THE G-64 BUS AT CERN AFTER 25 YEARS OF OPERATION

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ABSTRACT

The G-64 bus idea was conceived at CERN in the late seventies around the Motorola 6809 microprocessor and was commercialised by GESPAC SA in 1979. It was quickly exploited as the computer bus for the power converter controls electronics in the CERN Proton-Synchrotron (PS) and Proton-Synchrotron Booster (PSB), and subsequently made its way into many other machines.

Now, twenty-five years later, nearly 800 power converters at CERN are still controlled by electronics based on the G-64 bus and the MC6809 microprocessor running at just 4 MHz.

A key feature of any bus is the ability to divide functionality into separate cards. This modularity enabled variants of the same design to be rapidly adapted to a very diverse population of power converters. This was particularly important as more and more commercial power converters were chosen to keep down costs, and each type came with a different interface, often lacking certain functionality such as remote control of converter state, reference, polarity inversion or precise timing. In the end, more than 20 variants of chassis were (and remain) in operation.

This longevity is remarkable by any standard and justifies closer examination. How has it been possible to maintain and expand a system that belongs in a museum? This paper examines the strengths and weaknesses of the original design, and looks at the lessons that may guide our technology choices today, as CERN embarks on an ambitious renovation program of its older machines.

G-64 ORIGINS

Industrial bus standards have originated from a number of sources. As semiconductor companies introduced new microprocessors, they also built a series of board and system products designed mainly to simplify the use and speed the acceptance of their chips. These buses often were a direct extension of the microprocessor local bus onto a backplane. In fact, in the early days of the micro-computing industry, it was enough for a bus to ensure that boards plugged in the same backplane merely communicate. History includes a small number of bus architecture defined independently by other sources, for example, the S-100 bus from Altair or the G-64 bus from CERN/GESPAC. These buses have often done well in the market because they were aimed at specific needs and were relatively independent from any given chip or computer maker.

The G-64 bus concept was defined to meet the requirements of small, real-time industrial microcomputers systems. The G-64 was (and remains) an open architecture requiring no license for its use. Technically, the G-64 is a layered architecture comprising several levels of complexity and compliance, all of which are upward compatible. This layered architecture provided great flexibility and the ability to choose the most cost effective implementation for a given application. The G-64 bus concept was processor independent and was designed to handle 8-bit, 16-bit and even 32-bit microprocessor based systems. It was widely used in the industry, research institutions and even in aerospace. A diverse variety of modules were developed by a number of suppliers and institutes, and despite being more than two decades old, some modules are still produced and supported.

The backplane of the G-64 bus uses a standard female DIN 41612-C connector. G-64 modules use the corresponding male connector. The same family of connectors (with 96-pins instead of 64) are used in VME systems. These are pin-in-socket connectors which are very reliable and have excellent mechanical characteristics. The selection of this connector was the **first strength** of the G-64 standard. The price, reliability and robustness, and the simplicity of the mechanical manoeuvre to insert or withdraw a module have greatly satisfied the users over the years.

G-64 modules use the standard single Eurocard format (100 mm x 160 mm x 1.6 mm) and the metric DIN connector to provide a system optimized for rugged applications. The size of the boards was the **second strength** of the G-64 standard. The board height matched the size of the backplane connector and the dimensions are small enough to allow easy handling with only one hand. Like all Eurocards, the format has good mechanical resistance against shocks and vibrations but is still big enough to support several ICs. Even in the early days, it had sufficient area to implement fundamental elements of a system such as a processor board or a network interface.

THE CERN SUBSET

CERN only retained those signals from the G-64 standard that were used to interface I/O boards that were commonly available on the market. The support for multi-processing capabilities was removed and the CERN 8-bit CPU module was assumed to be the only master on the bus. Only backplanes without terminators and with a bus clock of 1 MHz were installed. The peripheral address space was restricted to 4KB (0xE000 – 0xEFFF) and these restrictions fulfilled CERN's specific needs and lead to the **third strength** of the G-64 standard: interfacing became extremely straightforward and required only inexpensive components. For example, with three ICs from the standard TTL family plus a PIA is was possible to implement a simple 16 channel digital I/O module, compatible with a CERN G-64 bus.

