Trade-off between different PLC based architectures of Instrument Control Hardware for ESO ELT class of instrumentation

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ABSTRACT

The Instrument Control Hardware design for the Extremely Large Telescope (ELT) class of instrumentation is largely based on the use of PLCs and EtherCAT fieldbus. The division into multiple subsystems that work independently for the most part encourages the use of different PLC CPUs for each subsystem, all connected to the same Control Network. However, some of the interfaces among the subsystems are more pervasive, and the necessity of a robust method of communication among subsystems arises. In this paper various methods for data exchange between subsystems, based on the use cases, are described and analyzed. Starting from this analysis, a trade-off among several architectures is presented, ranging between two opposite design approaches. All the solutions are compliant to the design requirements, but show key differences in the approach to the parameters presented in the paper.

Keywords: ESO, ELT, PLC, EtherCAT, fieldbus, network

1. INTRODUCTION

In recent years, the design of the control hardware for astronomical ground-based instrumentation has undergone a change towards an industrial automation-oriented approach.

The implementation of Programmable Logic Controllers (PLCs) has become the new standard for projects funded by the European Southern Observatory (ESO). The instrument control hardware design of the first class of instrumentation for the Extremely Large Telescope (ELT), and of the telescope itself, is largely based on the use of industrial PLCs and fieldbus protocols, with COTS elements.

This allows for rapid development, lower costs for spare parts and a widespread understanding of architecture among specialized firms.

EtherCAT fieldbus, paired with PLC terminals of Beckhoff firm, is currently the standard for the control hardware of ELT instrumentation. Since up to 65,535 devices can be connected to a single EtherCAT segment, and each EtherCAT copper cable connection can reach up to 100 m, the design possibilities are virtually unlimited. The flexibility of a fieldbus driven design, in fact, allows for many different possible architectures and topologies, based on the needs of the system. The control hardware of an instrument can be distributed over different physical locations.

It is the case of the control hardware for ELT instrumentation. The PLC based electronics can be distributed over multiple electronic cabinets, that in turn are located both on the Nasmyth platform and on an intermediate platform, placed 7 meters below the Nasmyth.

The PLC CPU can be even brought in the telescope computer room, using fiber EtherCAT connections for long distances. Furthermore, a decentralized architecture can be explored, with the control hardware distributed into "bricks", boxes that can be replicated in a modular approach and placed on the field, near the electronics to be controlled. In the last case, all that is needed to connect a brick to the overall network is one cable, with the only drawback being the compliance with thermal requirements [1].

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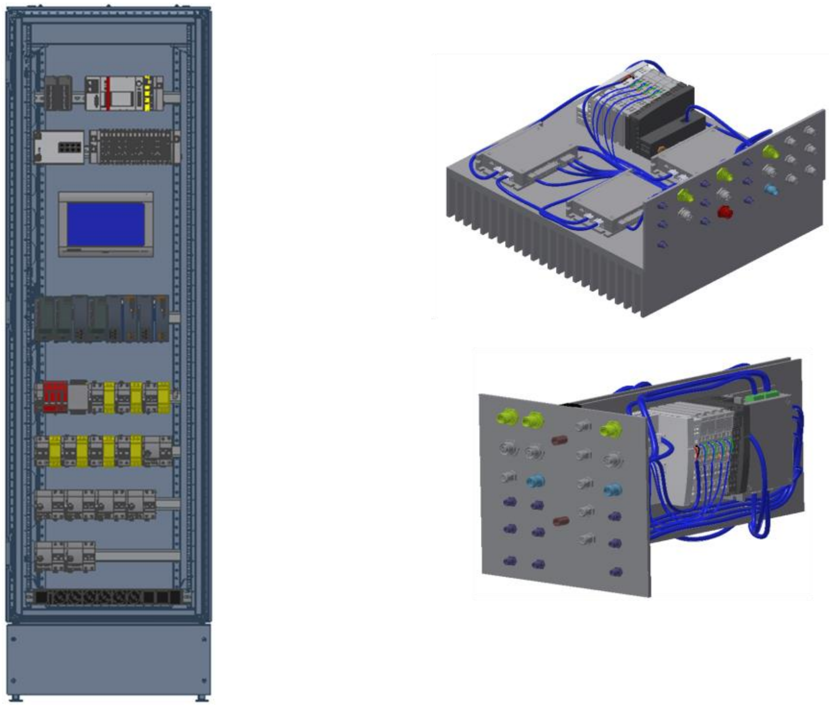

Figure 1. Examples of control hardware distribution: inside electronics cabinets or bricks.

