Improved E-ELT subsystem and component specifications thanks to M1 Test Facility

M. Dimmler*[a], J. Marrero[a], S. Leveque[a], P. Barriga[a], B. Sedghi[a], N. Kornweibel[a]
[a]European Southern Observatory, Karl-Schwarzschildstr. 2, 85748 Garching bei Muenchen, Germany

ABSTRACT

During the last 2 years ESO has operated the "*M1 Test Facility*", a test stand consisting of a representative section of the E-ELT primary mirror equipped with 4 complete prototype segment subunits including sensors, actuators and control system. The purpose of the test facility is twofold: it serves to study and get familiar with component and system aspects like calibration, alignment and handling procedures and suitable control strategies on real hardware long before the primary mirror (hereafter *M1*) components are commissioned. Secondly, and of major benefit to the project, it offered the possibility to evaluate component and subsystem performance and interface issues in a system context in such detail, that issues could be identified early enough to feed back into the subsystem and component specifications. This considerably reduces risk and cost of the production units and allows refocusing the project team on important issues for the follow-up of the production contracts. Experiences are presented in which areas the results of the M1 Test Facility particularly helped to improve subsystem specifications and areas, where additional tests were adopted independent of the main test facility. Presented are the key experiences of the M1 Test Facility which lead to improved specifications or identified the need for additional testing outside of the M1 Test Facility.

Keywords: E-ELT M1, segmented mirror control, segment subunit, PACT, ES, subsystem specifications, phasing gun

1. INTRODUCTION

Since the end of 2005 ESO has been working together with its user community and industry to define a new giant telescope. Called E-ELT for European Extremely Large Telescope, this new ground-based telescope concept will have a 40-metre-class segmented primary mirror and will be the largest optical/near-infrared telescope in the world. The E-ELT Project Office has produced a novel concept[1], in which performance, cost, schedule and risk are carefully evaluated.

During the advanced design phase of the E-ELT project different hardware components were built by contractors in the frame of prototype contracts with industry in order to improve the understanding of new technologies, to get a better price estimate for serial production, but also to reduce the technological risk by identifying short-comings early enough in the project. As already presented in detail in the 2012 SPIE Conference in Amsterdam[2] ESO selected some of these prototypes, namely 4 polished mirror glass segments, 4 segment supports, 2 sets of position actuators and edge sensors for 2 segments, and mounted these components on a representative cutout of the M1 structural support. This test stand has also been equipped with a control system to form the so-called M1 Test Facility.

The main motivation for the M1 Test Facility was to test the prototypes in a system context and to improve ESO's know-how of segmented mirror aspects. This was considered important, because the E-ELT primary mirror involves the integration of nearly 800 mirrors, each of them integrated to a support with 3 position actuators (PACT), 9 shape actuators (warping harness, WH) and 6 Edge Sensors (ES), giving a total number of about 2400 PACT, 7200 WH and 5400 ES. Given the large number of components, all derived from prototypes with tight requirements, it was considered important to reduce risks by system testing and eventually building additional qualification units before moving to production.

Tests with the M1 Test Facility started at the end of 2011. The first test phase focused on issues of components and subsystems considering M1 system constraints when executing similar tasks as during AIV at the telescope. This phase

---

[*] Further author information: (Send correspondence to M. Dimmler)
Email: mdimmler@eso.org, Telephone: +49-89-32006402

included activities related to assembly and alignment procedures and subsystem performance and interface tests (electrical, mechanical and information interfaces). In the second test phase parts of the system were extended/refurbished first solving some issues detected in the first phase, mainly on the side of the control system and control interfaces, and then further system and performance tests were executed. For all tests during the two phases the team tried to mimic the telescope operation, e.g. considering access constraints and limited view, and to classify issues observed in a telescope context, e.g. dropping screws during segment replacement operation is a harmless issue in a lab environment, whereas it is a serious one inside the M1 cell of the telescope.

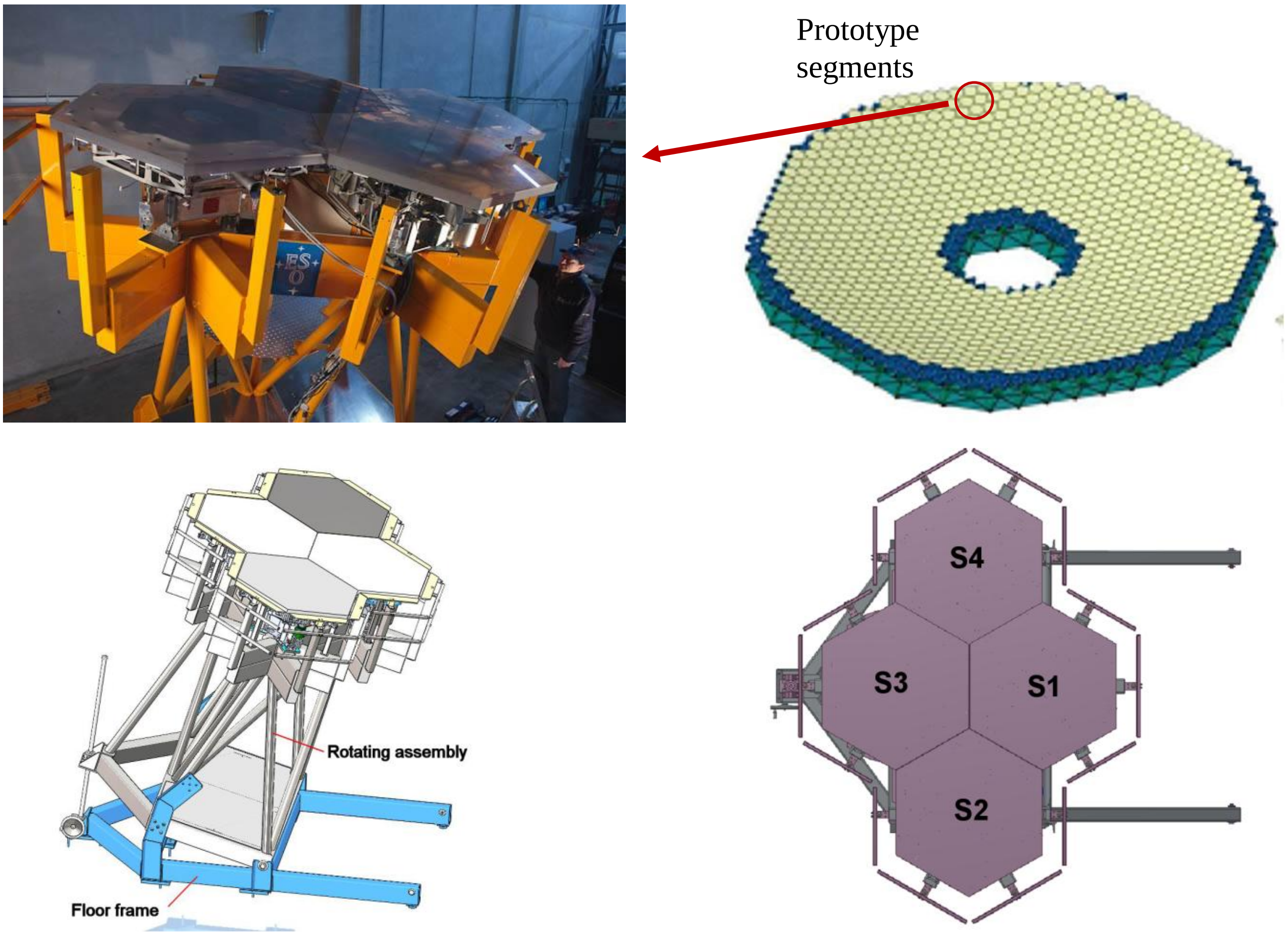

Figure 1. M1 Test Facility Overview.

