Lessons learned from 10 years building ground M&C Systems

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SCISYS has a long history in building ground M&C as well as ground data systems. Within the Meteosat Second Generation (MSG) ground segment, first M&C solutions have been implemented (DADF). The underlying concepts evolved and later M&C and data distribution systems within the ISS Columbus ground segment (IMS, MVDS-EM and DaSS) were the first step towards a generic M&C framework approach. A further major concept evolution and the integration of advanced functionality were then the enablers for the implementation of three major M&C facilities in the Galileo ground mission and control segments (GACF, GMNF and CMCF). The main design drivers and challenges for the M&C systems are presented in this paper and the history and lessons learned are outlined after having built M&C facilities in more than ten years. Recommendations are given to support the design, to ease the process during system implementation and finally to increase the usability of the M&C facility. An outlook and ideas on future M&C systems are derived.

I. Introduction

SCISYS Deutschland GmbH (formerly known as VCS Aktiengesellschaft) has developed a software framework for monitoring and control (M&C) for ground segments over the past ten years. The roots in development of such a framework go back until the year 1999. The need for reusable M&C components in ground segments such as facilities in scope of the Meteosat Second Generation was recognized and the M&C framework was created.

The first major version was then used and deployed in the years 2001 to around 2004 in scope of the Columbus Control centre projects. Here, SCISYS has built a significant part of the control centre's software components, all interconnected via the framework's middleware – the communication protocol for Monitoring and Control Communication (MCC). The versions v1.x of the framework has then been used in various projects – not only linked to satellite ground segments.

Since 2005, SCISYS is involved in the development of the European Satellite Navigation System, Galileo, and this involvement has been started with a re-factored version of the framework, which has been taken as an incentive to up-issue the version to V2.x.

The years 2005 to 2012 have seen many major extensions of the framework and the underlying protocol, the framework is now used in many different projects across SCISYS – among others in system monitoring facilities of BBC and other media broadcasting companies.

This presentation will give a summary of the philosophy and technology of the M&C framework, a look to some major ground segment installations and highlight important steps in the design of the M&C framework based on the experience learned with building monitoring and control facilities in the past ten years.

II. Monitoring and Control Software Framework

A. Overview and application scenarios of the M&C Framework

The M&C software framework is a JAVA based software framework with very light weight application server architecture (not using J2EE) and a resource effective middleware.

The main elements are these:

- TCP/IP based protocol as middleware, supported by an API (JAVA/C++)

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- JAVA component architecture to create custom applications – mostly by configuration.
- A set of ready-to-run applications with customizable components

The M&C software framework, evolved over the past 10 years, provides very universal and highly customizable system integration capabilities that make it suited for many tasks in complex integrated computer infrastructures, including, but not limited to, the following.

- Asset Monitoring and Control *focus: monitoring and control*
- File Handling and File Chain Processing *focus: file management*
- Automation and Scheduling of Tasks *focus: workflow automation*
- Presentation of homogeneous front-ends to Operators *focus: umbrella function*
- Configuration Control and Deployment *focus: configuration control*
- Data Collection, Analysis and Reporting *focus: data analysis*
- Alarm and Alert Management *focus: alarm management*
- Centralized Security Management *focus: security management*

The framework has been used to build software systems in different domains, often focused around monitoring and control, but also archiving systems and security management systems.

B. The Middleware - MCC

The M&C framework is built on a custom protocol called MCC (Monitoring and Control Communication) to efficiently transport the (monitoring) data and to forward commands and event messages (alarms, alerts). The M&C framework through its MCC protocol offered the following three services to realize a complex distributed M&C system.

- Data Services *To send and receive parametric data.*
- Messaging Services *To send and receive messages/notifications.*
- Control Services *To send and receive commands and command responses.*

Initially, the above three services provided almost all of the functionalities that one would need to implement an M&C system. Over the period of time, as the M&C systems evolved, they became more complex and huge chunk of data were exchanged between the components/entities that constitute the M&C systems. To efficiently handle large volume of data (which are stored as files on disk) and to support different ways to processing such data, file handling features have been added to M&C framework.