With increasingly complex systems, the possibility of implementing multiple fieldbus networks can be considered as well. Each subsystem could have its own PLC CPU, while the controllers are all connected among each other through Ethernet, using the ELT Control Network. This solution is ideal to keep the subsystems completely separated and independent from each other, both logically and physically. Thus, both the design phase and the integration and testing phase can take place in a relatively autonomous environment.

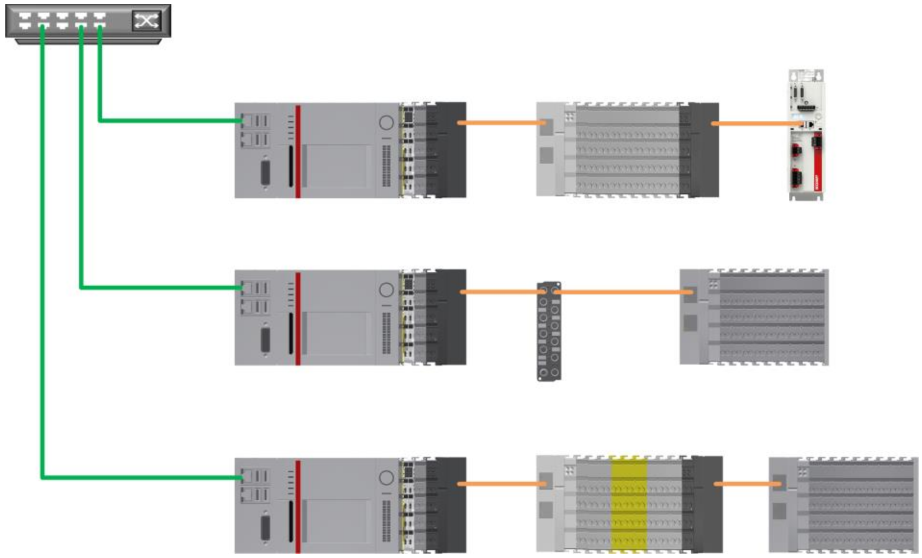

Figure 2. Multi-PLC connection scheme example.

However, a problem arises in case the subsystems need to communicate among each other in order to execute certain functions. While any topology allows intercommunication among subsystems to a certain degree, a trade-off between different possible architectures needs to be made to best fit the design under analysis. In the following section, multiple architectures for PLC based control electronics are described and analyzed, using as case study the instrument control hardware of the Multiconjugate adaptive Optics Relay For ELT Observations, MORFEO (formerly known as MAORY) [2][3][4].

2. ARCHITECTURE SOLUTIONS

A multi-PLC architecture is useful for keeping the subsystems electronics as separated from each other as possible. Ideally, the different PLCs are completely autonomous, and there is no need to establish any type of communication. However, this is not always the case.

The control electronics of MORFEO provide a fitting example of this issue [5]. Apart from a Main System, mainly regulating power and network distribution, they are divided into the following subsystems:

- Calibration Unit [6]
- Optomechanics [7]
- Deformable Mirrors
- Thermal Control System
- Natural Guide Star (NGS) wavefront sensor module
- Laser Guide Star (LGS) wavefront sensor module

For most of the use cases of the system, the subsystems control hardware is independent, suggesting a multi-PLC approach. This is, in fact, the solution that was adopted in the first phase of the preliminary design [8]. The Thermal Control System, however, is in charge of actively cooling electronics belonging to multiple subsystems [9][10]. In order to do so, it needs to read values of variables belonging to each subsystem, like temperature and humidity values. A direct connection of the Thermal Control System to the corresponding sensors would require connections to be duplicated, and it is not always possible, given for example the limited amount of space available for cabling to the MICADO co-rotating platform, where the NGS wavefront sensor module electronics are located [11]. Additionally, other potential use cases for communication between subsystems, such as safety functions, could present themselves.

When this issue arises, multiple ways of resolving it are possible. In the following paragraphs each of the main architectures for this purpose is presented with its pros and cons, gradually shifting from one design philosophy to another.

2.1 First solution: communication at workstation level

All the ELT instruments are connected in the ELT framework through the Control Network. An Ethernet connection to the PLC allows the variables of the PLC fieldbus network to become available to the control workstation in the computer room, via OPC UA protocol.

This means that, thanks to the Control Network, not only all subsystems of a single instruments, but all instruments have a common point to share data. Theoretically, no additional hardware or software needs to be added for this purpose.

However, this solution poses some problems. First of all, critical time functions should not be implemented with this architecture. This is not the case of the Thermal Control System, which only needs the relevant temperature values to be available within seconds, if not minutes.

