Cell-Based Architecture for Reconfigurable Wiring Manifolds

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Nomenclature

CU	=	cell unit
AWP	=	adaptive wiring panel
GND	=	ground
CMU	=	cell management unit
EDS	=	electronic data sheet
mA	=	milliamps
V	=	Volts

I. Introduction

Conventional spacecraft wiring harnesses are built with architectures that are fixed at manufacture, though evolving mission requirements often tend to favor systems that can adapt to support the concept of Responsive Space missions. With launch costs exceeding $30,000 per kg, reducing the mass of a spacecrafts wiring harness without compromising reliability is highly desirable [1].

A programmable wiring harness is being built which exhibits qualities similar to a field programmable gate array (FPGA), in that it is a pre-wired architecture that is soft-configured as needed, and ideally within minutes of a defined mission. By implementing reversible and dynamically programmable software wires, when embedded in a wiring system, these can be used to build a programmable wiring manifold. Adaptive wiring systems would have many useful properties, including the potential of self-healing/diagnostics and soft-definable probe signals. Algorithms used in FPGA and switch routing will be exploited to guide the formation of switchable wire paths in the adaptive wiring manifold.

A reconfigurable switch fabric enables dynamic routing of signals in many different applications. Power routing, and digital and analog signals can be routed for space systems, but the adaptive wiring concept can also be applied to terrestrial applications such as aircraft wiring and ground-based systems. Additionally, dynamic routing of media such as light or fluids can also be achieved using the same fundamental switch architecture.

II. Conceptual Architecture

The concept of adaptive wiring is straightforward, and this section describes a number of basic principles for adaptive wiring systems. To introduce the basic idea, an adaptive wiring structure that could be referred to as a *substrate* contains a number of input/output (I/O) termini, as suggested in Fig. 1. In the case of adaptive wiring, the termini can be thought of as representing a wiring “problem” (Fig. 1a), in which it is desired to connect termini together bearing the same label (i.e., “A” connecting to “A”, etc.) In general, the wiring problem can be referred to

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as a *netlist specification*. In this depiction, the actual adaptive wiring system is represented as a "cloud" within the substrate. A number of possibly non-unique solutions might exist to solve particular netlist specification, as depicted in Fig. 1b. The "cloud" of course notionally suggests that the problem is solved without detailing either how the interior fabric within the substrate might be defined or how the desired configuration is gleaned.

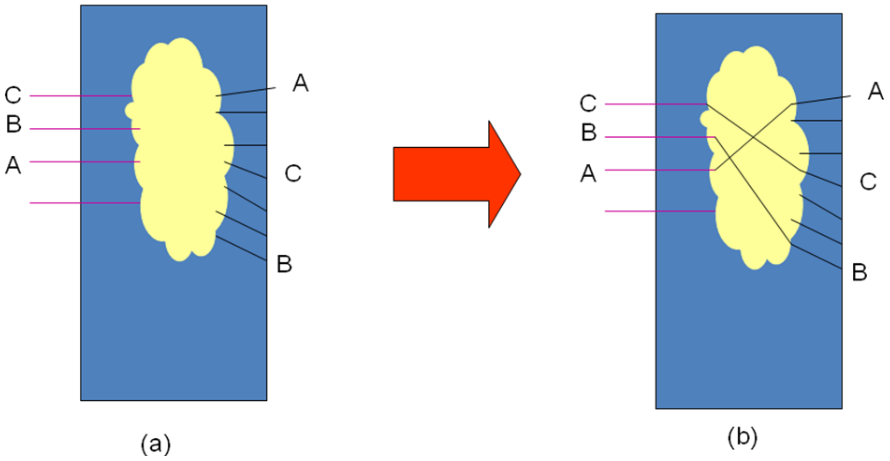

Fig. 1. Basic concept of adaptive wiring. (a) Substrate having a number of exterior termini defining a wiring "problem". (b) Depiction of wiring solution (divorced from implementation details).