Moreover, file handling features are necessary for an M&C system to

- Collect, validate and store configuration files from software entities within the entire system
- Collect and process monitoring and message information from entities stored in files (e.g. XML/ASCII status files from remote sites)
- Dispatch processed or newly created files produced by the M&C system (e.g. network sniffer recordings)
- Transform a file format from one format/structure to another format so as to enable communication between entities that expects file in certain format/structure.

On the other hand, the M&C file handling features could be used to handle payload data files which need to be collected, validated or dispatched between entities of a system.

C. Philosophy of integrated system management (ISM)

The design of M&C facilities usually follow a strategy called Integrated System Management. The implementation of this strategy is one of the goals of SCISYS's M&C framework.

Integrated System Management is based on three fundamental principles:

- **Functional integration:** this principle facilitates overarching system management for all technical system levels.
- **Site integration** allows the management process to transcend the physical boundaries imposed by discrete system locations.
- The principle of **Process Abstraction** allows the rule-based grouping of technical parameters, so that the first stage of system management can be founded on a process view.

The first fundamental requirement for an integrated system management solution is functional integration, which facilitates the all-embracing management of all system categories. The starting point for functional integration is provided by five distinct system levels:

- **Level 1:** Data acquisition systems or sensors, i.e. special systems and devices. Monitoring and control of this level is specific to the industry/manufacturer and interfaces are usually not supported by 'standard' M&C software.
- **Level 2:** IT network, i.e. all the LAN and WAN components that constitute the IT network; in many cases, SNMP-based network management solutions exist at this level.
- **Level 3:** IT hardware, in particular server and memory systems. Here again, SNMP-based monitoring tools are often used already, but in many cases they are tied to a single supplier.
- **Level 4:** System software. This level addresses operating systems and other system-related software components, such as database engines, as distinct from application software.
- **Level 5:** the actual application software, which is often the key functional stage in IT-based overall solutions.

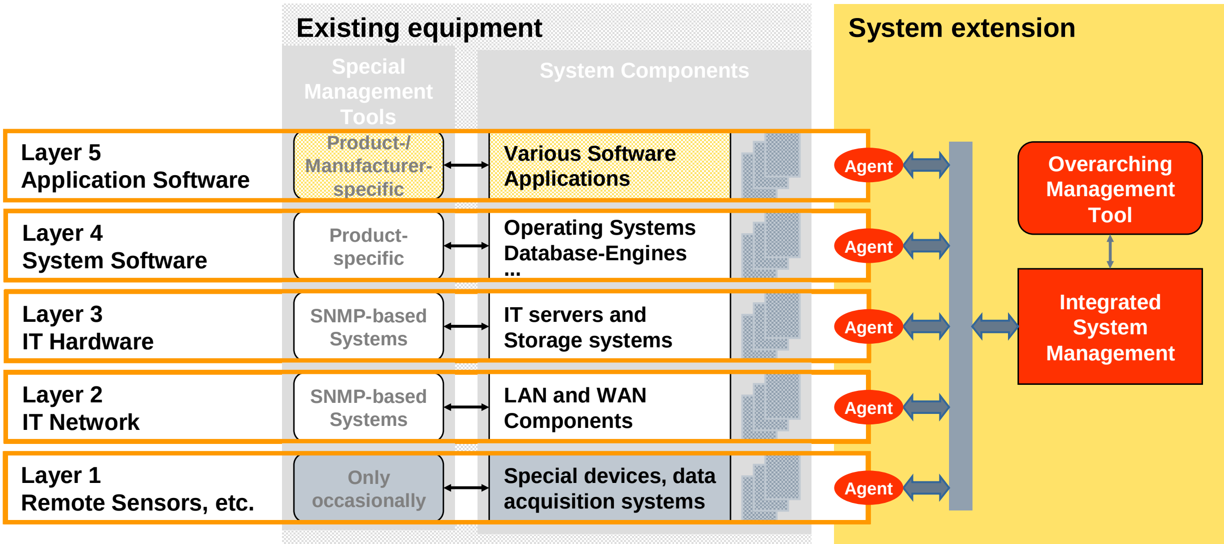

Figure 1. Schematic of site and process integration

The goal of functional integration is to bring together the monitoring parameters of the various sub-systems and components on all levels in a unified environment. Here, the monitoring parameters have been abstracted, (pre)processed and made available to overarching management tools (Figure 1).