The main outcome of the tests are lessons-learned reports describing short-comings of the prototypes, but also necessary components, subsystem and system specification updates and other recommendations for the requirements for the production units. These latter points help to improve the concept and reduce the risk before going into final production. ESO has already investigated or is still in the process of investigating in second generation developments for PACT, ES and segment subunits, which should incorporate improvements. These devices are also planned to be tested in the M1 Test Facility.

This paper will present, where and how the M1 Test Facility helped considerably to improve the M1 concept and its component and subsystem specifications. Some of the reported subjects are related to activities, which started in the early phase of the M1 Test Facility, and thus some of the information overlaps with the activity report given in the 2012 SPIE Conference in Amsterdam[2]. However, this paper is concerned with the improvements of the specifications due to the test experience and lessons learned rather than a detailed description of the test facility or specific tests. Each chapter is focusing on a different subsystem, starting with Chapter 2 discussing aspects related to segment subunits including warping harnesses, Chapter 3 presenting activities related to ES prototypes, Chapter 4 reporting experiences with the position actuators, Chapter 5 explaining lessons learned fed back from the control system. The last Chapter concludes on the activities executed so far and gives a perspective of the activities planned.

2. IMPROVING THE SEGMENT SUBUNIT SPECIFICATIONS INCL. WARPING HARNESSES

In the M1 Test Facility two types of Segment Subunits from different suppliers were analyzed mimicking AIV, operation and maintenance as in the telescope. Both designs consist of a part permanently attached to the telescope structure, the so called Fixed Frame, and another part supporting and moving the glass segment with the position actuators, the so-called Segment Assembly. The main function requirements of the segment subunits are to provide lateral and clocking support to the segments and allow the kinematic functions using the position actuators. In addition the segment optical figure can be changed using warping harness actuators.

However, there are a few other driving requirements of the segment subunits derived from operation and maintenance, which have a strong impact on the design. Each of the segments have to comply with a coating cycle of two years, which means that on average 2-3 segment assemblies a day shall be replaced with recoated units. This puts tight constraints on the initial alignment of the fixed frames, tight tolerances between fixed frame and segment assembly and strong emphasis on the interfaces in order to simplify the routine task of segment assembly exchange.

Exercising the fixed frame alignment with a laser tracker and performing several segment replacements in the M1 Test Facility turned out to be very helpful to better understand the constraints given by the limited access due to the M1 structure and to improve the interface and tool requirements.

Fixed Frame alignment tools

The Fixed Frames are attached to the telescope structure. They are aligned only once during the assembly process of the M1 unit. However, their alignment is crucial, because they constrain the lateral and clocking degrees of freedom of the segment assemblies and they provide the nominal positions of the PACT interfaces. The former has a strong influence on the co-alignment of segments and the latter has a direct impact on PACT stroke and the related segment collision risk. Two alignment tools are foreseen to reach the necessary alignment precision: a Fixed Frame Alignment Device to manipulate the Fixed Frame position before attaching it at the final position, and the Fixed Frame Alignment Tool used for the measurement of the Fixed Frame position hosting the retro-reflectors for the laser tracker. After using both tools at the M1 Test Facility, new more specialized requirements were derived. For both tools emphasis has been put on a clear separation of DoF, for the alignment this should lead to distinct and better accessible adjusters requiring less iterations for different DoF, and for the measurement tool this should lead to independent verification of the lateral and axial constraints imposed by the Fixed Frame.

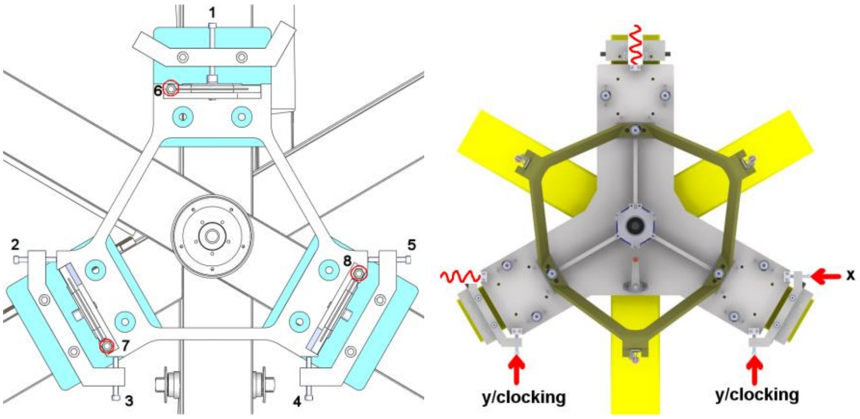

Figure 2. Tested Fixed Frame alignment device (left) with strongly coupled DoF requiring access from all sides and a possible improvement (right) with better separation of DoF and simpler access

Figure 3. Fixed Frame alignment tool without separation of lateral and axial constraints

Interfaces relevant for segment replacement

As already mentioned above, the E-ELT requires a daily replacement of 2-3 Segment Assemblies during its complete expected 30 years lifetime and thus, to ease this task, this operation and its interfaces have been investigated in detail. The segment assembly replacement procedure involves several interfaces, namely 3 mechanical interfaces each between Fixed Frame & Segment Assembly and between PACT & Segment Assembly, respectively, 2 electrical interfaces for warping harness and edge sensors and several interfaces relevant for the segment extractor. The main design drivers for these interfaces are reliability, repeatability, limited access, risk to drop tools or pieces or to damage items due to mistakes during routine operation and the need to minimize the time overhead. These concerns could be very well investigated with the M1 Test Facility and the new requirements are strongly influenced by experience from these tests. Figure 4 shows an example of how a cumbersome screw interface with difficult access could be replaced by a tool-free clamping mechanism.

