, within the context of micropower chemical systems, the controller implementation must minimize its parasitic power requirements to a small fraction of the total power projected from the device.

Within the context of control problems in micro and nanosystems in general, two workshops were organized by the U.S. National Science Foundation in 2003 and 2004 (Sitti [2003], Shapiro [2004, 2005]). The resulting workshop reports provided a variety of recommendations on future research opportunities in the control of micro- and nanosystems. The scope of both workshops was broader than just control of microreactors and covered not only control of micro- and nanoscale devices but also control of micro/nanofabrication processing technologies, biomimetic control and micro/nanoscale sensing that included control of AFM probes (Sitti [2003]).

However, several of the key recommendations from these workshops are also relevant within the context of integrated microreactors and are listed below (Shapiro [2004, 2005]):

- characterization of the impact of micro/nano component integration on control;
- development of both fundamental multiscale models, as well as parsimonious control relevant models obtained from system identification experiments or model reduction;
- on-chip or embedded control algorithms integrated with the micro/ nanosystem;
- evaluation of robustness of closed-loop in presence of fabrication uncertainty and disturbances.

In the rest of the paper, we will focus on issues involved in the development and implementation of model-based predictive controllers for microchemical systems.

## 6. CONTROL RELEVANT MODELING OF MICROCHEMICAL SYSTEMS

### *6.1 Continuum Models*

Fundamental model development for microchemical systems of the kind discussed in this paper poses unique challenges that stem from the complex coupling of multiple physical phenomena and unusual geometries of these micro-devices. The complex coupling arises primarily from the strong interaction between electrical, mechanical, thermal, microfluidic and chemical phenomena in compactly configured micro-geometries. The individual phenomena by themselves are complex, particularly due to the small channel dimensions.

Flow in micro-devices is characterized by departure, to varying degree, from the continuum assumption and this is measured by a dimensionless group called the Knudsen number (Kn) (Jie et al. [2000]) . For most microfluidic flows, Kn is less than 0.1 which puts the flow in the slip regime. In this regime, fluid flow can be modeled using the continuum conservative equations, with a modified boundary condition to account for wall velocity slip (Karniadakis and Beskok [2002]). Flow in microchannels is predominantly laminar (Jensen [2001]) due to the small hydraulic diameter. A number of related issues in microfluidic mixing and models to make predictions for improved mixing can be found in articles co-authored by G. Whitesides,

H. Stone and others (Stroock et al. [2002], Stone et al. [2004], Stone and Kim [2001]) and the references therein. A general consensus seems to be that for a large number of microchemical systems with dimensions in the size range of ten to hundreds of microns and atmospheric pressure, a purely continuum approach appears to be adequate.

We have studied the development of mathematical models that describe isothermal microfluidic steady flow in membrane microreactors by employing the Navier-Stokes equation with appropriate boundary conditions for fluid permeation through the membrane and velocity slip at the walls to account for Knudsen numbers in the slip regime (Alfadhel and Kothare [2003, 2005a]). The resulting model equations are solved using finite Fourier transforms. As special cases, we can recover the solution for the case of no permeation (no membrane) and no slip (conventional continuum approximation). Noteworthy is the fact that we are able to develop a near analytical solution with this approach and as a result, eliminate the cumbersome computational overhead incurred when adopting a purely numerical approach using finite elements. The presence of the slip boundary condition can reduce the pressure drop by nearly 30% for high Knudsen numbers compared to the pressure drop calculated from the no-slip condition.

Similarly, we have developed (Alfadhel and Kothare [2002, 2005b]) models for predicting concentration profiles in membrane microreactors using basic conservation laws. While molecular approaches to modeling concentration would perhaps be more appropriate, we found that the computational effort required to solve even the simplest such models would be prohibitively large and moreover, recent work (Snyder et al. [2003], Shen et al. [2003]) has shown that both continuous time Monte Carlo simulations (Snyder et al. [2003]) and molecular approaches to the solutions of the Navier-Stokes equation (Shen et al. [2003]) were in excellent agreement with continuum solutions for Knudsen numbers below 0.1, which is typically the case for microchemical systems. This further justifies using simplified models using constitutive laws. The model for membrane microreactors that we developed (Alfadhel and Kothare [2005b]) allows us to predict the operation of a palladium-based membrane microreactor of the kind we discussed in the previous section for separating hydrogen and carrying out water gas shift reaction.