Building on this structure, the principle of functional integration then has to be applied to several sites, thus creating a distributed architecture capable of facilitating spatial integration as well. These two integration stages together allow the forenamed abstraction at process level and the provisioning of more effective monitoring and management services for the solution as a whole. In this context it is important to point out that the assignment of systems is generally fluid; that is to say, each individual system contributes to one or several processes (Figure 2).

The extent of work associated with implementing integrated system management is considerable; especially if such a system is to be implemented in a single phase; it is a barely feasible task. It is essential, therefore, to regard integrated system management as a fundamental strategy to be implemented within the framework of a larger process. Nonetheless, major benefits can be realized by implementing sub-stages.

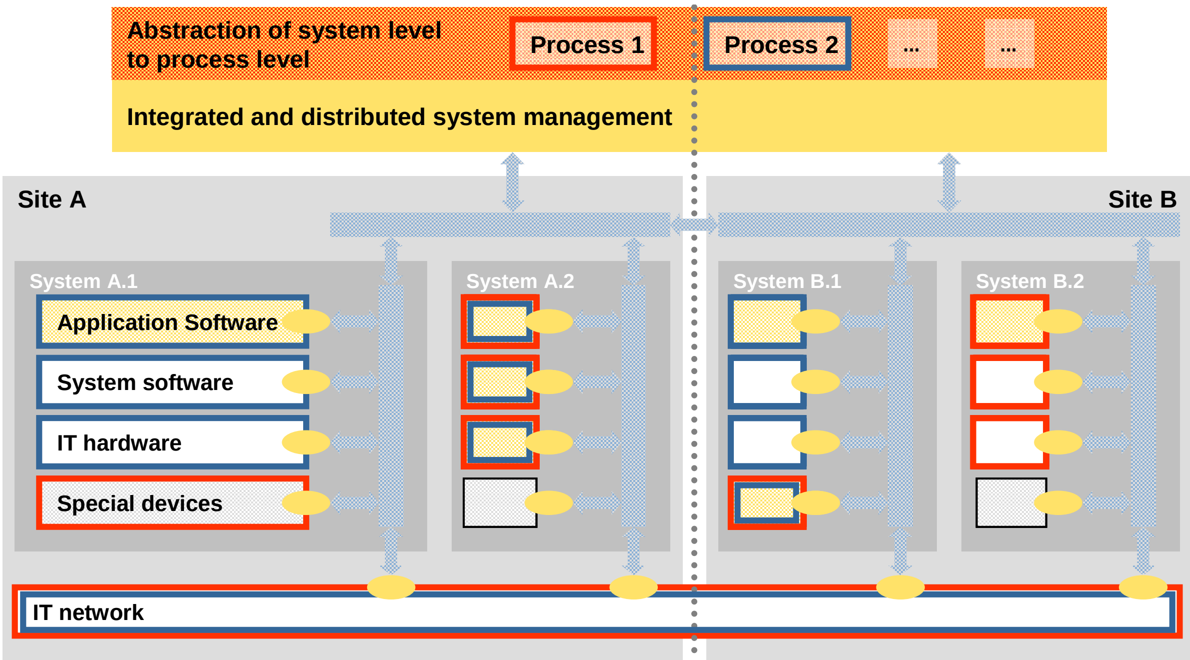

Figure 2. Principle of functional integration

III. Retrospection on built M&C Facilities in Ground Segments

This chapter provides an overview of major M&C facilities using the M&C framework. The range of tasks provided by these facilities includes basic monitoring and control of assets, the supervision of services, data and file handling and facility-specific tasks related to data access, security and processing.

D. MSG Ground Segment: Data Acquisition and Dissemination Facility (DADF)

As prime contractor, VCS Aktiengesellschaft has been awarded the contract to design, develop and implement the Data Acquisition and Dissemination Facility (DADF) being one of the most complex and therefore most demanding facilities of the Meteosat Second Generation (MSG) Ground Segment. As the central communication node within MSG Ground Segment, the main tasks of the DADF are:

- Performing data collection platform (DCP) and other data acquisitions
- Formatting and encrypting the Level 1.5 image data in dissemination formats
- Providing the near-real-time dissemination service
- Controlling the HRIT and LRIT data links
- Monitoring the dissemination performance

The DADF routes both stream data and files through the MSG ground segment and also contains a short-term rolling archive of the disseminated files, with an associated inventory. The underlying HRIT/LRIT format for MSG was specified by VCS Aktiengesellschaft, the DADF facility was also in charge for intermediate file processing, such as image compression and HRIT/LRIT encryption.

