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Upgrade of the HET segment control system, utilizing state-of-the-art, decentralized and embedded system controllers.

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ABSTRACT

Together with the ongoing major instrument upgrade of the Hobby-Eberly Telescope (HET) we present the planned upgrade of the HET Segment Control System (SCS) to SCS2. Because HET's primary mirror is segmented into 91 individual 1-meter hexagonal mirrors, the SCS is essential to maintain the mirror alignment throughout an entire night of observations. SCS2 will complete tip, tilt and piston corrections of each mirror segment at a significantly higher rate than the original SCS. The new motion control hardware will further increase the system's reliability. The initial optical measurements of this array are performed by the Mirror Alignment Recovery System (MARS) and the HET Extra Focal Instrument (HEFI). Once the segments are optically aligned, the inductive edge sensors give sub-micron precise feedback of each segment's positions relative to its adjacent segments. These sensors are part of the Segment Alignment Maintenance System (SAMS) and are responsible for providing information about positional changes due to external influences, such as steep temperature changes and mechanical stress, and for making compensatory calculations while tracking the telescope on sky. SCS2 will use the optical alignment systems and SAMS inputs to command corrections of every segment in a closed loop. The correction period will be roughly 30 seconds, mostly due to the measurement and averaging process of the SAMS algorithm.

The segment actuators will be controlled by the custom developed HET Segment MOtion COntroller (SMOCO). It is a direct descendant of University Observatory Munich's embedded, CAN-based system and instrument control tool-kit. To preserve the existing HET hardware layout, each SMOCO will control two adjacent mirror segments. Unlike the original SCS motor controllers, SMOCO is able to drive all six axes of its two segments at the same time. SCS2 will continue to allow for sub-arcsecond precision in tip and tilt as well as sub-micro meter precision in piston. These estimations are based on the current performance of the segment support mechanics. SMOCO's smart motion control allows for on-the-fly correction of the move targets. Since SMOCO uses state-of-the-art motion control electronics and embedded decentralized controllers, we expect reduction in thermal emission as well as less maintenance time.

Keywords: Active optic, SMOCO, HET SCS2, DECANIC, CAN based array control, Multi Object Spectrograph facility, electronics minimazation, microcontroller based motion control

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1. INTRODUCTION

Due to HET's 91 individual 1-meter hexagonal mirrors with three actuators each, a system is required that can control all 273 axes to align every segment relative to its adjacent segments and to the general surface of the primary sphere. In general, the alignment is maintained by feedback loops between a diagnostic subsystem and the segment control subsystem. Movement at the individual segment is completed by stepper-motor driven actuators on three axes I, J, and K. The diagnostic subsystems currently being used at HET are the Segment Alignment Maintenance System (SAMS), Mirror Alignment Recovery System (MARS), and the HET Extra Focal Instrument (HEFI). Each diagnostic system can be given *move authority* over the Segment Control System (SCS). *Move authority* is a SCS software term that designates which diagnostic subsystem has the authority to command SCS moves. The SAMS subsystem is made up of inductive edge sensors, which measure relative shear and gap between adjacent segments. The control software calculates tip, tilt, and piston moves for each mirror that will minimize sensor errors relative to initial reference values. MARS and HEFI are subsystems that give additional optical feedback on the alignment of the primary, rather than SAMS electro-mechanical feedback. The optical feedback loop is used during the daily calibration of the telescope before the actual science operation to gain optimal starting values for the SAMS's electronic feedback loop which runs throughout the whole night to keep the segments aligned.[1]

In HET terms, the segment control system consists of its diagnostic subsystems which give feedback on the segments current positions and the actual SCS which actuates the segments. While the HET has been heavily upgraded and will soon be back in science mode to pursue the Hobby-Eberly Telescope Dark Energy Experiment (HETDEX) and its other projects, some facility systems, like SCS, also need a major overhaul. The main reasons for this overhaul are the original vendor of the motion controllers (Diamond Motion) is no longer in business and the motion controller hardware is obsolete. Given those two facts it was rather clear that the SCS will have to be replaced by a new system. Given the need for a redesign we took the opportunity to solve several of the old SCS's weak points. Within the following chapters, those weaknesses will be addressed, while the advantages of the new SCS2 will be pointed out.[2]

The following bottom up system design overview from the individual segment all the way to the high level software serves the reader as a guideline for the upcoming chapters.