Fig. 2 depicts a notional implementation concept to provide some intuition about how an adaptive wiring system might actually be implemented. In this case, the substrate takes on the aspect of a physical panel featuring four sockets where components or "modules" can be mounted (Fig. 2a). To implement the amorphous "cloud" of wiring resources in Fig. 1, we depict here a deliberate configuration consisting of a matrix of wires in rows and columns, with circles shown at the intersection points. The circles represent electrical switches that, when closed, short together the associated row and column. At this moment, we are not concerned over the specific medium for switches. They could be, for example, metallic relays, solid state switches, microelectromechanical systems (MEMS) devices, or combinations of these and other switch types [2, 3]. Using such fabrics, implementing a solution to a particular wiring netlist amounts to closing a number of switches, as shown in Fig. 2b, which shows how a two-netlist problem (involving two placed modules) might be solved (through a total of six switch closures).

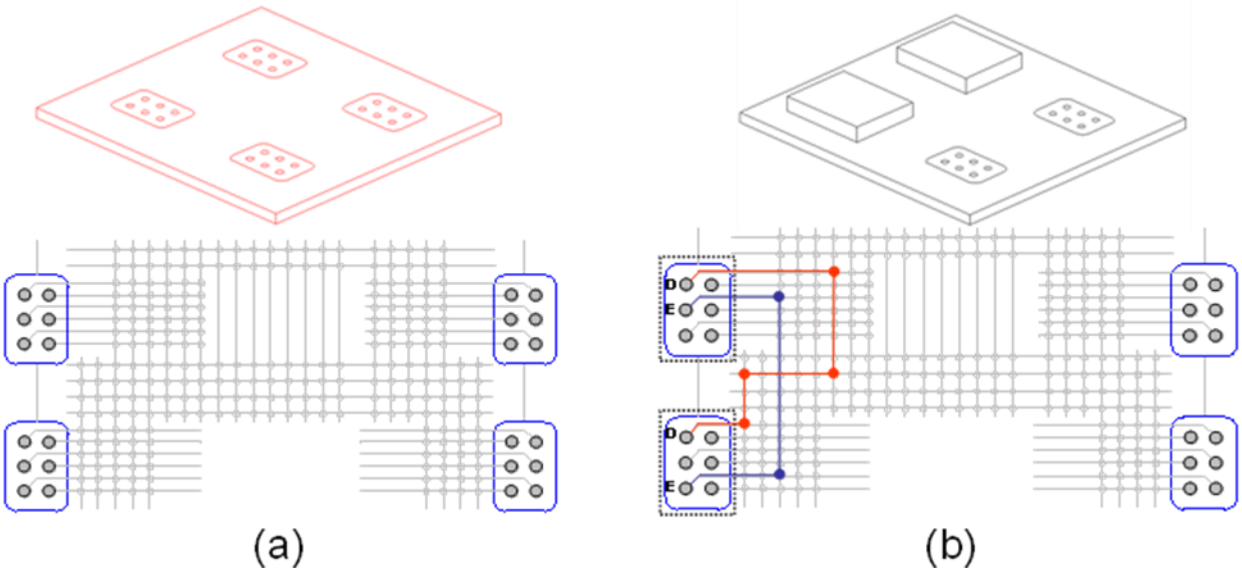

Fig. 2. A notional physical embodiment. (a) Unprogrammed substrate, containing a number of sockets for components (modules). (b) Example placement of two modules and wiring of a two-net netlist.

To permit scaling these implementations, we could consider a number of substrates that could themselves be tiled or otherwise connected together, as suggested in Fig. 3. In this case, two adaptive wiring substrates or "cells" form an extended system. Clearly, a netlist solution involves the definition of two compatible sub-solutions, one implemented in each cell, to generate the necessary overall connected paths between the termini of the source wiring problem (netlist specification).

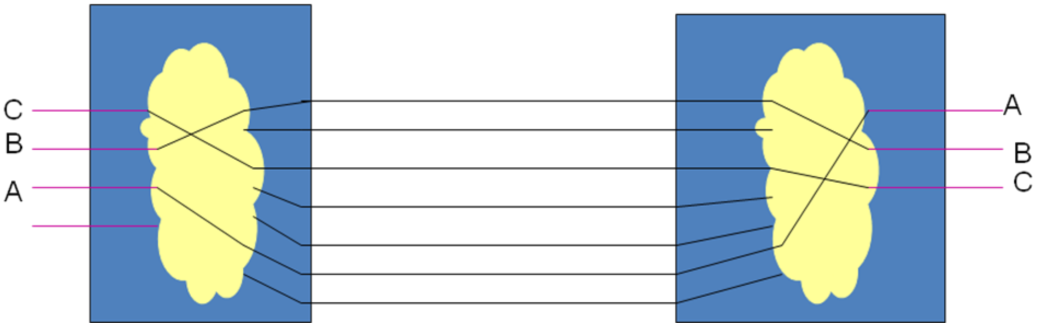

Fig. 3. Extended adaptive wiring system contain two "cells".