The DADF provided the ability to switch its configuration on-line, by organizing the configuration units in so-called "Data Units" (DUs), with the ability for the operator to switch from one version of a DU to another (using the change_DU command). The roots of the current M&C framework remain in the implementation of this facility DADF.

E. Columbus Control Center

The Columbus module is the European module attached to the International Space Station (ISS), the Columbus Control Centre (Col-CC) is located in Oberpfaffenhofen, Germany, and coordinates all data transfers to and from the module to the scientists world-wide.

The Col-CC is built with a central M&C system, the Integrated Management System (IMS), which is an M&C based system closely following the philosophy and design above-mentioned. Other Col-CC software elements have mostly adopted the MCC protocol in favor of SNMP to connect their facilities to the IMS via the framework's native protocol. The IMS monitors and controls among others the network, the video and voice distributing system, the storage area and several Col-CC facilities by using locally installed M&C element managers. The IMS follows a hot-redundant system deployment scenario with hardware and software in hot-standby mode.

The deployment of the M&C facility in Col-CC is a major system in terms of data throughput, it is based on the version v1.x of the M&C framework (currently v1.8), demonstrating the efficiency of this version of the framework.

F. TerraSAR-X Commercial Service Segment[2]

TerraSAR-X is the first satellite ever built in a Public Private Partnership (PPP) in Germany. In this partnership, the Federal Republic of Germany, represented by the German Aerospace Centre (DLR), and EADS Astrium GmbH have agreed to jointly bear the costs of constructing and implementing this X-band radar satellite. Infoterra GmbH, Germany, holds the exclusive commercial exploitation rights for the new TerraSAR-X, and supplies weather-independent, high-resolution, new-quality data as well as a variety of radar based geo-information products.

Special needs for the commercial exploitation of the SAR images have driven the design and implementation of the Commercial Service Segment (TSXX). This includes specific requirements for the monitoring and control system. All steps - from the reception of the SAR images at the direct access stations up to the image processing systems and the order tools – have to be monitored and potential problems or failures shall be identified easily by operators. Security related alerts and the final check of the products for sensitive data are handled by an independent security management system. The main purpose of the Auxiliary Management System in the Commercial Service Segment is to provide operators and system administrators an overall view on the current status of the Commercial Service Segment and to support offline actions such as the management of the inventory (hardware and software) or the automatic installation and reconfiguration of subsystems.

The Auxiliary Management System is an important system to guarantee the proper work-flow starting from the order, generation and image data acquisition up to the delivery of products. The design and usage of flexible monitoring and control interfaces support upgrades in the subsystems whenever work-flows are reorganized. The Security Management System monitors and controls all security related systems. The most important task of this system is a sensitivity check for each TerraSAR-X product order. According to the German law for satellite data policies (SatDSig) each order and delivery of a satellite image has to be checked for sensitive data: radar image resolution, geographic area, acquisition date and ordering organization or person. The sensitivity check is fully automated, allowing a smooth product order work-flow. Since the German Federal Ministry of Economics and Technology takes the final decision for sensitive critical product orders, an electronic interface to the administrative office has been established to speed up decision making by avoiding filling application forms manually. State-of-the-art offline tools and graphical user interfaces are used by the operators for administration and configuration of the sensitivity check that includes also interfaces to geographical information systems.

Due to the flexibility of the M&C system, all additional auxiliary functions for both Management Systems could be added as software plug-ins. Thus, a cost-efficient implementation was possible.

G. Galileo Ground Segments

The Galileo program is a major European undertaking to provide a global satellite based navigation system complementing the GPS system. The Galileo ground segment consists of the mission segment (GMS), responsible for the provisioning of the navigation signals, and the control segment (GCS), responsible for the control of satellite constellation.