The biggest issue stems from the fact that any interruption at workstation level, be it for maintenance, update, or any fatal error would consequently also end communication among the PLCs. The strength of a PLC based architecture resides on the fact that the low-level PLC control can work independently from any higher-level control apparatus, given that the PLC is in itself a computer with its own runtime. With this solution, this is no longer true. And since it is foreseen that the control workstation will not be available in a relatively frequent manner, in particular during the first part of the telescope life, this architecture becomes not acceptable.

This is especially true seeing as another software solution is already available in the current framework, without the underlined issues.

2.2 Second solution: communication via network variables

The baseline for the instrument control hardware of the ELT class of instrumentation is to employ PLCs and PLC terminals of Beckhoff firm, using the EtherCAT protocol as choice of fieldbus. This proves to be advantageous in terms of the matter at hand.

Different PLCs can in fact communicate with each other through the EtherCAT Automation Protocol (EAP). This protocol allows communication at PLC level, even for highly demanding real-time applications. The communication happens through the use of network variables and a publisher-subscriber mechanism: the variables that need to be shared among subsystems are published by the proprietary EtherCAT network, each variable with a specific ID number. The subsystem that needs to monitor the value of a certain variable, can subscribe to it using the corresponding ID number. As long as the communication via the Control Network is established, any real-time update of the value of the published variable is also detected by the subscribed subsystem.

This system proves particularly useful for safety applications that needs to travel among multiple subsystems, or even multiple instruments. If these functions are implemented with the use of safety PLC modules, then the same communication system can be established, through the Safety over EtherCAT (FSoE) protocol.

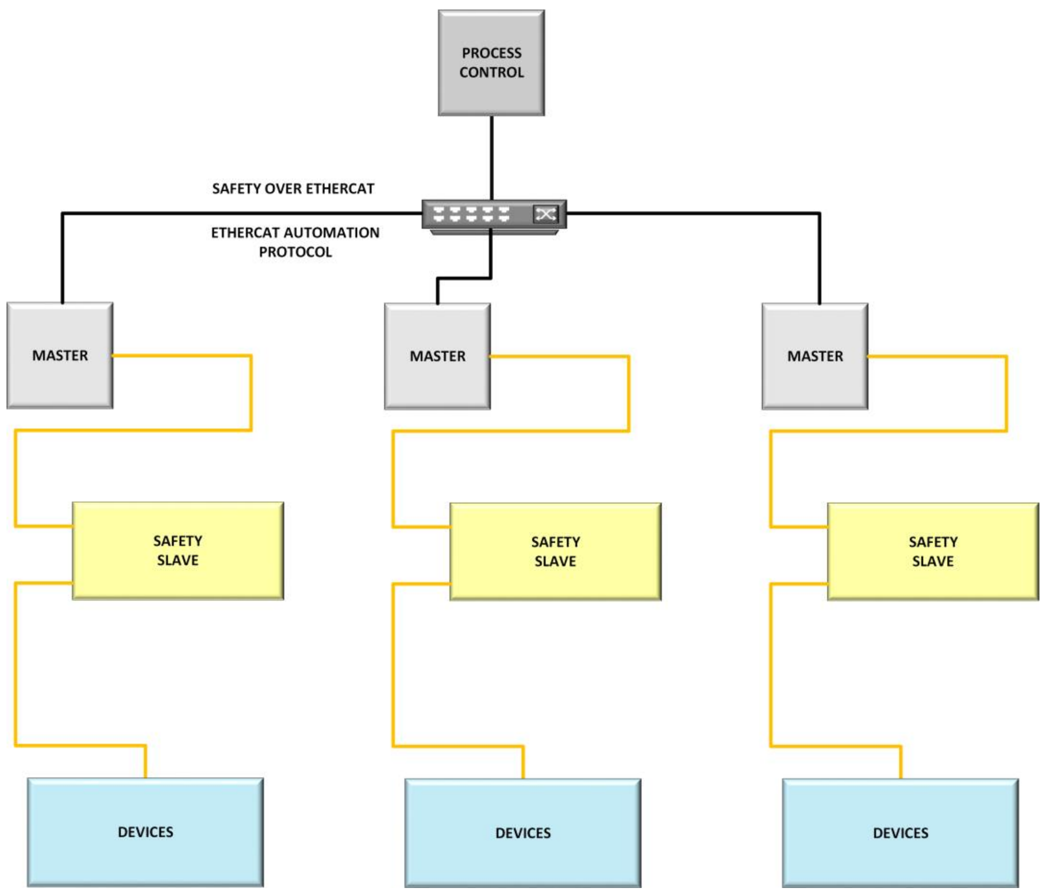

Figure 3. Safety over EtherCAT scheme example.

