Hypermodular Parallel Printing Systems

David Biegelsen, Lara Crawford, Dave Duff, Craig Eldershaw, Markus Fromherz, Greg Kott*, Dan Larner, Barry Mandel*, Steve Moore*, Bryan Preas, Greg Schmitz, Lars Swartz
Palo Alto Research Center, Inc; Palo Alto, CA/ USA; *Xerox; Webster, NY/USA

Abstract

Modularity in system design offers many potential advantages. Xerox has a long history of increasingly deep modularization of printing systems. The present work describes a system of parallel marking engines (MEs) enabled by a paper path that has a level of modularity near the finest granularity of the design spectrum ('hyper-modularity'.) The paper path consists of a small number of module types -- nip modules to provide bidirectional sheet motion and two types of directors for dynamic definition of path topology. Each module is capable of acting, sensing, computing and communicating. Modules, including MEs, are hot swappable, and the system is capable of auto-configuring. Realtime planning and control software, like the hardware, is designed to be modular, distributed, reconfigurable and scalable. The system can handle exceptions, such as sheet jams, while maintaining (reduced) throughput.

Modular printing systems

The use of multiple, relatively inexpensive print engines has many potential advantages over single engine designs. The throughput of such systems is relatively easily and inexpensively scalable without changing the look and feel to the user. Reconfigurability in number and types ('composability') of print engines, the ability to replace defective engines or path modules while running, etc. all provide powerful benefits to the user and manufacturer including customizability, high productivity and up-time, high parts reuse with concomitant economies of scale, uniform system improvement with module redesign, etc.

To enable such designs a highly reconfigurable paper path is desirable to act as the glue layer. Generally a system would consist of a hierarchy of modularity. The greatest degree of reconfigurability would correspond to the finest granularity of the modularity. We describe a system consisting of hypermodules (bidirectional nip assemblies and sheet director assemblies) each of which has its own computation, sensing, actuation, and communication capabilities. Auto-identification is used to inform the controller of the potential paths through the system as well as module capabilities. Motion control of cut sheets, which of necessity reside within multiple hypermodules simultaneously, requires a new abstraction, namely sheet controllers which coordinate control of each sheet as it moves through the system. Software/hardware co-design has provided a system architecture that is scalable without requiring user relearning. Here the capabilities are described of such a system consisting of 160 modular entities and four marking engines (MEs). The throughput of the system is very nearly four times that of a single print engine.

The printing system presented here consists of two towers. Each tower houses two MEs capable of printing single side images

Figure 1 *Two-tower hypermodular printing system*

at 55 ppm. Paper path modules are pinned into a frame providing a fixed pitch array. Frames, called highways, hold a 1x7 array of nip modules and directors. Smaller 1x1 frames are stacked or hung from highway frames to provide on and off ramps as well as inversion and sheet purge functionalities at the input and output of each ME. All modules, including MEs are removable from the array by sliding from the frame, perpendicular to the array.

Because the sheet trajectories are bidirectional, baffles between modules are interdigitated. To enable module extraction the interdigitated baffles are retractable. This decoupling of elements of the paper path also allows for novel rotary spindling of jammed sheets and sheet extraction perpendicular to the process direction.

Figure 1 shows the full two-tower fixture. Each ME is set to print identifiable patterns as shown on sheets affixed to the covers. Two sheet feeders are on the left side of the array and two output trays are on the right. Frames (1x7 and 1x1) can be seen from the side. Nip modules are inserted into the frames at a fixed pitch of 130 mm, determined by the constraint that the shortest allowable sheet should always be engaged by at least one nip pair. Spaces between nips are populated with directors – modules which can dynamically select possible paths between nips.

Hypermodules

Figure 2 shows a nip module. The left side is the back side which is inserted first into the frame. The long shafts have spring loaded pins which allow the module to be inserted into holes laser cut into the back and front faces of the frames. A stepper motor drives a shaft holding two drive rollers in opposition to two sprung idler rolls. Upper and lower retractable nip baffle pairs (here sprung into their retracted position) are interdigitated within a pair to facilitate bidirectional sheet guidance without stubbing. The baffle retraction pins are used by the director (described below) to pivot the baffles into interdigitated alignment with the mating baffles of the director path guides. Optical edge sensors are mounted in the windows in the baffles to provide information about sheet leading and trailing edge timing as well as skew. The printed circuit board at the rear end carries a DSP which oversees