The GMS and GCS are both distributed world-wide and centered around two Galileo Control Centres (GCC):

- Major Equipment in two GCCs in Fucino (Italy) and Oberpfaffenhofen (Germany)
- GCS: up to 5 Telemetry&Telecommand Facilities (TTCF)
- GMS: up to 10 Uplink Stations (ULS) stations for signal data up-linking, each station with 4 ULS instances
- GMS: up to 50 Galileo Sensor stations (GSS) for receiving satellite signals, each station with 3 GSS instances

The entire ground segment consists of more than 250 systems (called elements in the Galileo context) interconnected via two world wide networks, the mission data distribution network (MDDN) and the satellite data distribution network (SDDN).

There are three major Galileo elements based on the M&C framework, all three fulfill monitoring and control functions in the Galileo ground segment.

- GMS::GACF[3], the **Ground Asset Control Facility** responsible for the GMS
- GMS::GNMF, the **Galileo Network Monitoring Facility**, responsible for the MDDN

- GCS::CMCF, the **Central Monitoring and Control Facility**, responsible for the GCS

The CMCF generally provides monitoring and control of all GCS assets and functions in a uniform manner. It can be operated from within the GCS context but it can also act on behalf of the GMS::GACF – for this latter use case the CMCF also provides high level status summaries and supports macro directives from the GACF. With its detailed view and corresponding control capability of the TTCF stations the CMCF is particularly valuable in the context of troubleshooting the satellite control sessions (established between SCCF and TTCF). For contingency operations the CMCF can also be used to initiate the satellite contacts.

All three M&C elements monitor and control the entire Galileo ground segment infrastructure. The elements are built precisely following the philosophy of integrated system management; but each fulfilling also some ancillary functionality not directly related to monitoring and control.

- GACF[3]
    - Monitors and control all GMS equipment
    - Archives all mission network data via network capture for the mission lifetime
    - Archives all system logs, data exchanged between elements and other ancillary data of the ground equipment for the mission lifetime.
    - Provides complete configuration control for the GMS
- GNMF
    - Monitors and controls the MDDN
    - Performs extensive performance accounting functions
- CMCF
    - Monitors and controls the GCS
    - Provides a local archive to GCS, which is interface-compatible to the GACF

These M&C elements - in particular the GACF and GNMF - host very large data hierarchies with high combined update frequencies. The GNMF and CMCF both report their summary data to the GACF, which is required to perform up to 5000 parametric updates per second.