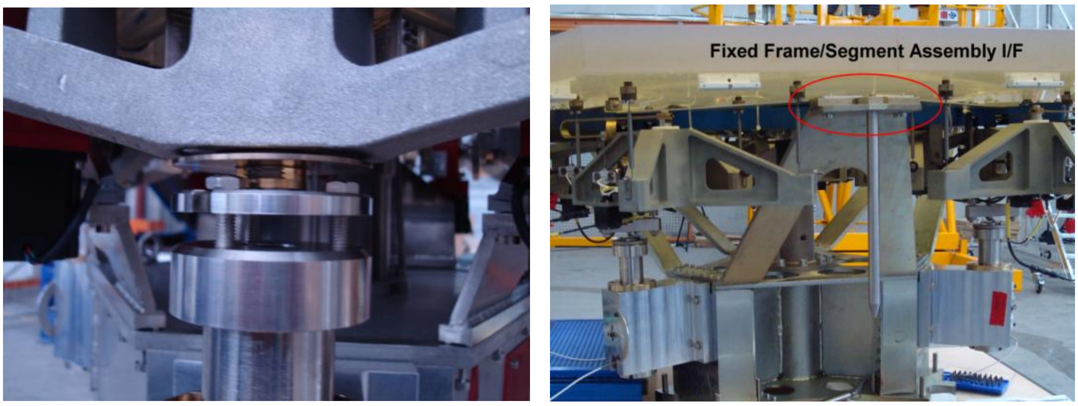

Figure 4. Screwed PACT/Segment Assembly I/F (left) and Fixed Frame/Segment Assembly I/F (right) with difficult access

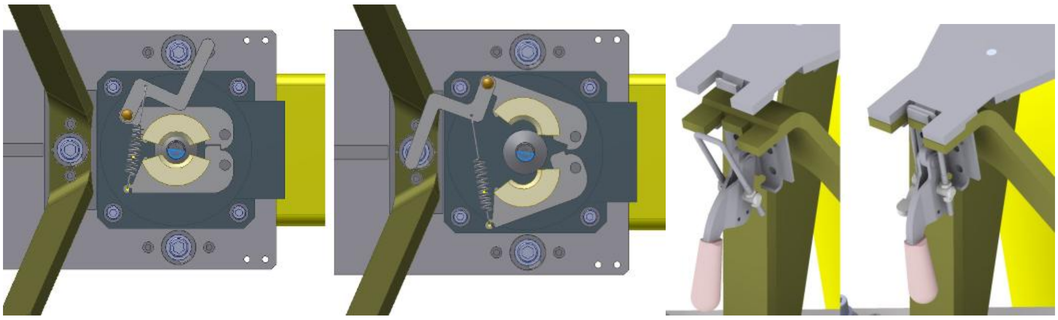

Figure 5. Possible PACT/SA I/F (left) and Fixed Frame/SA I/F (right) using tool-free clamping concepts

In the new specifications these interfaces involved in segment assembly replacement were changed in the following way:

1. For the mechanical interfaces between Segment Assembly & PACT and between Segment Assembly & Fixed Frame, respectively, a single operator shall be able to execute the full operation of attaching/detaching a segment assembly using only one tool not needing more than minutes of maintenance time.
2. For the external segment extractor the option of a central jack was simplified by providing a central hole in the M1 support structure below the center of the fixed frame.
3. For wiring and electrical interfaces of warping harness and edge sensors several requirements have been added to simplify access and replacement of cabling/components from the back of the segment. Now connection boxes for signal concentration are required and cable numbers, connector locations and types, and external cable lengths are defined beforehand. As indicated in Figure 6 only 4 connectors need to be removed for a segment replacement.
4. For the alignment of the interface between segment assembly & PACT the new specifications make reference to the glass surface. Together with the new mechanical interface of the edge sensors, see below, this leads to a much better starting position of the ES after segment replacement.

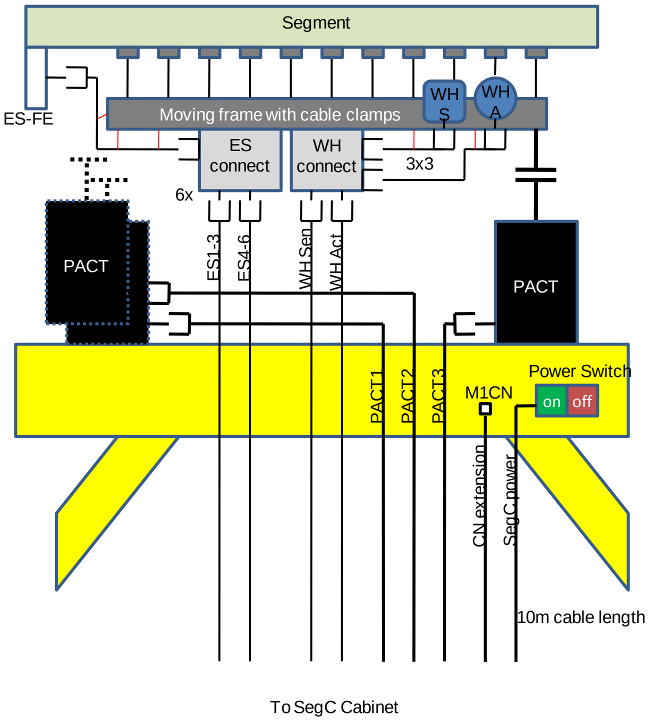

Figure 6. Constraints required for segment wiring (connection boxes, connectors, number of cables) in order to simplify segment/spare part replacement and wiring

Interfaces between PACT & Fixed Frame

In the actual design Position Actuators are assembled laterally to the Fixed Frames. Therefore, the gravity load of the actuators has to be supported by an operator in a difficult position until the fixation is partly accomplished. This actuator replacement has been done several times in the M1 Test Facility and considering the limited access this operation was difficult, tiring and error prone. By changing the interface plane between the PACT and the Fixed Frame as illustrated in Figure 7, the Position Actuator and the Fixed Frame becomes structurally simpler (less weight, lower cost) and the installation is easier.

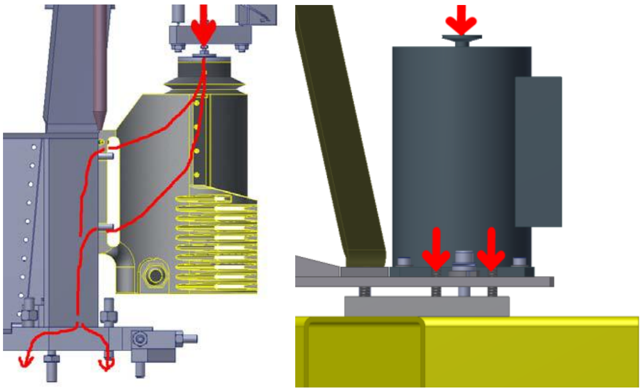

Figure 7. Load paths of the present and new interface between PACT & Fixed Frame

Warping Harness mechanism and control electronics

The warping harness systems of both prototypes were tested with control electronics and through engineering interfaces, which were different from what is foreseen for the M1 control system. This did not cause any restrictions for the investigations in WH issues of the segment subunit like fail-safe operation, induced vibrations, maintenance access or wiring. This concept of splitting the development of WH mechanism and final control electronics will also be maintained for the second generation prototypes in order to focus the suppliers on their core competences and to allow adapting the control interfaces to the needs of the M1 control system, as will be mentioned below in the M1 control chapter.

Even though concerning the WH mechanism in the segment subunit only few specifications needed to be updated, the WH tests in the M1 Test Facility were useful to better understand the way the system needs to be operated to minimize induced thermal power and vibrations and to understand the constraints for maintenance and wiring. In the new specification the WH mechanisms are explicitly requested to be fail-safe including mechanical end-stops to avoid damage of components as in the prototypes. Concerning wiring and spare parts replacements new requirements were added for a connection box, cable routing and connectors, as already described in Figure 6.