THE CERN G-64 CHASSIS EXPERIENCE

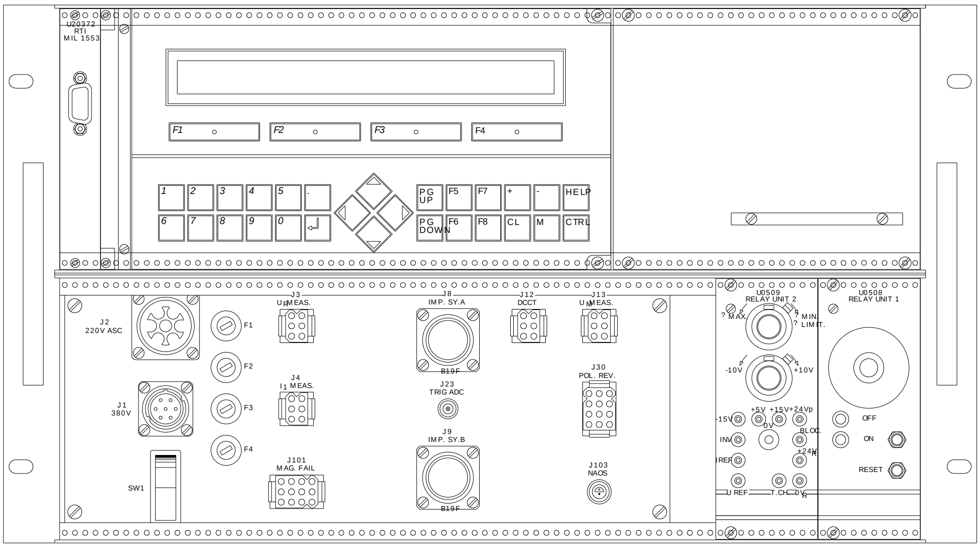

Figure 1: Front view of a CERN G-64 chassis

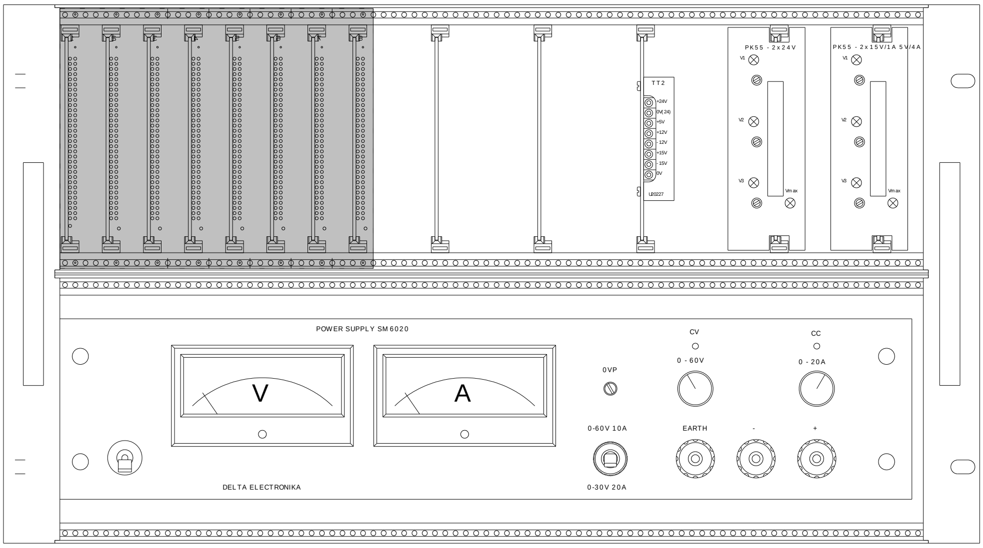

Figure 2: Front view with the display and connector plate removed

Chassis Hardware and Modules

At CERN the G-64 bus is a key element in the so-called “G-64 Chassis”, used to supervise power converters. Nearly 800 power converters in service today are equipped with these G-64 Crates. The chassis includes not only the G-64 bus and G-64 modules but also other kinds of modules with the responsibility for some or all the following tasks (depending on the type of power converter): (i) remote control, (ii) status monitoring, (iii) regulation, (iv) firing circuitry, (v) interlocks and protection.

Figures 1 and 2 shows the mechanical distribution of elements within a typical CERN G-64 chassis. At the front of the upper 3U row is located the flat keyboard and the dot matrix display used to locally command the power converter and to display the status and fault information for the human operator. Additionally the display and keyboard is used as an access door to the G-64 bus behind. This protects the cards from be disturbed accidentally. The lower row of figure 1 shows the connectors for external signals such as timing and interlocks. In some cases these connector are placed at the back. Figure 2 shows the same view but with display and connector panel removed to reveal the modules behind. The G-64 backplane is shown in grey on the left of the upper 3U row. The rest of this row is for the *analogue* backplane. In the lower 3U row a commercial power converter is shown.