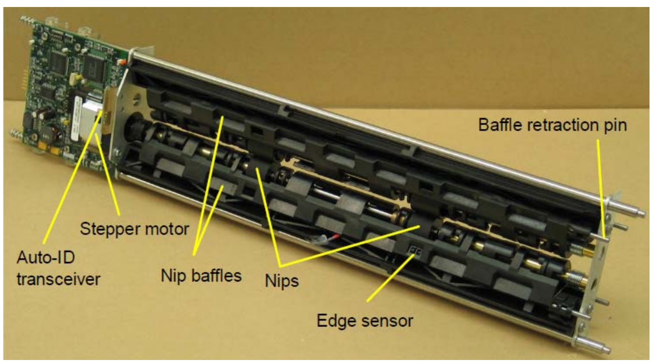

Figure 2 *Nip module*

the motor controller, sensors, local computation and communication. The gold pins at the rear of the PCB are spring-loaded connectors which enable hot swappable connections for power and communication. A final function, integrated onto all modules, is the auto-ID optical transceiver. Each nip module has two nearest neighbors with transceivers. DSPs on each module have a stored code which points to a data base enumerating the capabilities of the module. Simple nearest neighbor communications allow the module DSPs to learn their neighbors and transmit the information over the bus. A central processor can then deduce all possible sheet paths and module capabilities (including ME characteristics, health state, etc.)

Figure 3A shows a straight-through director module. The right side corresponds to the front of the module. The aluminum plate at the bottom is part of the drawer mechanism for sliding the module out of the frame. The handle at the right has been rotated part way through the ~360^{o} of its full rotation. During the initial rotary motion the shark-fin-like structures (blue and red here) allow the retraction pins on the nip baffles to spring open. Then the mechanism rides up and over the pins to allow full rotation of the director core. At the end of rotary travel the unit unlatches from the frame, is depowered, and can be pulled out with any jammed sheet roughly centered on the director now spindled and removable through the opening in the frame. An auto-ID transceiver can be seen again. Only when the director is in place with its proper angular position will the system accept the module as functional.

Figure 3B shows a '3-way' director (in an oppositely oriented view.) Many of the parts are reused, such as the bottom director baffle. As can be seen in the inset the inner walls of the paper path are formed by three flippers sharing a common axis. Idle rollers help guide sheets through the 55 mm radius turns. The flippers are driven by the solenoids mounted on the end plate and driven by the PCB hidden below the bottom director baffle. The flippers take ~10 ms to change state in either direction. Cut sheets incident to any of the three ports can be guided to either of the two other ports, thus allowing six possible trajectories through the module.