Verification tests for critical areas

Typically with prototypes many issues are recognized as secondary effects during intense AIV activities focusing on different topics. The discovered issues are often verified by design analysis only and no explicit verification by test is requested in order to reduce cost. A frequent mistake is to restrict the analysis to the nominal design not considering manufacturing tolerances and varying material properties. Issues such as these were found through the continuous operation at the M1 Test Facility. Functional and performance tests carried out over a period of more than two years turned out to be particularly helpful. Many critical issues were detected, which could have been avoided with more extensive verification tests. Most of these verification tests would only be necessary to qualify the functional design of the preproduction units, meaning the number of tests on the final production units will remain relatively small. Here only the major points are listed. Other issues were already described in the 2012 SPIE Conference in Amsterdam[2] and thus more details can be found there.

- The kinematic functions of the segment subunit and their corresponding stiffness are requested to be verified by test in the complete dynamic range needed for telescope operation, i.e. typical tip/tilt corrections at different piston positions, and not only around the nominal rest position. This turned out to be crucial due to several non-linearities observed when scanning the entire range. These were mainly caused by internal collisions of parts due to tight tolerances and non-linearities in the flexure parts.
- The stiffness of the complex membrane connecting moving frame and glass segment needs to be verified by test. During verification tests the actual stiffness was measured to be more than twice the nominal design value. This could cause segment misfigure, which cannot be completely corrected with the warping harness system.
- The load transfer when lowering the extraction jack needs to be verified by test in different inclinations. The tests have shown that tight tolerances, partially imposed by requirements to comply with earthquake safety, could lead to extraction forces that could damage the segment support.

- The repeatability of the segment assembly integration needs to be verified by test with different segment assemblies on one fixed frame. Tests have shown problems in clocking orientation, which only became apparent when considering that the replaced segments will not be mounted on the same fixed frame again.
- Warping Harness actuators need to be verified by test in their extreme positions. Tests have shown that insufficient hardware protection of the dynamic range could lead to fatal following errors in the support requiring a long and difficult repair period. In our case a damaged power supply cable led to 4 broken flexures of the WH mechanisms of one segment. These rather complex mechanical pieces had to be manufactured and replaced. In the telescope context a larger group of segments could have been affected by the same failure.

Limitations of the M1 Test Facility for the Segment Subunit Tests

Since there was no segment crane built into the M1 Test Facility, segment replacement could only partially been execised. Segment extraction was carried out by fully extending the segment, raising it above its neighboring segment. From this point on a fork lift was used to transport the segments. In this limited exercise, the load transfer of the segment from the fixed frame to the M1 segment crane has not been prototyped in detail. In mid 2014 the M1 Test Facility will be moved into the new assembly building of ESO, which is equipped with a proper crane. This would allow executing this kind of test.

The M1 Test Facility has not yet been equipped with a metrology system, which would allow a measurement of the segment shape. Therefore, the Warping Harness system has only been operated “blindly”. There is a concept of involving deflectometry for segment shape measurements and ESO’s metrology specialists are in touch with different groups[3,4] investigating into this technology. However, it has not yet been decided, if the M1 Test Facility will be upgraded with such a measurement system.

3. IMPROVING THE EDGE SENSOR SPECIFICATION

In the E-ELT concept each segment will be equipped with 6 edge sensors measuring the change in piston, but also shear and gap, of neighboring segments. In the first phase the M1 test facility was equipped with ten inductive edge sensors distributed along the inner edges of all segments. The sensors measure piston (change of relative height) between segments with a coarse precision over a catching range of +/- 1mm and with nm level precision over a measuring range of +/- 200 microns. Gap and shear (in plane motions) between segments are monitored with a precision of 1 micron over a range of several mm.

Beside the tough requirements on precision, low temperature and humidity drift of the sensors themselves, there are several driving requirements related to their mechanical interface, namely initial alignment, mounting repeatability and long-term stability. These issues have a strong impact on AIV, operation and maintenance. The M1 Test Facility was particularly suited for analyzing the procedures and properties related to the edge sensor mechanical interface and how to integrate edge sensors into the M1 control system. Verification measurements focusing on the sensor itself requiring controlled environmental conditions and precision in the nm regime were done on a separate setup in a controlled lab environment. Both activities delivered important input for design improvements described below.

Sensor alignment and repeatability

Each sensor is composed of a transmitter and a receiver, mounted on the rear side of two adjacent segments. The edge sensor mechanical interfaces shall deliver a final co-alignment of the transmitter with respect to the receiver along the six degrees of freedom with a precision of i) 50 microns along piston ii) 100 microns in the plane of the segment iii) 1mrad along the three angular positions (tip/tilt/clock) independent from the variations in segment geometrical tolerances, namely thickness and shape of the back surface.

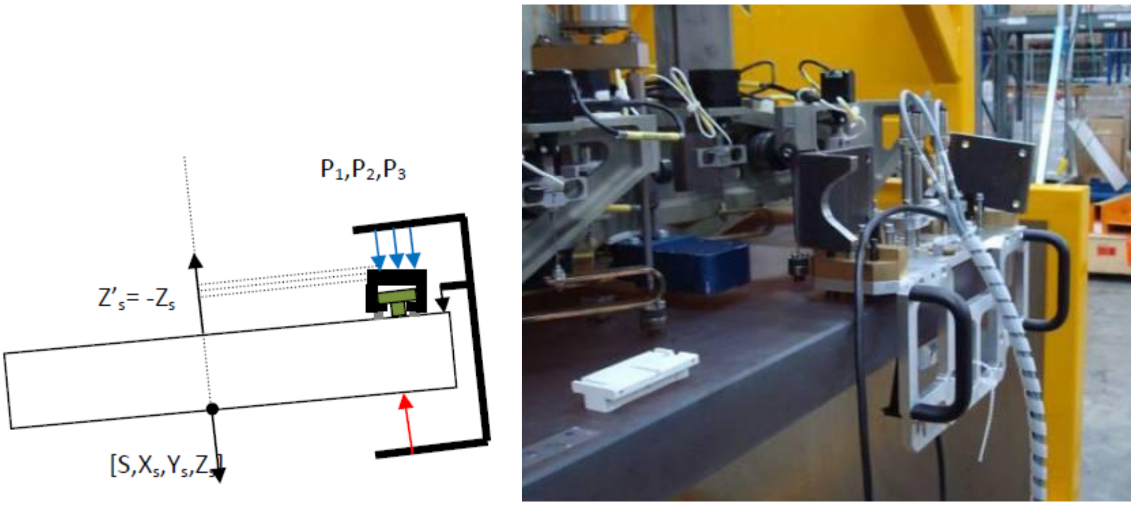

Figure 8. First generation Edge Sensor alignment during integration (left: measurement principle, right: tooling)

For the first generation of edge sensors, dedicated adjustable mechanical interfaces and an alignment tool was provided by the ES supplier. The integration and alignment procedure was extensively tested at the M1 Test Facility. Although the prototype alignment was possible, the mechanical interface is considered to be too complex for mounting and aligning over 5000 production units. In addition, other issues with stability, stiffness and repeatability were strongly linked to the interface material and the specific mechanical design. Therefore, the system concept was reinvestigated with the objective to simplify the ES mechanical interface and allow a more stable ES carrier material. The new concept proposes a segment back surface, which is machined at the locations of the ES in order to provide a precise passive reference not requiring any additional adjusting elements. The edge sensor mechanics is also made of non-adjustable and thus very stable glass ceramics supports.