As previously discussed, adaptive wiring manifolds offer a number of benefits in developing new systems. Since the adaptive wiring substrates (or panels) may be pre-built and inventoried until use, it is possible to retrieve them as needed and configure them on demand. Rather than wait for custom-defined wiring harnesses to be developed and delivered, a process that could take weeks or months, the adaptive versions can be configured very quickly. Unlike custom wiring harnesses, whose wiring pattern is permanently locked in, adaptive panels can be altered as needed to accommodate late-point changes. Adaptive wiring systems furthermore, have two powerful benefits that are impossible in any other wiring technology.

One advantage of this architecture is the ability to adapt to faults that occur after a system is placed in the field. Since wiring patterns can be software-definable, defects can conceivably be circumlocuted by computing an alternate configuration. This concept is illustrated in Fig. 4. In this cause, a faulty connection between B-B can be rectified by configuring other wiring resources that can achieve an equivalent connection without removing a system from the field (which is often impractical, as is the case for space systems).

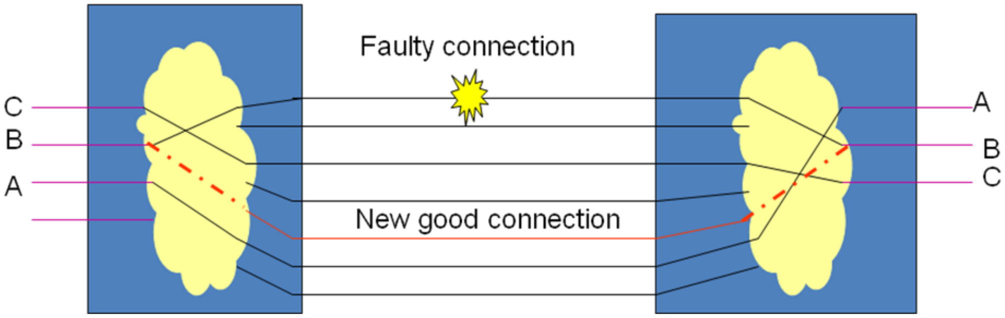

Fig. 4. Demonstration of fault/defect tolerance.

The second unique advantage of adaptive wiring systems is the ability to form probe connections for diagnostic and maintenance purposes. Temporary probes can be inserted at normally inaccessible buried nodes within a wiring system and "dissolved" when no longer needed. This concept is depicted in Fig. 5. In this case, we use the adaptive wiring system to set up a temporary connection to check a possible problem with terminal C on the right panel.

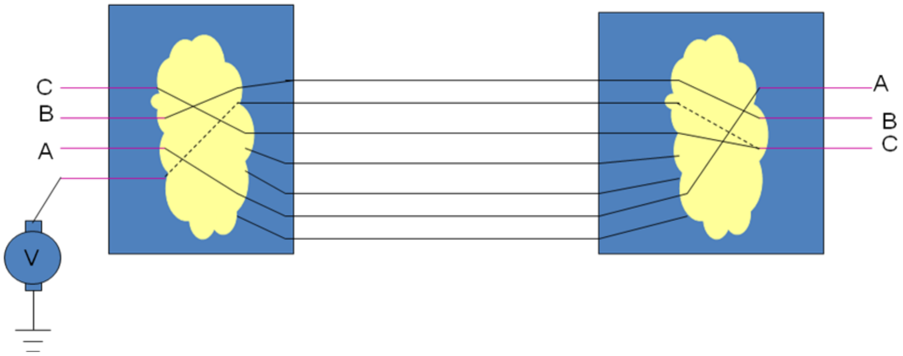

Fig. 5. Demonstration of temporary probe formation.