As shown in Figure 4, no additional physical connection, aside from the already present Ethernet connection to the telescope Control Network, is required. The Figure shows a scheme with a Main System responsible of distributing the network to all the subsystems, in a star topology, as it happens in MORFEO.

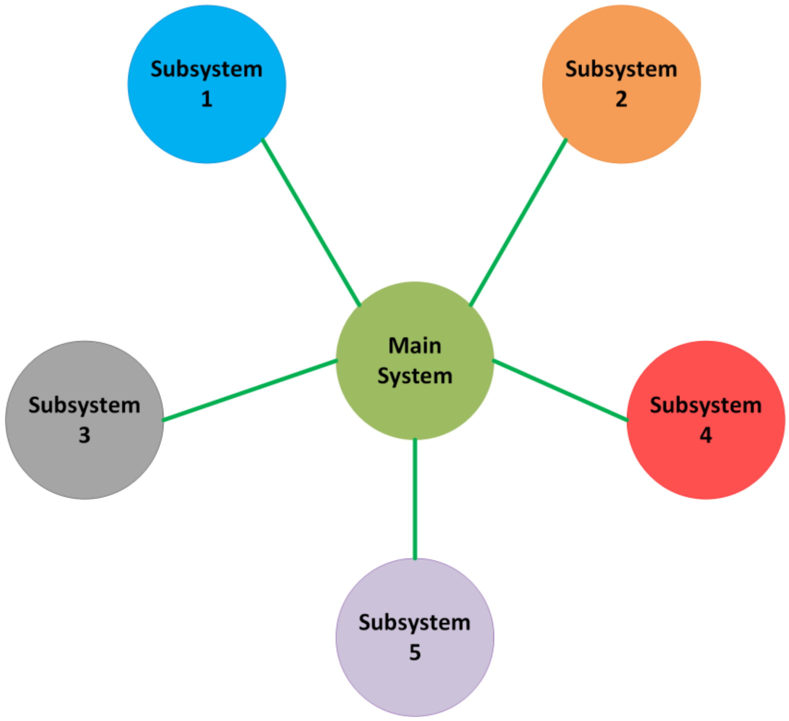

Figure 4. Network variables solution scheme.

The main advantages of this approach are listed below:

- No dependency from the control room workstation is created. Even when the workstation is not operational, the subsystems can keep exchanging data.
- No additional connections are needed, and in particular EtherCAT connections are made only between the segments of the same subsystem.
- The approach is generalized and uniform for all subsystems. The variable network exchange is possible from and to any subsystem PLC, without any further hardware implementation. A simple software implementation, with the right variable being published, is however required.

The last point leads to the evaluation of potential drawbacks of this solution:

- While the independent nature of each subsystem is seemingly maintained, a subtler software dependency is established, that is no immediately visible. This aspect can prove to be problematic if not followed with attention during design, integration and maintenance.
- Due to this interdependency, the status of one subsystem has an influence on the other. If the subsystem publishing a network variable is not active, then the network variable is not updated for the subscriber. In most cases, the system is not operational anyway. In some cases, however, this configuration could pose an issue.

As shown in Figure 5, the preliminary design of MORFEO instrument control hardware was based on this method of variable exchange.

From the Power Distribution Cabinet (PDC), the Control Network, with connections shown in green, was distributed to all subsystems, with EtherCAT connections, shown in orange, was established only among the same subsystem cabinets/subrack. The exception is the EtherCAT connection between the Thermal Control System PLC and the

Deformable Mirrors electronics, which might not be equipped with the PLC needed to establish an EAP variable exchange. This difference in topology partially compromises the consistency of the solution.

Another issue is represented by the required data exchange between the Thermal Control System and the NGS wavefront sensor module electronics, in order to control the cooling flow to the cameras. In this configuration, the sensors are not directly connected to the Thermal Control System electronics, which cannot operate on the cooling flow when the subsystem PLC is not operational. In addition, the limited allocated volume for cooling pipes to the MICADO co-rotating platform led to the use of an active manifold on the platform, meaning that the Thermal Control System PLC would also have to control valves using network variables. While this is feasible, it could lead to unwanted movement of the valve, and thus change in the cooling flow, with a faulty update of the variables.