While we have incorporated kinetic models within the context of an overall systems modeling for microreactors, a number of authors have focused on the issue of kinetic mechanism development (Mhadeshwar and Vlachos [2004], Chatterjee et al. [2004]) and the interaction of various spatial and time scales in microreactors. Our on-going work includes the study of heat effects in microreactors which was presented in (Alfadhel and Kothare [2004]) and a publication on this topic is forthcoming.

Beyond unit modeling, recent work has focused on developing optimal design and steady state operating conditions for micro-reforming using formal optimization tools (Chachuat et al. [2005]).

*6.2 Embedded Feedback Control of Microchemical Systems*

Control of MEMS devices has been a growing area of research in the past few years. Most reported studies have focused on control of MEMS oscillatory gyroscopes (see recent article "MEMS in Space" in the July'01 issue *IEEE Spectrum* (Cass [2001]) which are used to measure angular velocity in many applications such as navigation, homing, maneuver control, attitude stabilization and tumble recovery. In Park and Horowitz (Park and Horowitz [2001]), fundamental models were derived from spring-mass force balances and used in studying adaptive control of a Z-axis gyroscope. On the other hand, an input-output empirical ARX (Auto-Regressive eXogenous input) model was identified (M'Closkey et al. [2000]) for the MEMS gyroscope being studied at the Jet Propulsion Laboratory and used to study the inherent frequency characteristics of the gyroscope. There are no such comparable studies reported in the literature that deal explicitly with control of microchemical systems.

As should be evident, the dynamics of microreactors can be described by distributed parameter models. Systems described by such models (Robinson [1971]) have their states, manipulated inputs, system outputs and parameters varying spatially as well as temporally. In some situations, the manipulated input is either available throughout the spatial domain (Christofides [2001]) or at the boundary of the spatial domain (Winkin et al. [2000]) or both. We have studied (Bleris and Kothare [2005c]) the problem of regulation of thermal transients in a microsystem using empirical eigenfunctions that we proposed previously (Bleris and Kothare [2005a]). Proper orthogonal decomposition is applied on an ensemble of data to obtain the dominant dynamic structures, called empirical eignefunctions, that characterize the dynamics of the process. These eigenfunctions are the most efficient basis for capturing the dynamics of an infinite dimensional process with a finite number of modes. In contrast to published approaches, we have proposed (Bleris and Kothare [2005c]) a new receding horizon boundary control scheme using the empirical eigenfunctions in a constrained optimization procedure to track a desired spatiotemporal profile. Figure 2 shows a schematic of the feedback control system block diagram for this receding horizon controller.

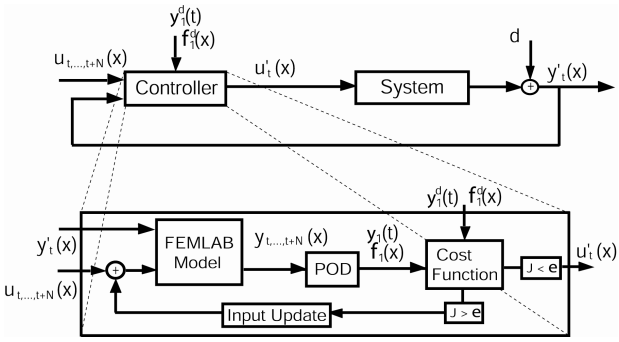


Fig. 2. Receding horizon controller block diagram

As shown in Bleris and Kothare (Bleris and Kothare [2005c]), this controller was demonstrated to maintain a desired temperature profile in a microreactor geometry

using resistive heaters as manipulated inputs. We have also reported its successful use in regulating flow in microchannels and in switching flows (Bleris et al. [2005]) for distributing micro-flow patterns.