Two families of second generation inductive edge sensors were developed from two different companies (Fogale and MicroEpsilon). All these sensors have already been delivered to ESO and they are now under extended verification tests in a controlled lab environment (humidity and temperature controlled climate chamber) at ESO. For this purpose ESO developed an edge sensor test stand, shown in Figure 9, including a commercial 6 axes high precision remote controllable Invar table[6], a zerodur support, remote controlled/monitored by a custom data acquisition/control system. Later it is planned to add suitable interfaces to the prototype segments of the M1 Test Facility and test the new edge sensor in operation.

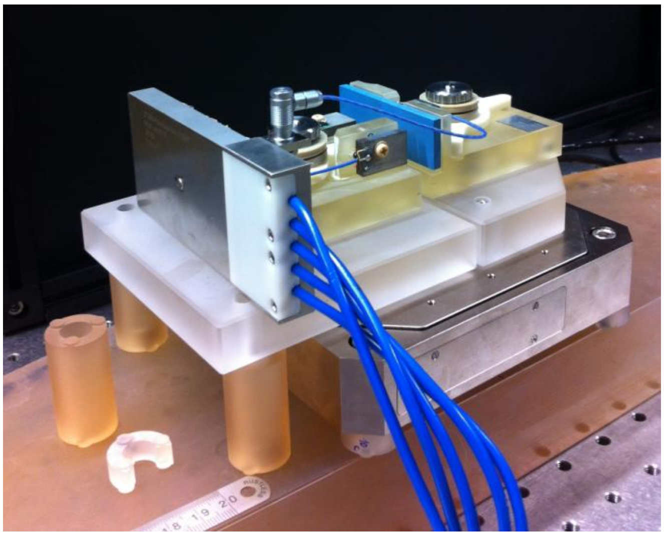

Figure 9. Edge Sensor test stand for tests in controlled lab environment, control system is based on equipment from National Instruments

Wiring and control interface

Beside the mechanical interface, the integration of the edge sensors in the M1 Test Facility provided opportunities to analyze hardware and software issues in detail and develop an improved concept for the production units. In the first phase, the edge sensors were tested with focus on signal integrity, limits of dynamic range and noise induced by the uncontrolled test environment. For these tests different kinds of sensors/actuators were used, e.g. reference movements were imposed by position actuators or displacements were measured by external accelerometers and PACT sensors at the same time. This helped to better understand the devices and to improve some details on the original ES information interface. In the second phase, the edge sensors were analyzed at the M1 Test Facility in the context of the M1 system. Improved concepts for the interface to the M1 Control System, hardware interface of the ES to Segment Assembly and the organization of the wiring inside the Segment Assembly were derived. The new concept for the control interface was directly implemented and tested, whereas the new wiring/connector concept enters into the new specifications as already introduced in Figure 6.

Evaluating promising concepts for Phasing Gun

After segment replacement, new segments need to be aligned in surface height with respect to neighboring segments (local phasing) with an accuracy of some tens of nm. As the edge sensor mechanical interface is not precise enough to provide an absolute phasing reference with such accuracy, external sensors are needed for the phasing procedure. This could be done with special wavefront sensors on sky during night time using precious observation time or locally during day time using high precision distance measurements. ESO is investigating a device for the latter approach, the so called "phasing gun". There are several potential candidates, mainly from the field of multiwavelength interferometry. As reported in the 2012 SPIE Conference in Amsterdam[2] some basic tests with LuphoSmart probes were already made in 2012, monitoring the absolute position of neighboring segments with nm precision over a non ambiguity range of 1mm. Two new concepts are being considered. One concept is based on multiaperture/multiwavelength interferometry, whereas the second concept is based on multiwavelength shaerography derived from a system developed by BIAS[7]. Figure 10 shows the extension of the M1 Test Facility for the basic setup of the shearing interferometry tests.

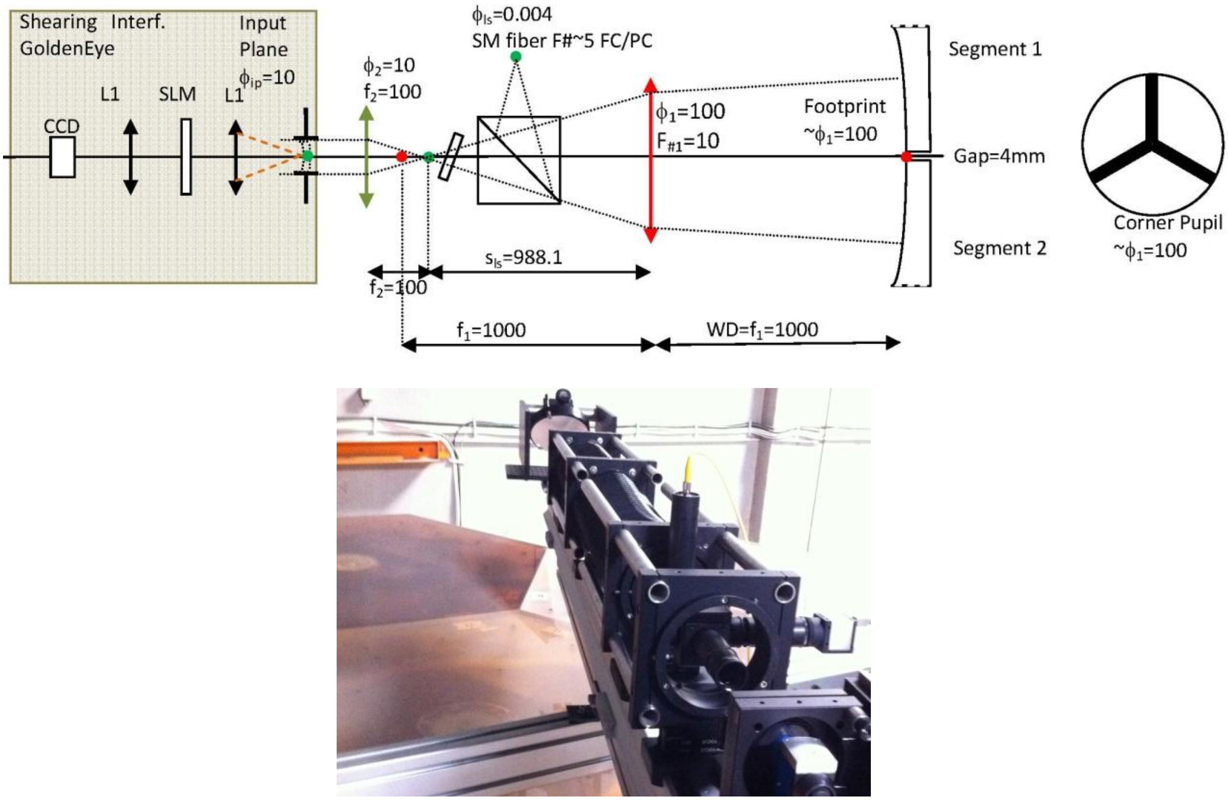

Figure 10 Extension of the M1 test facility to support phasing gun test at the corner of 3 segments.
Configuration for multiwavelength shearing interferometry.