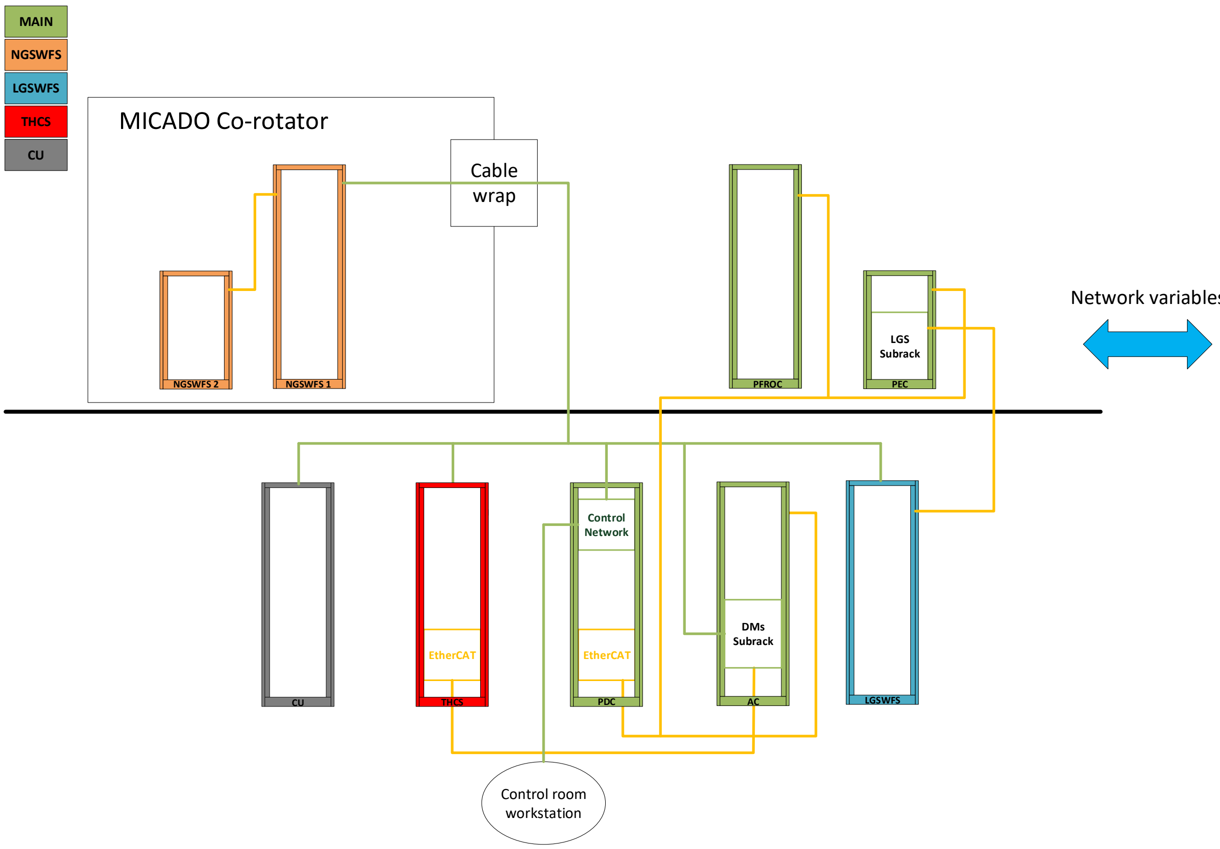

Figure 5. Network variables solution for MORFEO.

2.3 Third solution: communication via EtherCAT segments

To avoid dependencies at software level, a hardware communication, easier to manage, can be established instead. Thanks to the distributed possibilities offered by fieldbus connections, it is possible to connect a PLC segment that is physically located in a subsystem to the network of another subsystem. The subsystem cabinet will then host all the control electronics of the subsystem, plus a dedicated segment of electronics belonging to another subsystem, connected through a simple cable to its PLC, located for example in a different cabinet. There is no real data exchange between the two subsystems, as the only thing being shared is the physical volume of the cabinet. Of course, if both the subsystems need to access the same information, and software dependencies are to be avoided, the connections need to be doubled.

In the case of MORFEO, for example, the Thermal Control System PLC could be connected via EtherCAT to a segment inside the NGS wavefront sensor module electronic cabinet, and thus to the corresponding temperature, humidity or leakage sensors, and the cooling flow valve actuator. The connection scheme would be as in Figure 6.

The main two advantages of this solution are as follows:

- The EtherCAT segment is now directly dependent to the subsystem that needs the information. In the MORFEO case, the Thermal Control System PLC has direct control on the sensors and actuators for the cooling, regardless of the other subsystem status. Of course, this is true as long as power is provided to the electronic cabinet.
- The implementation is simple, as only one connection on the Ethernet physical layer needs to be implemented between the two subsystems. The EtherCAT segment is also easily disconnected for maintenance, and with hot connection is quickly detected by the TwinCAT application once back on, without the need of a reconfiguration.