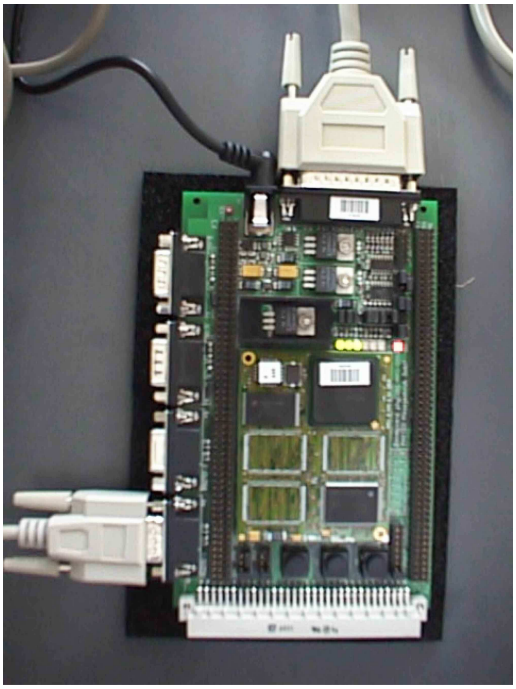

Fig. 3. PhyCORE-MPC555 board with the MPC555 processor (2cm × 2cm)

*6.3 Embedded Hardware Implementation*

The criteria that the final controller implementation must satisfy in the context of microchemical systems are summarized below:

- the controller must be small enough to be "embedded" with the physical system, i.e., the microreactor;
- the controller response time must be small, i.e., in the order of milliseconds, to respond to potentially fast transients in microchemical and micro-combustion systems;
- the parasitic power requirements of the controller must be minimal to make its implementation viable;
- the controller cost should be preferably, but not necessarily, a small component of the overall device cost;
- the controller must be appropriately thermally and chemically isolated from the microreactor system to protect the temperature sensitive CMOS circuitry.

We have proposed two possible approaches to embedding this control algorithm in hardware (Bleris et al. [2004], Bleris and Kothare [2005b]) for System-on-Chip (SoC) applications. In the first approach (Bleris and Kothare [2005b]), we use the high performance single board computer phyCORE-MPC555 which packs the power of Motorola's embedded 32-bit MPC555 microcontroller within a miniature footprint. The MPC555 is a high-speed 32-bit Central Processing Unit that contains a 64-bit floating point unit designed to accelerate the advanced algorithms necessary to support complex applications. All signals and ports of the MPC555 extend to two Molex high density (0.635 mm pitch) 160 pin header connectors. These high density pins allow it to be plugged like a "big chip" into user target hardware. Figure 3 shows the phyCORE-MPC555 board with the MPC555 processor that we have used to implement a receding horizon control algorithm in hardware for fast sampling rate applications of the kind encountered in microdevices.

The second approach we have taken (Bleris et al. [2004, 2006b], Bleris and Kothare [2005b]) proposes reducing the precision of the microprocessor to the minimum while maintaining stable control performance. Taking advantage of the low precision, a logarithmic number system (LNS) based microprocessor architecture is used that allows the design of a reduced size processor, providing further energy and computational cost savings. We have demonstrated a new application specific instruction processor (ASIP) architecture for embedded Model Predictive Control that optimally partitions the MPC computations into an FPGA (Field Programmable Gate Array) hardware implementation for the most intensive operations and software for the reconfigurable parts that need updating (initialization, model updates, etc) (Bleris et al. [2006a,b], Vouzis et al. [2005]). For the specific case under consideration, we have used ADCUS Inc.'s 16 bit EISC (extended instruction set computer) architecture for the reconfigurable software portion and a Xiling Virtex-4 FPGA for the hardware portion of the embedded MPC implementation.

## 7. CONCLUSIONS AND OPEN ISSUES

In this paper, we have summarized some problems in microchemical systems that provide unique opportunities for synthesizing novel controller design architectures. While the fabrication and operation of microreactors appears more and more feasible compared to a few years ago, a number of issues remain unresolved. For the broader problem of microreactors, packed bed catalytic microreactors appear to be not well-suited for carrying out chemical reactions due to the unusually high pressure drops, even despite the new designs that we have developed using radial geometries. Alternative techniques for deploying catalytic surfaces and materials need to be developed. A number of recent developments in this direction have been reported (Ouyang et al. [2005], Ganley et al. [2004]). Finally, in the context of embedded control, new hardware architectures and high performance advanced control algorithms that can be embedded and integrated with the microchemical system need to be developed.

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