SCS2 design overview:

(A) **Segment topology:** To establish context for the segment motion, the mechanical layout of an individual, 1 m hexagonal mirror and its three actuators is explained. (Section: 2)

(B) **Actuator:** Each mirror axis is actuated by a stepper motor-gearbox assembly, the moment of which is transmitted to the mirror segment through the mechanical advantage of a lever. (Section: 2)

(C) **Controller:** Each segment has its own CPU and motion controller to handle all three motor drivers; hence, movements are executed simultaneously to every segment. (Section: 3)

(D) **CAN Bus:** Each CPU is an active node on a single CAN bus network which is hosted by a commercially available CAN/Ethernet bridge. (Section: 3)

(E) **SMOCO:** A set of four controllers is implemented on a single SMOCO board which is the main component of SCS2. To operate the entire array of mirrors, 23 SMOCOs are connected via a 19" rack backplane. (Section: 3)

(F) **CAVE:** All SMOCOs are connected via a 19" rack backplane within the Common Actuator Vectorization Entity. CAVE further houses the power supplies, the CAN bus and the cabling bulkhead. (Section: 3)

(G) **Power supplies:** SCS2 has three separate power networks. 1. $V_{logic} = 12VDC$: CPU and communication, 2. $V_{sensor} = 24VDC$: Hall Effect sensor and 3. $V_{Axes} = 24VDC$: Stepper motor (Section: 3)

(H) **Control software:** Due to the modular HET software design, only minor parts of the high level software have to be changed. In addition, an interface code which translates high level commands into the according CAN messages is needed. (Section: 4)

2. SEGMENT TOPOLOGY AND ACTUATORS

(A) Segment topology: In order to keep 91 individual segments aligned on the primary sphere, correctional tip, tilt, and piston moves are executed by three linear actuators, labelled I, J, and K, located at 120-degree intervals. They are placed on the vertices of an equilateral triangle in the segment support as can be seen in figure 1. Tip and tilt rotations are piston free. Consequently, we get the following instructions to execute the smallest possible tip, tilt and piston movements:

Axes	I	J	K	Units
$\Delta tip =$	+2	-1	-1	± 0.024 arcseconds
$\Delta tilt =$	0	-1	+1	± 0.014 arcseconds
$\Delta piston =$	+1	+1	+1	± 0.018 microns

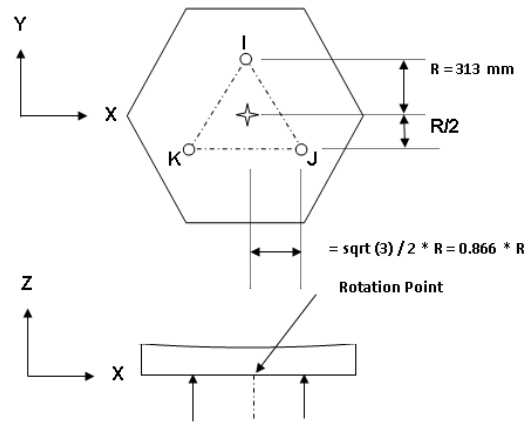

Figure 1. Segment design schematic.

(B) Actuator: After the HET staff de-constructed the existing actuators, it was found that crucial parts, like the stepper-motor/gearbox assembly are long-term, commercially available parts. Therefore, it has been decided to keep the working motor-gearbox configuration for a minimum of risk. Each linear actuator consists of a 2-phase stepper motor (24 V 24 steps/rev.), a gearbox (485:1) and a 40.0000 turns/inch drive screw. Figure 2 shows the functional scheme of the actuator.

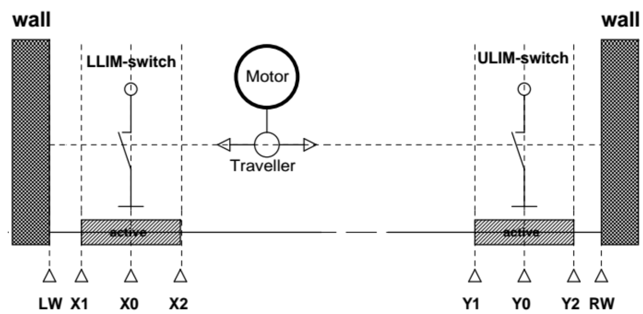

Figure 2. Functional actuator schematic.