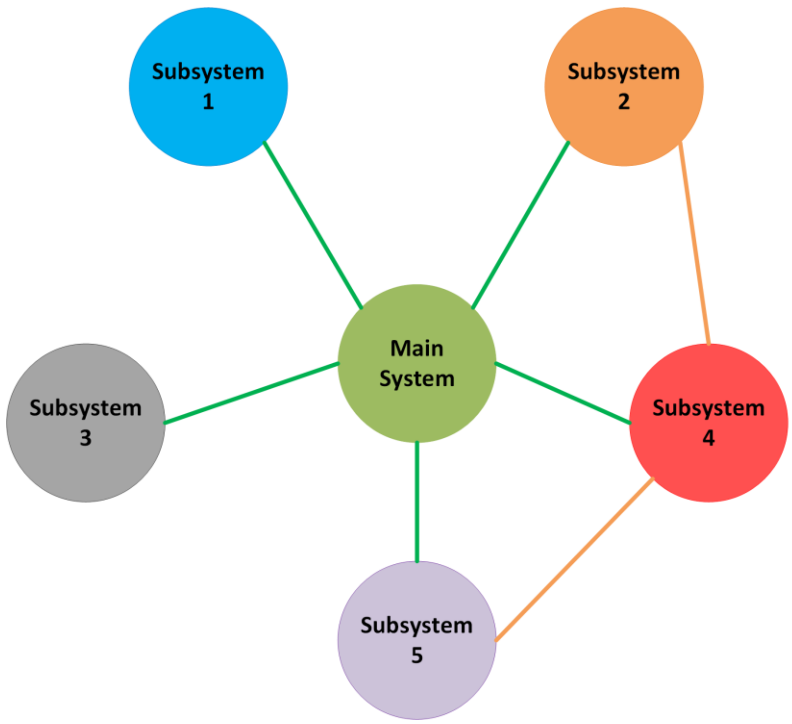

Figure 6. EtherCAT segments solution scheme. The control network connections are in green, while the fieldbus network connections are in orange.

The solution comes, as said, at the cost of just one additional cable. In the case of MORFEO, the star topology, with connections only coming from the Main System, is only partially lost.

This approach is however not generalized. If other use cases arise, new EtherCAT connections between different subsystems have to be made. And, while implementing a new connection to another EtherCAT segment is not especially difficult, the system as designed is not already configured for all potential applications. If many use cases require variable exchanges among multiple subsystems, the fieldbus network topology can quickly become chaotic, as shown in Figure 7.

Safety related functions could also become tricky to implement, if they require the logics of all the corresponding subsystems to be involved. A true connection between PLCs is in fact not established, and the networks are still fundamentally separated. This is a potentially good aspect in terms of the independence of the subsystems, but it fails to completely address the need of intercommunication.

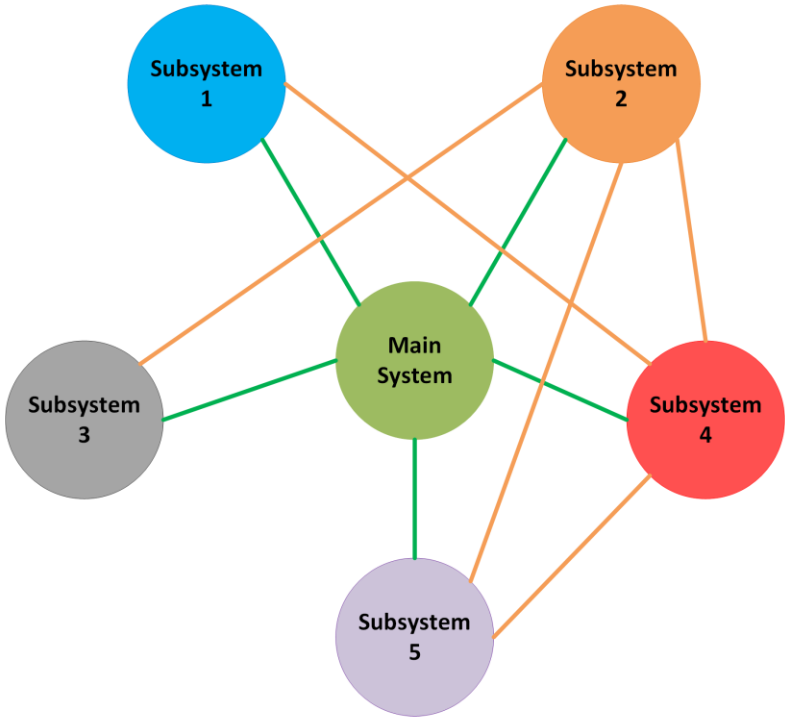

Figure 7. Multiple EtherCAT segment connections.