4. IMPROVING THE POSITION ACTUATOR SPECIFICATIONS

At the M1 Test Facility two types of Position Actuators (PACT) from different suppliers were analyzed. Both cover a 15mm travel range with nanometric precision using a combination of DC torque motor for the coarse stage and fine stage using one common high-precision encoder mounted on the PACT shaft. However, they differ in the way the fine stage is implemented (soft actuator: suspended voice coil, hard actuator: piezo stage). The main functional requirements of the Position Actuators are to provide precise and smooth movements of the segment subunit to compensate for gravity sag and enough stiffness to reject wind forces.

The Position Actuators are configurable active control systems, which form an important part of the M1 control system and interact strongly with the segment subunits and the M1 Local Control System. During AIV they have to be tuned according to the dynamical behavior of the telescope. This configuration is then maintained for operation. The M1 Test Facility was particularly useful to exercise a complete AIV procedure of the PACT in order to better understand short-comings in the interaction with the rest of the M1 System and to identify missing parts of the M1 Control System, especially in the area of measurement, tuning tools and control interface.

Tools needed for controller tuning

The PACT specifications for the prototypes mainly focused on critical performances requirements to demonstrate technical feasibility. Neither the access to the segment subunit prototypes was provided, nor were there any detailed requirements on tuning tools or control interface included at that time. Therefore, performance and acceptance testing was done with a mass-test-stand, which matches in good approximation the simplified dynamical behavior seen by a single actuator in the segment subunit. The test system was stand-alone, i.e. it was not commanded externally from a telescope control system. Knowing that the dynamical behavior of the M1 E-ELT will be different and that the PACT are part of a demanding M1 Local Control System which coordinates 800 segments to form the 39m primary mirror, there is a need for a configurable system with proper access for control analysis and equipped with a well-defined control interface. The M1 Test Facility provided a suitable environment for mimicking the full AIV procedure from PACT delivery, through system analysis, controller tuning until operation in the M1 Local Control System. Like this the needs in terms of analysis, stimuli and configuration tools and control interface could be identified early. In addition, being in prototype state with a programmable Labview/PXI system from National Instruments the soft PACT prototype system could be reworked to implement the new concepts, and test and use them in depth. The firmware of the hard PACT prototype could not be changed. However, it already provided some of the requested functionality for the delivered prototype.

The outcome of this activity is a small set of requirements for development tools and control interface, which on the one hand considerably simplify the work of control engineering for the M1 Control System, but on the other hand do not add much complexity to the PACT control system. On this subject the new PACT specification requests are:

1. A configurable controller implementation, where not only the building blocks (controllers, filters, etc.) can be parameterized, but also some of the interconnections in order to enable/disable parts of the controller scheme and allow to route references and stimuli to different parts of the scheme.
2. A simple stimuli interface in the form of externally generated stimuli files in a defined E-ELT-TCS format, which are transferred to the PACT control system with standard FTP and applied there. The effect of stimuli is defined by the routing configuration described above in #1. This allows generating all kinds of stimuli with the tool preferred by the control engineer and applying it to the selected part of the system, e.g. open-loop voice coil.
3. A probing interface, which stores traces of the most relevant signals for a specified duration in data files in a defined E-ELT-TCS format. The data files also contain all configuration information and they can be retrieved by standard FTP from a control host and analyzed there with the tool preferred by the control engineer.
4. A control interface based on UDP multicast with a synchronization mechanism based on hardware trigger or a UDP broadcast messages using a small set of commands common for all M1 field devices (PACT, edge sensors and WH), which fits into the overall control concept described in the next chapter.

Dynamic control analysis of segment subunit

Using the tools described above dynamic control of both segment subunit prototypes with both types of PACT could be analyzed in detail. SISO and MIMO frequency responses are measured, and a model-based controller tuning strategy could be used to design robustly stable controllers for the segment subunits. This is very similar to how it was done for the analyses based on finite element models during conceptual design of the E-ELT[10]. The main dynamic requirements for the PACT closed loop system derived from the analysis in the past, to provide enough stiffness for wind rejection and enough bandwidth to close the edge sensor loop with sufficient margin could be met with both actuator types. The flexibility of the new soft PACT control system even allowed prototyping and analyzing of individual PACT control versus control in PTT (Piston/Tip/Tilt). Both schemes provided robustly stable controllers with sufficient bandwidth without the need of adding passive damping to the actuators. In parallel to the work described ESO investigated and implemented active damping strategies for hard actuators allowing a considerable increase of the hard actuator damping without the need of additional sensors[8, 9] thus further improving robustness and improving vibration immunity.

Various short comings observed thanks to continuous testing

The PACT were operated over several hundreds of hours for the dedicated PACT tests, but as well saw regular use as test devices for the analysis of the segment subunits. During this period various issues were identified. Some are PACT design specific, but others are caused by the interaction between PACT and segment subunit. Here just a few items are selected, which will be considered in the new specifications and verification plan.

- The full PACT travel range (output shaft, not coarse stage limits!) must match the segment survival range under all load conditions to avoid damage on either component. Especially the hard actuators can produce very high blocking forces. This applies to the mechanical limits of the PACT, which are often almost 1mm behind the operational limits. Since PACT will be verified independently not only the travel range must be verified, but also the correct position of the PACT reference. During our tests wrong PACT reference positions led to collisions in a segment subunit before reaching the end of the PACT travel range.
- The mechanical interfaces of the PACT to the segment subunit fixed frames shall be designed in a way that an operator is quickly released from supporting the PACT weight of 10kg and that the PACT are guided to their end position. This issue has already been introduced in Figure 7.
- Particular care shall be put in the design of the coarse stage of the PACT, especially non-linearities like play or friction shall be avoided in these nm devices. This issue has already been raised during the PACT prototype development and the tests have confirmed that these nonlinearities lead to more complicated, often non-linear, PACT controllers. This leads to low robustness introducing sporadic errors especially for low tracking speeds or velocity reversal. In addition, a good coarse stage can produce additional stiffness to a soft actuator lowering the bandwidth requirements of the PACT controller.
- The PACT stiffness of the production PACT shall not vary by more than 5% in order to avoid cross-coupling due to the non-symmetry of the 3 PACT below one segment subunit. During the tests strong discrepancies were recognized for both prototypes, which would lead to performance issues in the E-ELT baseline concept using identical controller settings for all segment subunits.