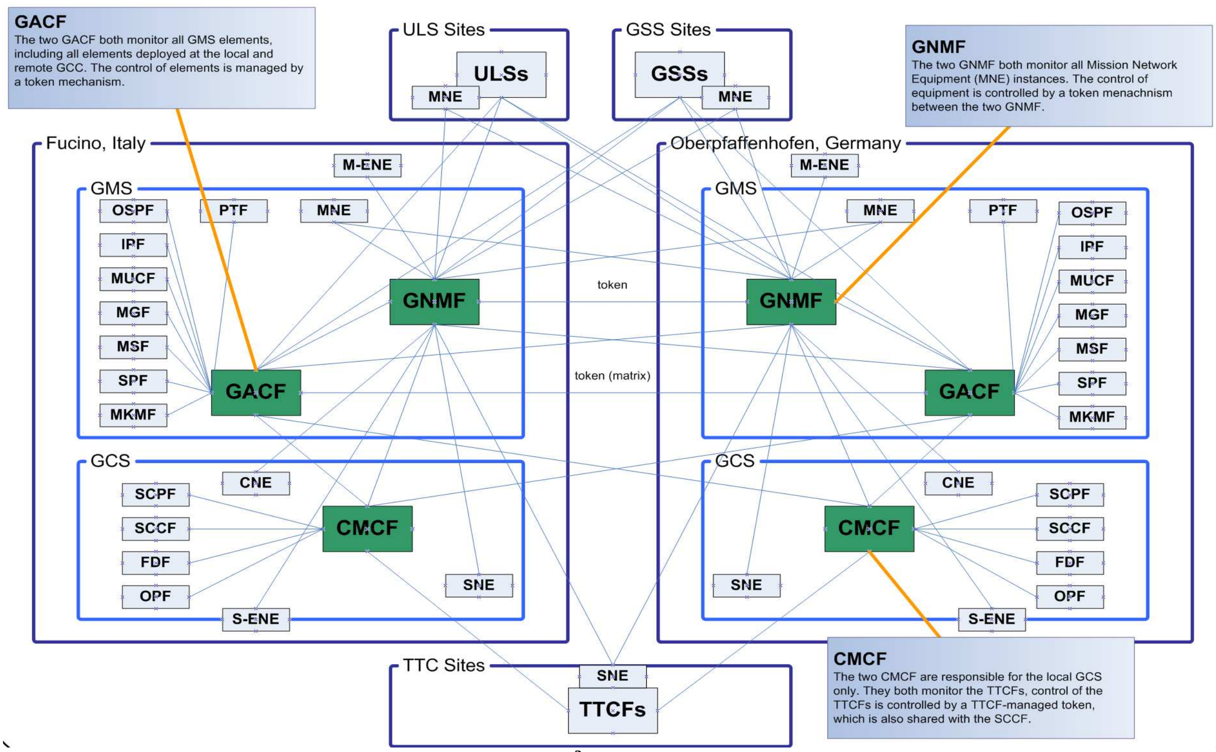

Figure 3. Galileo M&C Systems Interconnectivity[3] *Three Galileo M&C systems and their interconnectivity – all connections are made using SNMP, many of these include file transfers for archiving and configuration management services.*

IV. Lessons learned from building an M&C framework

Each of the implemented and deployed M&C facilities in the past ten years have contributed to the overall system design and to the core components as they are applicable now. With each facility new system features, software interfaces and applications have been added to the framework. Mostly all features of the M&C framework have been evolved and are more mature than ever before. This chapter briefly highlights five lessons learned – beginning with the finding after a decade of using and deploying such an M&C framework that the initial design goals are still valid and have been proven to be a fertile ground for a successful software framework.

A. Refining the design goals of an M&C framework

The M&C framework has been designed from the scratch after years of experience with complex IT infrastructures in the scope of satellite ground segments. The early designs were modified repeatedly until a stable, tested and very powerful architecture had been reached. The software design and system architecture was driven by a four goals:

1. Flexibility

The M&C framework uses state-of-the-art software technology to make the framework applications highly configurable and adaptable to special user scenarios. The framework uses a component architecture, which allows building applications from small building blocks, which are finely grained allowing adaptation to diverse implementation scenarios. The component architecture is set up in such a way that the process of adaptation involves no code writing, but can be performed entirely using the framework's configuration tools.

2. Scalability

The M&C framework uses a highly efficient proprietary TCP-based network protocol for its inter-process communications. This protocol enables M&C applications to be distributed easily over large networks. Via the hierarchical data structures employed in the framework, data processing and data collection become a distributed process.

3. Expandability

Although the framework is a closed source product in control of SCISYS, a number of hooks are provided to allow the easy expansion of M&C installations:

- Protocol API available with documentation and examples; including source code in C++ and JAVA
- Scripting Interfaces (python, ruby, bash, etc.)
- Public Protocols Support (Web-based protocols, SNMP, JMX, CORBA, etc.)
- Components Specification available

The expandability enables customers with M&C installations to do the following:

- Easily integrate in-house products with M&C components using the API.
- Easily integrate third-party products with the M&C framework via public protocols and scripting capabilities.
- Extend the M&C applications by coding components compliant with the component specifications (software plug-ins).

4. Cost Efficiency

The Cost-Efficiency of the framework comes as a consequence of the above-mentioned three design goals. Since components are re-used in many projects, a great amount of testing has been completed in previous projects. Likewise, many capabilities which normally go to the "nice to have" list instead of the requirements baseline will come as off-the-shelf components of the framework.

This allows facility designers and integrators to request useful but often neglected features at an early stage, rather than ordering them in subsequent packages. To do so enables the procurement team to better evaluate the true cost of a solution and make valid comparisons between offers.

B. Open available communication layer - Middleware MCC

The decision to use an open available communication layer as middleware was taken very early in the design and implementation phase of the framework. Therefore, the framework's MCC protocol enjoys a special support by an openly available API. This API is currently available in two programming languages: C++ and JAVA

Via the Java implementation, tests have been done in additional Java-based scripting languages such as Jython and JRuby. The APIs come with extensive documentation and sample programs. The C++ version exists in a native library implementation for Linux and Windows, but also in a Qt version, using the Qt network functions to provide platform independence. All of this, it supports users in developing their own M&C interfaces and allowing them the stepwise integration into an overall M&C facility of existing, but not yet connected hardware and software components.