2.4 Fourth solution: single PLC

A hybrid approach to the problem would be to integrate the subsystem that needs to monitor the variables into the Main System itself. In the case of MORFEO, the Thermal Control System would become part of the Main System, with its control electronics belonging to the Main System PLC network. This would have the main effect of preserving the connection topology.

This solution is not functional in solving many of the issues that have been described for the EtherCAT segments approach. New connections would still need to be foreseen for other use cases, and there would not be anything in place for two different subsystems altogether to communicate among each other.

The next step is thus to bring all the instrument control hardware electronic under the same PLC, in a single EtherCAT network for the entire system. EtherCAT couplers are used instead of PLC CPUs for all the subsystems. This way, communication between subsystems becomes extremely easy, as they all belong to the same network.

The main advantages of this solution are:

- The connection topology is preserved. As shown in Figure 8, the Main System, where the PLC CPU is located, is now in charge of delivering the EtherCAT network to all the other subsystems.
- The architecture is ready to satisfy any use case, as all subsystems are already connected and the variables all belong to the same network.
- No additional connections are needed. The fieldbus connections can substitute the Control Network ones. This is only true if no other devices inside the subsystem need to be connected directly to the Control Network (like cameras or power supplies).

The main drawback of such a solution is the loss of independence between subsystems. A way to partially solve this issue would be to still use a PLC CPU for each subsystem, to be connected to the Main System PLC as a slave device. However, in a system that only works when every part of it is operational, this is an unnecessary measure.

On software level, the need of balancing the PLC tasks for all subsystems on the same CPU must be considered at the subsystem integration and testing phases, eventually merging all the functions at the system integration.

Finally, the computational power required from a single PLC could be not enough to carry out all the tasks of the system, depending on its complexity.

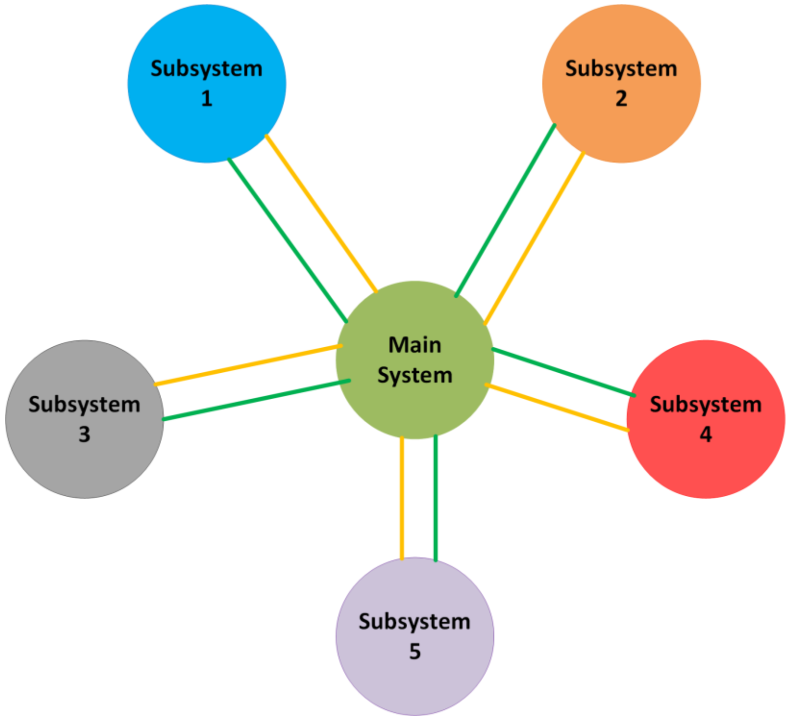

Figure 8. Single PLC solution scheme.

Another potential problem of this solution is tied to the way the electronic cabinets cooling control is implemented. If the control PLC is also responsible for managing the cooling of the cabinet, then any event putting it in a non-operational status would prevent any cooling of the electronics. In most cases, this is not an issue, since when the single PLC is not operational, the control electronics are not expected to be working, and with all the electronics being switched off, no cooling should be needed.

An effective way to separate the two tasks would be to have a second PLC exclusively in charge of cooling. The network of this PLC could replicate the one of the control PLC. This way, when the control PLC is being cycled or is not functional for any other reason, other than a power failure, the housekeeping PLC can still manage and monitor the electronics temperature, at the cost of additional cables between the Main System and all the electronics cabinets.