The techniques demonstrated in Fig. 4 and Fig. 5 can be combined with algorithms to form a self-healing system. Self-healing, as an “active” concept, can be viewed as having two phases, the first being diagnostic, the second being restorative. Clearly, the use of temporary probes can serve to probe an adaptive wiring system, even in situ, to explore the continuity of wiring resources. Upon discovery of defects, an algorithm in the “live” system can compute an alternative wiring path. In earlier AFRL-sponsored work [1], we learned it was possible to achieve self-healing as a linear-time process in an active system. To see this, consider that diagnostics can be implemented on live networks by forming first a redundant path connection to a given node pair, then disconnecting the original path for the purpose of continuity probing. If the original path is found defective, the defect is noted and the defective resources are not re-used in the future. The originally redundant connection remains in place as the new primary connection. Clearly, it is never necessary to ever restore the primary connections after probing, so this approach implements self-healing as a linear time procedure (proportion to the number of switch resources) that is based simply on refreshing all system wiring configurations for the purposes of probing them at a repetition interval chosen under system-wide control.

In the next discussion, we discuss a particular wiring manifold approach that supports a number of useful features, as well as implementing the necessary infrastructure for controlling both local (cellular) and global configurations, the automatic detection of cellular boundaries, and the discovery of placed components.

III. Scalable Cellular Implementation of Adaptive Wiring Manifold

The Adaptive Wiring Panel (AWP) is a manifold of adaptive wiring cells cast as a single overall panel. The panel is a pegboard-like structure, which (unlike Fig. 2), do not articulate specific sockets, but rather provides a continuous grid of contact pads and mechanical mounting holes. The AWP implementation is based on three basic elements: (i) cell units, (ii) a cell management unit and (iii) modules. Cell units are defined as the minimum independent unit of the AWP, all with interconnections and communications with other cells, and form the switch fabric by which we wire components to each other. The Cell Management Unit communicates independently with all cells and manages the wiring path and switch connections of the panel. Finally, modules are the “widgets” that make up components to be wired. Examples include power supplies, gyros, thermisters, electrical components such as capacitors, resistors, etc.

In the next sub-sections, we describe the high-level functionality of these components.

A. Cell Unit

Each cell unit (CU) is the minimum independent unit to create the AWP. For the initial design study, each CU measures 5x5cm. In Fig. 6 we show the top view of a CU. This block has: (i) 12 signal connectors, (ii) 3 power connections (one is a fixed connection to GND), and (iii) 1 mechanical connector.

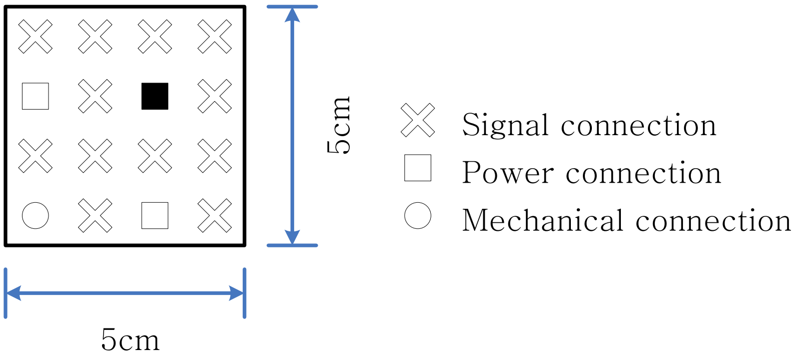

Fig. 6. Cell block. Each cell block has 16 connectors: 12 for signals, 3 for power and 1 for mechanical connections.

For the initial version of the AWP, each CU will be implemented using an FPGA board. The functions of each CU are:

1) Control the programmable connections of the AWP.
2) Communication with (up to) four neighbors: each CU needs to communicate with its physical neighbors to recognize spatial orientations.
3) Read Electronic Data Sheets from modules via probe pins: each module has a probe pin (to be described in the next sub-section) that transmits its module-ID and the information about required connections to other modules on the AWP.
4) A low current power supply will be sent to power the modules to enable transmission of electronic data sheet information through predefined probe pins.
5) Communication with the cell management unit: each cell unit transmits and receives information to/from the cell management unit (i.e., cell units aside from neighbor recognition cannot communicate directly with each other.) Each cell block, upon system powerup, will send identification information such as ID of the CU, the IDs of its neighbors and relative orientations, and module Electronic Data Sheets, if connected to that CU.