Giving compliance to requirements of M&C facilities of various ground segments in the past, following SCISYS internal technology roadmaps and listening to users' recommendations, the MCC API has evolved and offers currently following features:

- Support for basic M&C services:
  - Data service *publish-subscribe*
  - Control service *point-to-point*
  - Message service *publish-subscribe with some point-to-point aspects*
- Efficient use of network bandwidth:
  - Structure and values of the monitoring data are transmitted separately
  - Data encoding in binary format
- TCP-based protocol
  - Encryption can be enabled (TLS/SSLv3) on TCP links

The protocol and API use service-client architecture and cleanly separate this concept from the underlying connection. On each connection, several services can be announced on either side and can be operated independently. The service announcements and subscription to services is organized hierarchically to support large installations with wide scopes of data being transported.

C. System Configuration and user domain configuration

One of the key assets of the M&C software framework is its flexibility. Flexibility, and scalability, had made the framework successful in various different domains as a generic monitoring and control system. But this flexibility comes with a price: the expertise required for maintaining the configuration of the software. Once installed at the customer site, the hand over to the client is not an easy task. Tuning a simple property may indeed be a very complex task, and give a wrong impression of the M&C software framework configuration capabilities.

To address this issue, a system for user domain specific configuration has been developed in the recent past; this binds user configuration files to actual M&C configuration items, making to the user visible only a subset of the actual configuration capabilities. The glue in this case is a special configuration created at system development time, the so-called bindings.

This approach also allows presenting to the user a configuration file specific in its choice of configuration items to the domain specific needs. The operators of a satellite control centre could thus be presented with a different wording for the same configuration item than, for example, the operators of a radio broadcasting station.

The approach has been implemented together with a graphical front-end to manipulate the user configuration, to provide a simple end-user configuration front-end to the applications generated with the framework.

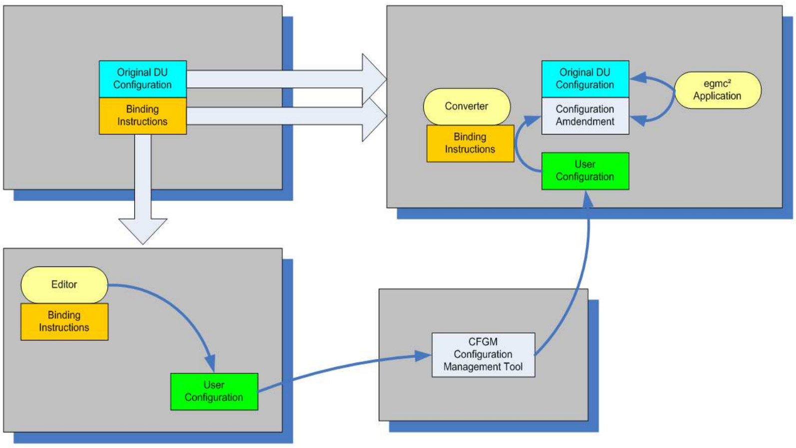

Figure 4. User Domain Configuration approach

The main goal for the editor application is to provide the user with comprehensive and yet convenient means to edit an existing application configuration.

- The usage of the editor application shall not require any advanced skills.
- The complexity of the configuration shall be hidden to the user.
- The user shall be able to define, edit and maintain configuration items that are meaningful for his particular business domain.

D. Standardization in Procedure Execution

The early versions of the M&C framework used internal timelines to trigger sequences of commands automatically. The more the framework evolved and the more user requirements for automated handling of command sequences (also called command macros or command procedures) should have been fulfilled, the stronger were the needs to define and implement automation functions within the M&C framework.

Since three years, these automation functions are all based on a procedure language which is established as an ECSS standard, the "Procedure Language for Users in Test and Operations", abbreviated as PLUTO. The Standard ECSS-E-70-32[§] identifies the requirements to be satisfied by any language used for the development of automated test and operation procedures. It also defines a reference language that fulfils these requirements.