5. IMPROVING THE CONTROL SYSTEM SPECIFICATION

The main function of the M1LCS is to provide a reliable deterministic infrastructure to collect edge sensor and PACT sensor readings and to distribute new PACT references. The higher level Central Control Systems implements the so-called M1 figure loop to coordinate all segment subunits to form and maintain the M1 mirror shape. Beside this main function the M1LCS is also providing an infrastructure for control of the power supplies and warping harnesses, and for detecting component failures. Figure 11 shows the M1LCS baseline architecture.

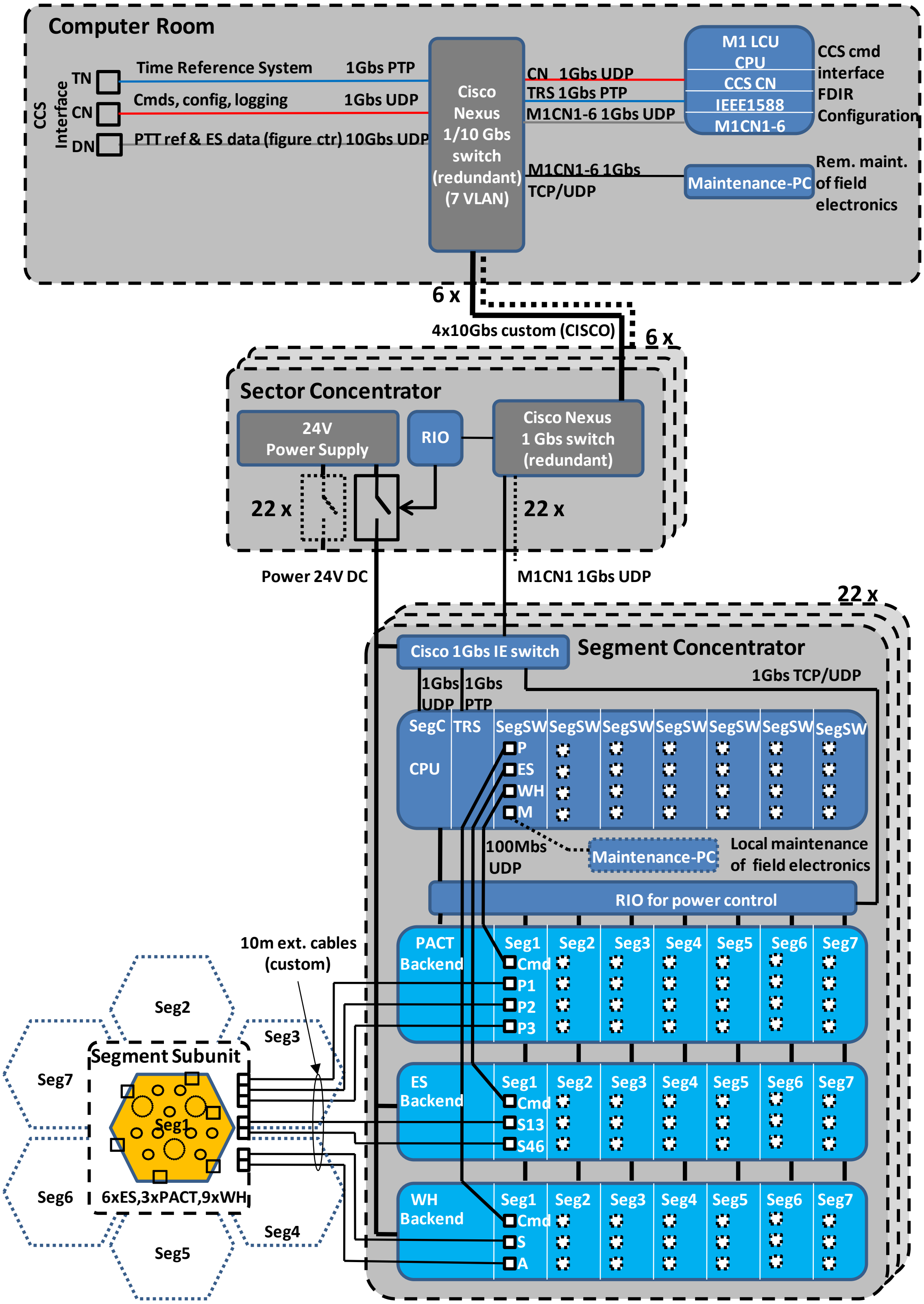

Figure 11. Overview of the baseline architecture of the M1LCS

The main features are:

- The M1 control system logically divides the ~800 segments of the M1 into 6 identical sectors collecting all ES readings from the segments in its sector, and distributing the mirror segment correction (expressed as Piston, Tip and Tilt) references for PACT and segment mirror deformation force references for WH. The sampling frequency for ES and PACT data is 500Hz, for the WH it is much lower.
- An electronic concentrator termed the “segment concentrator” (SegC) provides interfaces for the field electronics of up to 7 segments, resulting in 22 SegC per sector (some not fully populated with 7 segments), and 132 SegC for the total M1.
- The SegC consist of a CPU and seven 4-port switches interconnected with a backplane bus. The field equipment (PACT, WH, ES) is connected to the segment concentrators by dedicated 100BASE-T Ethernet connections using UDP/IPv4 protocol. The fourth port of each switch is used for local maintenance of the field electronics of one segment using standard computer equipment. The choice of separate switches per segment reduces the management of different addresses and thus simplifies failure detection.
- The main function of the SegC is to concentrate the measurement traffic of 7 segments (many UDP packets at low payload) into fewer, larger UDP packages for the upstream interface to the Control System. Downstream the SegC receives position/force corrections from the Control System and dispatches the traffic to the segment devices. In addition, each SegC handles the command, configuration and remote maintenance interface of the group of 7 segments attached.
- Piston-Tip-Tilt control for segment positioning and force control for WH motors is done locally for each segment in the PACT and WH field electronics, respectively.
- The network for deterministic data is organized as a hierarchical tree with 6 identical sectors assigned to different VLANs. A central 1/10 Gbs cut-through-switch located in the computer room is connected with fast (up to 40Gbs) uplink ports to 1Gbs cut-through switches in the sector distribution cabinets. Inside the sectors the SegC are interconnected in star topology with 1Gbs interfaces. The uplink data is sent on a single 10Gbs interface to the M1 Local Supervisor, not part of M1LCS. The downlink data follow the opposite path closing the M1 figure loop.
- Time synchronization in the M1 control system is based on IEEE-1588 protocol. It will be used down to the level of the segment concentrators. The field devices (WH, PACT, ES) are synchronized using dedicated UDP multicast trigger messages or a hardware synchronization managed by the segment concentrator (not shown in Figure 11). The field devices only use an approximate clock for time stamping of log messages and non-critical data stamping, it is set once at device initialization.
- For improved availability some redundancy is built into the communication infrastructure, e.g two Cisco Nexus switches in the computer room and the Sector Distribution Cabinet, redundant network cables in the sectors (not all redundancy is shown in Figure 11). Redundancy in the SegC and Control System servers with automatic handover and failure recovery has been avoided due to its complexity. Instead more effort has been put into failure detection.
- All SegC units and field devices are powered by 24VDC. Power is managed by the M1 Control System and can be interrupted remotely at three different levels: i) Inside the SegC for one segment, the PACT controller or SegC only ii) One complete SegC incl. field devices for all 7 segments iii) One Sector. In addition a built-in hand-over in case of failure to a spare power supply is foreseen at sector level.
- For local equipment-specific diagnostics an additional Ethernet port is provided at each segment switch in the SegC. If diagnostics are required from a remote location, the same maintenance functions provided locally are supported by piping Ethernet frames over the M1 control network, i.e. a computer connected in the computer room would be capable of sending messages to the field devices as if connected locally at SegC level with an Ethernet cable.
- The Sector Distribution Cabinets are located at a central location under the corresponding segments of each sector. The 22 Segment Concentrator Cabinets of each sector are located under the central segment of a group of 7 segments. Both types of cabinets are mounted at the M1 structure leaving access to segments from below.