The *analogue* bus is separated from the G-64 bus, but uses the same Eurocard module format and DIN 41612-C connector. This *analogue* bus can hold an analogue current regulation board or the digital equivalent based on a DSP. If the power converter is small enough to fit in the lower 3U part of the chassis, then the analogue bus can also have a module dedicated to the control of firing.

The G-64 chassis can hold modules to drive a CERN designed power converter as well as completely different modules for commercial power converters. This flexibility is the **fourth strength** of the G-64 design. CERN has defined about ten different broad controls functionalities, implemented on more than 65 different Eurocard designs. About 70% of the designs correspond to replacements for the same functionality due to obsolescence of certain components. This division into modules has prevented the overall collapse of the G-64 crates when confronted with the obsolescence of individual components, which can happen with single multi-purpose boards. The main functionalities defined for the CERN G-64 crates are:

- Communication with the centralized system that remotely operates all the power converters (two modules):
  - The first one using CAMAC (still in use in 2005!)
  - A later one using MIL-1553
- G-64 Master CPU that drives the G-64 bus (four modules):
  - The first three are evolutions of the same MC6809 CPU
  - The fourth is a replacement using a new Mitsubishi microcontroller
- Display and Keyboard: three modules, one being an evolution of another
- ADC measurement interface: four modules with different characteristics, plus evolutions of each brand due to performance needs or obsolescence
- DAC reference interface: three modules with different characteristics, plus evolutions of each brand due to performance needs or obsolescence
- Digital I/O: five modules with different characteristics and evolutions, non-isolated, opto-isolated, with relays, etc…
- Analogue closed loop regulation: several modules with different characteristics and evolutions, P loop, PI loop, PID loop, switching PWM, limiters, etc…
- Digital closed loop regulation: one DSP module with four evolutions, one digital thyristor gate control module for 6/12/24 phases with 4 evolutions

This diversity of modules enabled variants of the same design to be rapidly adapted to a very diverse population of power converters used in different ways. This was particularly important as more and more commercial power converters were chosen and each type came with a different interface, often lacking certain functionality such as remote control of converter state, polarity inversion or precise timing. In the end, more than 20 variants of G-64 chassis were developed and remain in operation.

The *analogue* bus was implemented with wire-wrap. In the past, converters were always installed in small series; the manpower available was significantly larger than today so linking hundred of wires by hand never presented a production problem. Nobody seriously tried to define the real needs of the *analogue* bus and because wire-wrap always fits the requirements, there was no motivation to create a PCB backplane instead. Today with less manpower, training a technician to follow the cloud of wires with schematics that sometimes do not strictly correspond to the implementation is not acceptable. The last generation of G-64 crates have a PCB backplane.

Software Development and Maintenance

Flexibility is nice but care must be taken or the shear number of variants can become unmanageable. One software developer working alone was in charge of the embedded software for a big portion of the power converters in the PS complex. The parameters for every type of chassis were hard-coded in his programs and stored in EPROM instead of using even basic techniques such as menus or auto-detection of hardware. As a result, any slight modification in the hardware resulted in a completely new program, derived by cloning an existing program. For example, for the same type of chassis and functionality a different measurement card was selected due to a new precision requirement, so two programs were developed. A couple of years later the commercial power converters installed in the crates were enhanced with an internal polarity inverter. The result was four different programs. Unfortunately after some years the display had become obsolete and a new one was chosen, leading to eight different programs. Another display change and a new communication protocol for a new experimental area were followed by other enhancements to the measurement cards to be unipolar or bipolar. A new ADC chip replaced an obsolete device but returned its value in two's complements instead of complementary offset binary, and so on. After 18 years working on the project the developer retired leaving 350 3.5" DD floppy disks containing more than 300 different programs!

The programs were poorly documented and executables running in operational power converters did not appear to have a corresponding program on any of the floppy disks. The system was very close to being in the state of "Nobody touch anything because at least it works!" that can afflict aging systems, preventing any chance for a smooth transition towards a new architecture. Experience shows that if this happens, the next step is usually a rushed total renovation that costs a lot more money and effort than a progressive upgrade.

In this case, a focused consolidation effort on the software added auto-detection for different types of display and menus to select between the different types of boards. This has greatly improved the situation and we will soon have only three programs for more than 800 power converters.

Early computer buses such as the G-64 bus provided effective hardware solutions at a time when hardware development was difficult. CAD tools were non-existent and testing methodologies rudimentary. Just using a PCB was not inevitable – cards based on wire wrap were still being produced in the early eighties. The software component of the overall system was limited by necessity – processors were slow and memories were small. The numerous hardware permeations that could be created thanks to the modular nature of the system were manageable, even with the primitive software development technique of "clone and modify".