Within the M&C framework of SCISYS the PLUTO language is used now for generating procedures. Procedures are saved in XML files which might be difficult to read and to edit. A Procedure Editor has been developed which simplifies generating and editing procedures – also by the operators within a Ground Segment. Basically, the editor displays the XML file in a clearly represented tree structure and allows editing the tree. All the functionality necessary for editing procedures is supplied, such that directly editing the XML file can be omitted.

E. Test automation

The M&C framework is typically used in scenarios where testing at various levels (i.e. unit tests, integration tests and acceptance tests) plays a major role in the project lifecycle. Since the testing of M&C interfaces, internal data processing and verification of correct and up-to-date status displays in Graphical User Interfaces (GUI) became more and more a costly and time-consuming, but still remaining an error-prone affair, SCISYS has developed over the years two test frameworks associated to the M&C framework and the corresponding systems derived from it.

- A unit test system, based on TestNG, which greatly simplifies framework component unit testing by providing an external component setup using dependency injection via JAVA annotations.
- An integration and acceptance test framework, based on the MCC communications library and scripted via JRuby.

In addition, the marathon testing framework (based on Jython) is used to automate GUI tests to provide a consistent quality of the M&C framework GUI applications themselves. These test automation infrastructure targets both the quality assurance of the framework itself as well as facilitating tests of M&C based end-user systems. The integration test framework supports the full requirement verification cycle, including verification matrices and traceability reports.

V. Recommendations

In addition to the above-mentioned findings from the lessons learned chapter – especially that an M&C system shall be flexible, scalable and expandable to support cost-efficient system developments in the initial phase, but also during maintenance – a few recommendations are outlined hereafter:

- *Interface design and consolidation in early system phase*: Define and adopt the hardware and software interfaces between the M&C facility and all other participating elements already in a very early stage of the ground segment design phase.
- *Involvement of System Operators and Analysts in the design and layout of GUIs*: Invite the end-users of the M&C system to actively participate in the design, layout and content of the graphical user interfaces.
- *Enforce the use of a middleware as a communication layer between all elements*: The communication protocol between the M&C facility and all other elements should be standardized and its implementation should be simplified for other elements' providers; e.g. provide a communication layer API or define to use standards like Enterprise Service Bus technologies.
- *Do not consider the M&C Facility a second-class element in the Ground Segment*: The M&C facility is often seen as an "auxiliary system" in a Ground Segment. Do not forget that a tailored and to all system components fitted M&C Facility can significantly decrease the operating costs. Raise the awareness for proper design and implementation of monitoring and control interfaces throughout all Ground Segment elements.

[§] European Cooperation for Space Standardization; Standard ECSS-E-70-32 defining the Procedure Language for Users in Test and Operations (http://www.ecss.nl/)

VI. Outlook

The development of SCISYS's M&C framework is constant and never-ending due to steady rising challenges in monitoring and control of new hardware equipment or software technologies. For example, the introduction of virtual hosts and virtual storage systems in ground segments lead to a new understanding of monitoring and managing physical hosts and operating systems. This new technologies will also change the concepts of how hardware and software redundancy needs to be interpreted.

The enhancement of existing display capabilities and the support for new GUI client technologies in M&C systems is another field of interest in the upcoming months and years. Web Client solutions, virtual desktop clients and support for mobile devices will enter more and more the market of 'classic' M&C systems and solutions.

Appendix A
Acronym List

Col-CC	Columbus Control Center, located at Oberpfaffenhofen, Germany
DADF	Data Acquisition and Dissemination Facility (DADF) for Meteosat Second Generation; Ground Segment
GCC	Galileo Control Centre
GUI	Graphical User Interface
HRIT	High Rate Information Transmission
ISM / IMS	Integrated System Management; Integrated Management System
ISS	International Space Station
LAN	Local Area Network
LRIT	Low Rate Information Transmission
M&C	Monitoring and Control
MCC	Middleware of SCISYS for System Monitoring and Control Communication
MMI	Man-Machine Interface, usually Graphical User Interfaces (GUIs)
MSG	Meteosat Second Generation
PLUTO	Procedure Language for Users in Test and Operations; European Cooperation for Space Standardization ECSS-E-70-32
TT&C	Telemetry, Tracking and Command
WAN	Wide Area Network

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