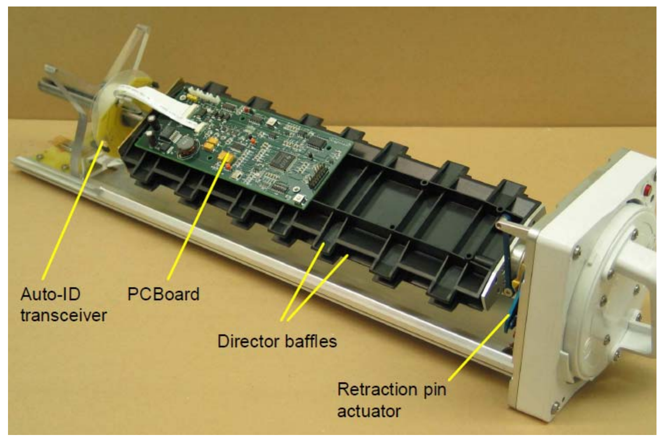

Figure 3A *Straight through director module*

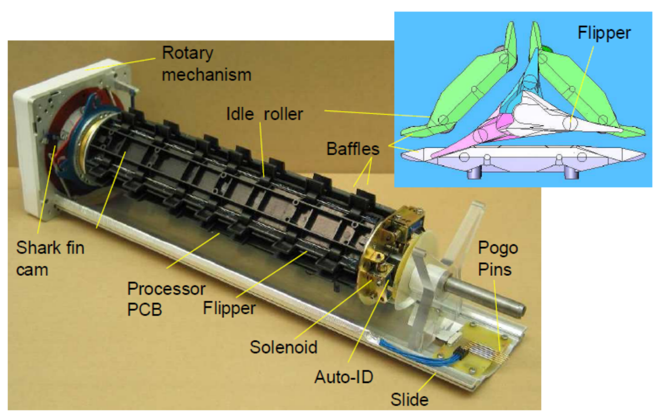

Figure 3B *Three-way director module*

Architecture and reliability

Many ways exist for configuring multiple marking engines (MEs) to work together. We have chosen a tower arrangement as the highest level of modularity. Each tower can host stacked print engines. (We have used commercially available printers which have been stripped of extraneous features such as duplex return paths and paper trays; the housing sizes, kept for expediency, limited us to using two engines per tower.) It is desirable in a highly parallel printing system to be able to transport a sheet from any engine output to any other input. For example, if one ME is a color ME and another is monochrome and a given sheet calls for one side to have color and the other to be monochrome, then it can be optimal within a job to transport a sheet in a retro direction from one ME to another. To enable optimal system throughput the paper paths must therefore have sufficient speed and parallelism to enable the system throughput to be limited only by the productivity of the MEs printing at maximum capacity in parallel.

One architecture which satisfies these goals (and corresponds to the photo in Figure 1) is shown in Figure 4. Two 2-ME towers have been abutted. The paper path modular frames (shown as dashed lines) form a fixed pitch array populated by nips and directors. Solid lines between nips indicate possible paper paths. The three horizontal paths in the center (highways) enable bidirectional redundant paths for connecting any outputs and inputs. Sheet inversion (and purging) can occur at any of the path terminations. The degree of inter-highway connectivity can clearly be chosen at will. The choice is related to system throughput (including the event of jam clearance), desired redundancy, reliability of parts, relative speeds of MEs and path nips, etc. As a system scales to more towers, either more highways can be inserted or higher speed path elements can be used to keep pace with the higher ME capacity.

All nips must be not only bidirectional but also capable of driving at a range of speeds. For example, the vertical on- and off-ramps must buffer sheet speeds between fast highway speeds and the relatively low speed of the MEs. Similarly, obtaining maximum throughput requires sheet speed changes to enable trajectory crossing and timing. Because multiple nips in contact with a given

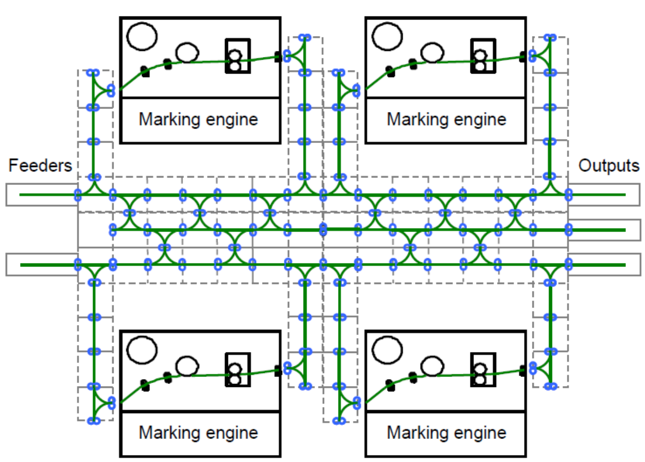

***Figure 4** Two-tower, 3-highway architecture*

sheet need to run at the same speeds, tight control between motor controllers needs to be supported (see discussion below).

The apparent complexity of this system forces one to question the relative reliability and cost of the hypermodular architecture in comparison with architectures using much coarser-grained modularity, but still with the same number of MEs. Studies were carried out using as many part-for-part equivalents as possible. The bottom line was essentially that for the same degree of functionality the cost and reliability of the systems was approximately the same. This is due to two factors. First is that the dominant source of unreliability is the ME; and for the paper path the costs and unreliabilities are dominated by the actuators (motors and flippers). Because systems with the same functional capabilities have nearly the same numbers of actuators, the costs and reliabilities are quite similar. In comparison with a more custom-built monolithic architecture it was concluded that cost and reliability scaling for equivalent performance strongly favored the modular, multi-marking engine approach.

Sheet control, job and path planning, and exception handling

Module communication occurs over a CAN (Control Area Network - a fault-tolerant serial communications protocol) bus. Because bandwidth was limited by the CAN specs at the time of implementation two buses were used for each tower. Each bus is daisy-chained through all module controllers on its net and thence to a central PC. The central PC collects all information about the physical capabilities and interconnectivity of all modules.