3. ARCHITECTURE TRADE-OFF: CASE STUDY

A case study was conducted on the MORFEO control hardware architecture. In the preliminary design, the network variables solution was deemed the best fit for the system instrument control hardware. The main reason of this choice was to keep the subsystems as independent from each other as possible. Each subsystem is in fact designed, integrated and tested in a different Institute, with all the laboratories spread among Italy, France and Ireland.

However, the drawbacks of the network variables architecture that have been described to this paper led to an in-depth trade-off, the results of which are summed up in Table 1.

Table 1. MORFEO network architecture trade-off.

Solution	Network variables	EtherCAT segments	Single PLC
Number of connections	+1	-0.5	+1
Subsystem functional and HW independency	+1	+1	-1
Ease of integration for DMs and NGS wavefront sensor module	-1	+1	+1
Reliability	-0.5	-0.5	+1
Star topology	+0.5	-0.5	+1
Uniform approach	+1	-1	+1
Integration and testing of subsystems	-0.5	+1	-1
Total	**+1.5**	**+0.5**	**+3**

In the Table each parameter is assigned either a positive or a negative value for each of the three main solutions that have been presented, applied to MORFEO instrument control hardware. The weight is based on how much of an impact each architecture has on the parameter under analysis. More specifically:

- The number of connections to be made among the subsystems is not increased with network variables and the single PLC solutions. In the first case, every connection is made via software; in the second case, the fieldbus connections among the PLC terminals replace the Control Network ones among PLCs. The EtherCAT segments solution requires one additional cable for every new connection to be established between two subsystems. The number of additional connections can vary based on the use cases.
- The subsystems are kept independent from each other in the network variables and hardware solutions. In the first case, there actually is a dependency at software level, but the PLCs can autonomously execute their respective tasks. In the second case, there is a full separation of functions between the subsystems. This independency is lost in the single PLC solution.
- The third parameter is specific to MORFEO. Given that the Deformable Mirrors electronics require an EtherCAT interface no matter the solution, the homogeneity of the architecture is lost in the case of the network variables, as at least one hardware connections would still be required. This method of variables exchange is also not ideal to control the valve that regulates the cooling flow to the NGS wavefront sensor module.
- The single PLC solution provides a significant improvement in terms of reliability of the system [12]. Since every subsystem in MORFEO is always crucial for the operational status of the system, every PLC CPU represents a single point of failure. With this architecture, only one PLC is employed, and the EtherCAT couplers used for the other subsystems have a much higher MTBF, and can be replaced much more easily, without needing any type of configuration. The reliability of the system decreases with the use of multiple PLCs, but is still compliant with requirements [13].
- A clean star topology is only kept in the case of the single PLC architecture. The other solutions require additional connections between at least the Thermal Control System and the DMs and NGS wavefront sensor module control electronics.
- The only solution that does not require changes in the design in case of new use cases is the single PLC one. A new connection and EtherCAT segment must be installed every time in the hardware approach; while the hardware design of the network variables solution does not change, the new dependencies must be tracked at software level, with a new EtherCAT Automation Protocol device.
- Ultimately, during integration and testing of a subsystem, only the hardware solution ensures that these activities can be carried out in a completely autonomous way. In the case of the network variables, the

publisher/subscriber mechanism must at least be simulated. The lack of dependency is even more clear cut with the single PLC approach, as one CPU is in charge of all subsystems, with one single fieldbus network. However, during the integration and testing phases of the single subsystem, the presence of the system PLC can be simulated, either with the use of a dummy PLC, or with a workstation with a port that is compatible with real-time applications. In the case of MORFEO, the computational power required to carry out all the systems functions does not seem to pose an issue, from the first analyses that have been made (with a foreseen CPU load of about 30%). Even if this were not the case, a more performant PLC CPU is already available under the ESO standards.

As shown in the Table, the sum of all parameters weights leads to the conclusion that each of the three solutions is not only compliant, but mostly advantageous for the system under study. However, the single PLC solution has a lesser number of drawbacks, that can also be mitigated more easily.

For these reasons, with the new inputs and use cases coming from the subsystems during the preliminary design phase, a change in the architecture of the MORFEO instrument control hardware was made, shifting from a multi-PLC solution to a single PLC one [5].

4. CONCLUSIONS

In this paper a number of different architectures and topology for fieldbus and PLC based control electronics were described and analyzed, ranging from one philosophy to the other, gradually covering the whole spectrum of possibilities. A final answer on which solution is preferable does obviously not exist, as their viability is strongly related to the specific application, but a list of criteria to make this design choice can be used.

Focusing on the case study of MORFEO, the single PLC solution appears to be the best fit for the instrument control hardware. The possibility of further decentralizing the control hardware, by moving the PLC CPU from one of the Main System cabinets to the telescope computer is currently under investigation.

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