Today, embedded systems can be more power than a mainframe from 1980, and the software has become the hardest part of the development. Systems must now be built to run standard software and not the other way round.

Software Tools

The first development environment chosen for G-64 software at CERN used the C language based on OS9, but it required a license for each system so alternatives were quickly investigated. Soon after the licence free OmegaSoft Pascal compiler running under the Flex Operative System was selected by many developers including the developer of software for the power converters in the PS complex. His programs did not include Flex OS, it was just used on the development system to run the compiler and manage the source files. Porting to the new environment took a considerable effort at the time and not all the teams made the move. To this day, some systems in the PS remain written in C under OS9.

Flex OS was designed in late seventies. Its typical "machine" was a G-64 backplane populated with an MC6809 CPU board, memory board, two 3.5" DD floppy drives, serial interface module to connect a serial terminal and printer, all in a nice 3U "portable" case with a power supply. Eventually, Flex OS and the Pascal compiler reached the end of their development lives, but as stable and mature products they continued to fulfil the needs of the software developers so the software support was not jeopardized. What become must more critical was the hardware platform on which it ran, which was frozen in 1983.

Recently, an open source collaboration on the internet created a Flex emulator running under Linux and Windows. This enabled all the programs stored on the 350 floppy disks to be moved to network file servers and program development to continue using modern Windows based text editors. A nice consequence has been a reduction in compilation time from one and half hours on the old 8-bit MC6809 microprocessor to 56 seconds on a Pentium III emulating the 6809! The original “portable” Flex development machine was donated to the CERN computer museum.

Final upgrades

We are starting development of a completely new embedded controls solution for the PS complex to enable the renovation of the converter controls. This will start in 2008 with the replacement of the oldest pre-G-64 systems, but over a period of years, all the G-64 systems will be eventually be eliminated. However, many new converters have been installed in 2004-5 and more will be added in 2006-7. These systems need controls and the only solution available at the moment is the G-64 chassis.

More than 100 news systems have been needed, which has required a new CPU card because of the obsolescence of the MC6809. The new card is based on a relatively new 16-bit Mitsubishi microcontroller running at 3.3V. All the development tools runs under Windows and the C language is used instead of Pascal. The new software uses MicroC/OS-II from Jean Labrosse[3]. At the same time as the numerous Pascal programs were being consolidated, a new version written in C was developed for the new card.

One more new card may be developed for the new G-64 crates, to support analogue and digital I/O. This is regrettable for a system at the end of its life, but there is no way to escape the treadmill of obsolescence.

SUMMARY AND CONCLUSIONS

At this point in time when studies are underway to choose the technologies that will replace the old G-64 systems, it is useful to consider how this aging solution has survived so long. We can only hope that the new design will provide such good service and still be operating effectively in 2030!

A first lesson is not to over-dimension the requirements; remain as simple as possible. We always tend to over-specify solutions and later must support all the hardware and software features that are never used.

A modular approach is the key to flexibility that gives the freedom needed for the natural evolution of the original system in the face of component obsolescence. This is true whether the solution is based on a standard commercial bus or a homemade backplane. We must resist the temptation to integrate more and more functionality into the same card to achieve spectacular but unnecessary performance. It is worth remembering the lessons given by the VME bus. In the early days, memory or peripherals could reside on VME boards separate from the CPU board with no impact on performance. As clock rates increased, external memory boards were less used in favour of memory directly on the CPU board. More recently, all but the slowest peripherals have moved to mezzanine modules on the CPU board. In many cases, the VME bus is reduced to a mechanical support and a power supply. At a certain point, it becomes time to think of a new bus technology or to question if the extra performance is really needed to solve the problem.

Long term control projects such as the power converter controls for the CERN PS complex are in a state of perpetual evolution. The set of elements chosen for the development environment, both hardware and software, have a substantial impact from a human resources perspective. Everything may be straight forward in the beginning, but as time passes and elements become obsolete the effort and skills needed to keep everything going can become a serious problem. It is worth remembering that it will take more effort to understand a poorly documented system in the future than it did to design it in the first place. So saving time now by not documenting will add to the cost of replacing or upgrading the system in the future.

Finally when talking about buses, the electronics aspects take the predominant role but it is very important to remember the mechanical aspects. The environment where the bus will live for a long period of time may be affected by vibration. The users responsible for the maintenance and repair must have easy access to the modules, and above all, the connectors must be reliable.

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