The system control architecture [1-4] is shown in Figure 5. Each of the 164 processors (TI F2811 DSP) runs a module controller, residing in the DSP, that is responsible for driving actuators and monitoring sensors. Coordination among module controllers is mediated by an abstraction called a sheet controller, spawned one per sheet, which resides, in this particular design, in the central PC. The sheet controller has three main roles: to interpret and distribute the timed path generated by the planner, to share feedback among the module controllers acting on the sheet, and to monitor the sheet's progress and report back to the planner if there are any problems. At the top of the control hierarchy is the planner. The planner, with knowledge of the system capabilities

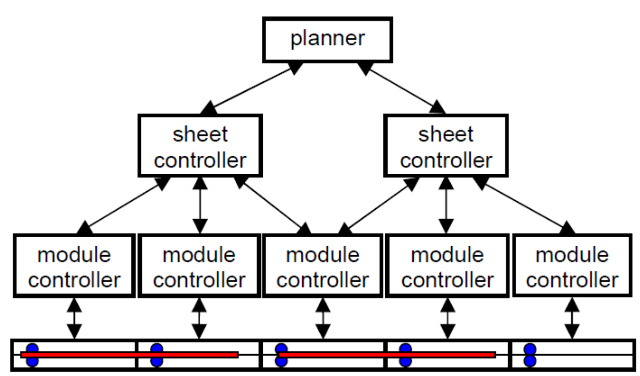

***Figure 5** System control architecture*

and interconnections, creates sheet itineraries from job descriptions and passes these itineraries to new sheet controllers.

There are many trade-offs in parsing the control architecture. One principle seems likely. The local, module-specific control software should be resident in the module. That way, different type modules can have different control software, and no centralized entity needs to keep track of details that it otherwise does not need; this is the principle of encapsulation, keeping knowledge where it is needed (much like object oriented programming). With local knowledge, the modules have a significant degree of autonomy, and can be delegated tasks by higher control levels. The modules simply then need to be able to accept delegated commands and then report back to the higher levels if there is a problem (escalation of error conditions). Complexity in system scaling is thus reduced.

Coordination between nips engaged with a single sheet is the central task in the control problem. It could be solved at the module level, through local communication (the system has nearest-neighbor communication for auto-configuration) and the coordination function could travel with the sheet, or it could be centralized; it could even reside in the planner. In any architecture, coordination necessitates high bandwidth communication among modules and lower bandwidth communication with the planner. The choice of communication means is thus key in converging on a scalable and reconfigurable system architecture.

The planner accepts multiple job requests and creates near-optimal plans to launch and guide sheets from feeders to output trays via multiple MEs as needed. The planner must also support changes to sheet routing due to exceptions such as soft jams (which allow automatic recovery by backing sheets away from the jam point) or hard jams (which require guided user intervention.)

The current planner/router design features an intuitive and compact modeling representation, reuse of heuristic computations between sheets, and an efficient representation in the temporal constraint network. In addition, a time-bounded search algorithm was added to the planner, so that a greedy plan can be found in a very short time and then improved upon.

Results and Conclusions

Using nip modules providing 1.25 m/s sheet speeds with sufficient torque at speed for smooth control and four MEs with process speeds of 0.26 m/s (55 impressions/minute) system throughput was demonstrated at 210 impressions/minute, almost 4x the single processor throughput. Real time rerouting and planning were also successfully demonstrated as well as rotary jam clearance with computer guidance and nip assist.

On-line replanning and rerouting of sheets in the system was demonstrated. A module in the fixture could be failed after a sheet had already launched, and the sheet would reroute around the failure. Additionally, if a sheet were to jam, the planner would reroute out-of-order sheets to the purge tray and recreate the jammed sheet and all subsequent sheets. Alternatively, the out-of-order sheets could be routed around inside the system until the jammed sheets were reproduced.

A systems analysis indicated that cost and reliability of hypermodular systems should be closely comparable with custom systems when equivalent functionalities are enabled. However, if the high level of functionality enabled by the described hypermodular system is not required, then a coarser-grained transport system can be designed that achieves a lower cost and higher reliability.

The present work has demonstrated a parallel printing system which is deeply modular and reconfigurable in both the physical and software realms. There are clearly many trade-offs involved in the design of modular parallel printing systems and hypermodular approaches in particular. Aspects such as degree and ease of reconfigurability, parts count, scalability, etc. likely lead to different optimizations. However, it has been shown that building systems using fixed pitch placement of paper path elements, using marking engines with inputs and outputs commensurate with the same pitch, and using a hierarchy of modularity (e.g. towers, highways, a few types of hypermodules and a reduced set of standardized parts) can lead to the goals of scalability, easy reconfigurability, path redundancy, etc.

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Author Biography

David Biegelsen is a Research Fellow at Palo Alto Research Center Incorporated. He has published widely in many fields and holds over 100 US patents. His primary focus in the past decade has been in the design of smart matter systems composed of agents which can sense, act, compute and communicate to provide highly coordinated and dynamic capabilities.