Since SPIE 2012 Conference many critical items of this baseline architecture were implemented and tested in the M1 Test Facility and in an additional dedicated test stand logically representing the communication infrastructure of one M1 sector. Since only 4 segment subunits and a limited number of edge sensor and PACT controllers are available, some of the tests are done with the data traffic generated by real hardware and other tests were using custom built traffic generators based on FPGA boards.

The prototype tests mainly focused on three areas of the baseline architecture:

1. **Control interfaces of the field electronics** For edge sensor, PACT and warping harnesses common interfaces were designed based on UDP multicast communication with a synchronization mechanism based on hardware triggers or broad- or multicast UDP Synchronization messages. These interfaces also provide common services for device configuration, telemetry and performance analysis. Tests were done on real hardware encapsulating the private prototype interfaces by so called facades, i.e. hardware adapters providing the new interface to the outside while using the prototype interface on the inside.
2. **Microburst condition of cut-through switches** Traffic in the M1 sectors consists of a large number of packets arriving simultaneously. These periodic peak loads, so-called micro-burst conditions, could cause packet loss or latencies. These conditions were analyzed and tested in detail by generating equivalent traffic as in the real system using traffic generators. The Cisco hardware under tests proved to be very robust for the traffic needed in M1 Control System, i.e. no packets were lost, neither were there any unexpected latencies.
3. **Latency of the segment concentrator and other components of the figure loop** Under all circumstances the components involved in the figure loop need to guarantee latencies, which are in sum lower than the intended sampling period of 2ms. Otherwise there is risk of jitter or data loss. The necessary processing time was analyzed and tested using traffic generators comparing it to the baseline time allocation. Particular care was taken for the segment concentrators, which patch/dispatch data from PACT and edge sensors from a group of seven segments. It could be confirmed that this periodic task can be executed reliably in a few hundreds of µs fitting to the overall timing requirements.

The tests of the M1LCS data infrastructure delivered important input for the evaluation and refinement of the E-ELT baseline architecture. The majority of the prototype hardware used in addition to the E-ELT prototypes is based on Labview real time systems using PXI and cRIO platforms. The traffic generators used free programmable National Instruments FPGA boards with network interfaces, which support parallel synchronous traffic generation (MIMAS boards from company Prevas, Sweden). For prototyping the Labview environment with the large availability of hardware has proved to be very suitable. In the meantime the M1 Test Facility provides a rich software infrastructure in the form of software coding standards, libraries and a broad range of example applications.

To complete the tradeoff analysis in mid 2014 additional tests of an alternative Segment Concentrator architecture completely based on commercial switches are planned. A preliminary design review of the M1 Local Control System is foreseen for the end of 2014.

6. CONCLUSION AND FUTURE PLANS

The M1 Test Facility has continued to be very valuable to gain experience on the E-ELT M1 segmented primary mirror. Thanks to the developments on the control system during this second test phase many prototypes could be tested in a system's view focusing on the interaction of components, and as a result gaining important input for the design specification of improved prototypes and the M1 system concept. This should further reduce risk and associated cost of the E-ELT project.

The feedback of all static and dynamic tests for the segment subunits had a strong impact for the specifications of a second generation segment subunit contract planned to start beginning of 2015. The experiences gained from the first edge sensor tests have led to second generation edge sensors development with improved mechanical interface, which are currently under test. For the Position Actuators their intense use for dynamic and static tests returned a lot of experience and an important list of lessons learned considered in the new specification and verification. The new area of the control system including the field device interfaces returned important know-how to refine and verify the baseline architecture.

For the next months several tests are planned in the area of metrology needed for locally aligning inserted segments. In parallel there is much activity related to the control system in order to reach preliminary design by end of 2014. For the last 3 years the M1 Test Facility was located in a storage building, which was sometimes strongly disturbed by loading/unloading traffic in the direct neighborhood. This affected mainly edge sensor and PACT dynamic tests. This should considerably improve in the future with the planned moving of the M1 Test Facility into ESO's new assembly building in 2014 providing a real lab environment.

7. ACKNOWLEDGEMENTS

The author would like to acknowledge the valuable support of Bernard Buzzoni for the optical setup and alignment of the metrology tests and Robert Frahm for the Labview implementation of the ES Testbed and M1CS performance tests. This is much appreciated.

REFERENCES

[1] The E-ELT Project Office, [The E-ELT Construction Proposal], European Southern Observatory, Garching, (2011), http://www.eso.org/public/archives/books/pdf/book_0046.pdf

[2] Dimmler, M., Marrero, J., Leveque, S., Barriga, P., Sedghi, B., Mueller, M., "E-ELT M1 Test Facility", SPIE 8444, 84441Y (2012),

[3] W. Li, J. Burke, "Simulation of deformation measurements with deflectometry", Proc. DGaO B27 (2014), http: //www.dgao-proceedings.de/download/115/115_b27.pdf (in press)

[4] J.Reitberger, "Deflectometry and its application in optics manufacturing", 1st European seminar on precision optics manufacturing, Technische Hochschule Deggendorf, April 2014

[5] Wasmeier et .al., "Inductive sensors based on embedded coil technology for nanometric intersegment position sensing for the E-ELT", SPIE Conference, Montreal (2014), Paper 9145-62

[6] Piezo nanopositioning, P-562.6CD, http://www.physikinstrumente.com

[7] C. Falldorf et al., "Shearing interferometer based on the birefringent properties of a spatial light modulator", Optics Letters, Vol. 34, Issue 18, pp. 2727-2729 (2009)

[8] Gago, F., Marrero, J., "Vibration Control of the Main Mirror of the E-ELT Telescope", Proc. of Actuator 2014 Conference, Bremen.

[9] Barriga, P., Sedghi, B., Dimmler, M., Kornweibel, N., "Status of E-ELT M5 scale-one demonstrator", SPIE Conference, Montreal (2014), Paper 9145-59

[10] Sedghi, B., Mueller, M., Dimmler, M., Bauvir, B., Erm, T., Bonnet, H., Cayrel, M., "Dynamical aspects in control of E-ELT segmented primary mirror," SPIE 7733, 77332E-9 (2010).