Each CU will have three layers: (i) top layer for pins to connect the CU with the modules, (ii) middle layer with the array of relays and (iii) bottom layer with the FPGA to control the system.

B. Cell Management Unit

The cell management unit (CMU) manages communications and performs routing configurations of all cell blocks on the AWP. An architectural diagram is shown in Fig. 7.

The functions of the CMU are:

1) Manage the communication bus: I^{2}C is the chosen communication bus between the CUs and the CMU, and the CMU serves in single master mode.
2) Read and organize initial location/orientation information from the CUs.

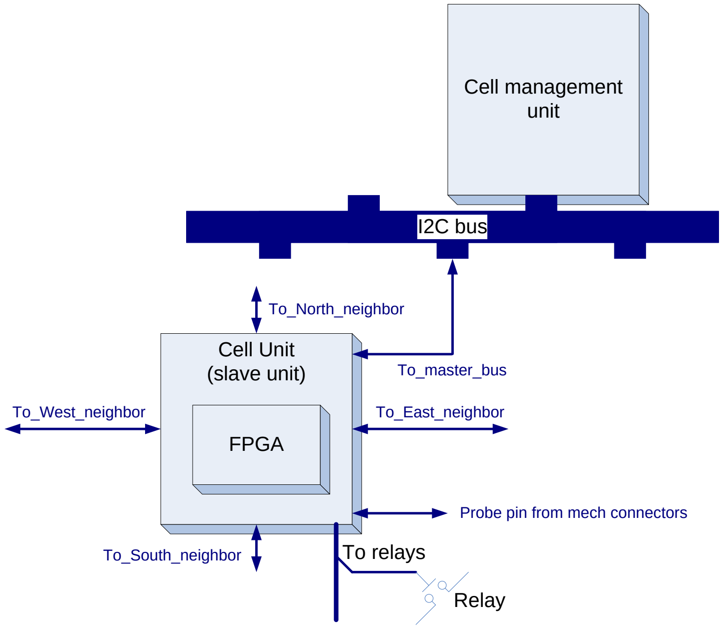

Fig. 7 Cell Management Unit (CMU) with a typical connection to a Cell Unit.

3) On a periodic basis, scan for IDs of any modules connected to a particular CU, and read module Electronic Data Sheets.
4) Compute the shortest path and routing of required signal connections: the CMU has a priori knowledge of the layout of relays in each cell block. When the geometry of the AWP is created, a complete graph related to the AWP and the connections is built by merging the subgraphs of each individual cell. After reading the module Electronic Data Sheets containing required switch connections, the CMU computes the shortest path to connect corresponding terminals on the modules.
5) Command cell blocks to open or close specific relays.

C. Modules

Modules (the components to be wired) have an interface to the cells with a minimum of 5x10cm with 24 signals connectors , 6 power connectors and 2 mechanical connectors (not all of which need to be connected). The system is designed with the capability to route signals such as power, ground, and high frequency signals (for example) on separate sub-graphs, such that dedicated wires can be used for routing signals with different requirements.

IV. Conclusion

We have presented an introduction, motivation, and a high-level architecture of the Adaptive Wiring Panel, and described the interactions required between modules, cells, and the Cell Management Unit. Current work targets a working prototype and proof of concept demonstration. This requires graphing algorithms that intelligently program switches to wire the required module connections. Dijkstra’s shortest path algorithms provides an initial solution for connecting modules in more sparse environments, and is the planned algorithm for joining sub-graphs of individual cells together to form a master switch graph.

Acknowledgments

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V. References

Proceedings

[1]Thompson, Sarah, Mycroft, Ian, "Self-Healing Reconfigurable Manifolds," *Proc. DCC'06: Designing Correct Circuits,* Vienna, Austria, Mar. 25-26, 2006.

[2] Lyke, James, Wilson, W., Contino, P. MEMS-based reconfigurable manifold. In *Proc. MAPLD* (2005), NASA, available at http://klabs.org/mapld/index.htm.

Patents

[3]Lyke, James C., R., Wilson, Warren G., and Broyls, Ren H., Albuquerque, NM, U.S. Patent Application for a “Adaptive Manifold,” Pub No. US 2002/0141130 A1, filed 3 Oct. 2002.