Each actuator operates over a range of 480,000 actuator steps. The upper and lower limits of travel are detected via hall-effect sensors in the actuator housing. On the original SCS setup, these hall-effect sensors drove a high-impedance, 5V TTL input on the controller. In this configuration, they were highly susceptible to electro-magnetic interference (EMI) which caused random false-triggering. SCS2 uses the same hall-effect sensors to drive a 5 mA closed-current loop at 24V. This not only solves the EMI contamination but also allows the detection of broken wires. To avoid internal EMI, the motor signals and the sensor signals are routed on separate and shielded cables as can be seen in figure 3.

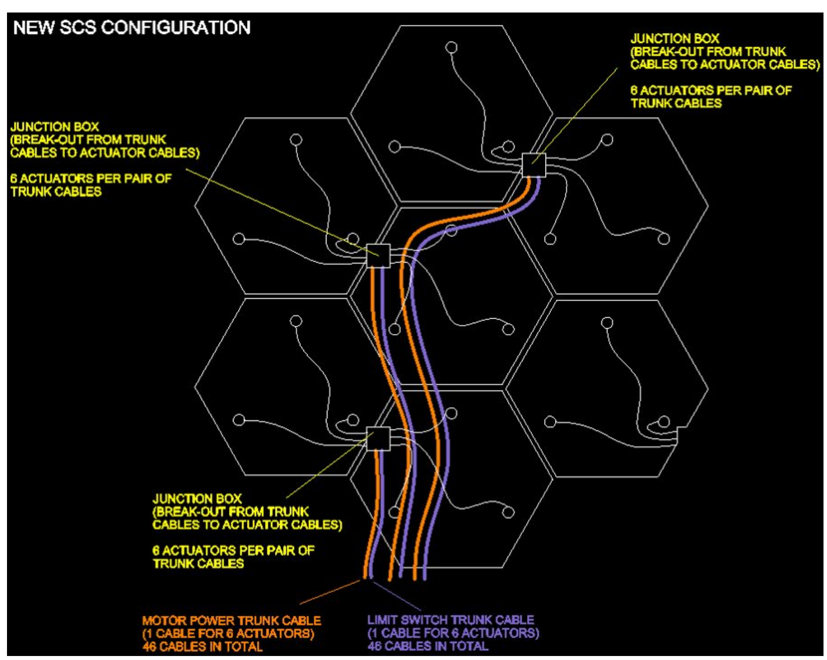

Figure 3. Motor and limit switch cabling schematic.

3. ELECTRONICS

(C) Controller: A significant limitation of the old SCS design is the commercial motor controller. Though state-of-the-art when they were initially implemented, they were never specifically designed for the HET SCS application. Being a proprietary commercial product, they have the following weaknesses:

(I) They can only handle 2 axes per controller. This results in the artificial coupling of two neighbouring segments to segment pairs, each controlled by three boards

(II) The source code and according motion control was not available to HET, so troubleshooting and error handling is difficult to impossible.

(III) They can only actuate one axis at a time, which caused the segments to be in suboptimal positions while moving. Additionally, it increased the reconfiguration time for the correction feedback loop.

(IV) The positions were transmitted via a daisy-chained RS232 network leading to long ($\approx 10s$) communication delays.

(V) Failed or incomplete moves are not or are insufficiently reported.

(VI) In order for the controllers to be functional with the hall-effect sensors, they need to be located directly behind the mirrors. This forces the emission of nearly 1.0 kW of waste heat just behind the segmented primary mirror. Additionally, it makes in-situ maintenance difficult and time-consuming.

Throughout the rest of this section, these weaknesses will be addressed, while the new system will be presented in detail.

It allows single CPUs to communicate via CAN with a high level computer and each other. Figure 4 shows a functional block diagram of one segment CPU. In the HET application each CPU handles all three axes of one segment. Further the full source code of the CPU is available to HET, so troubleshooting and maintainability is ensured.

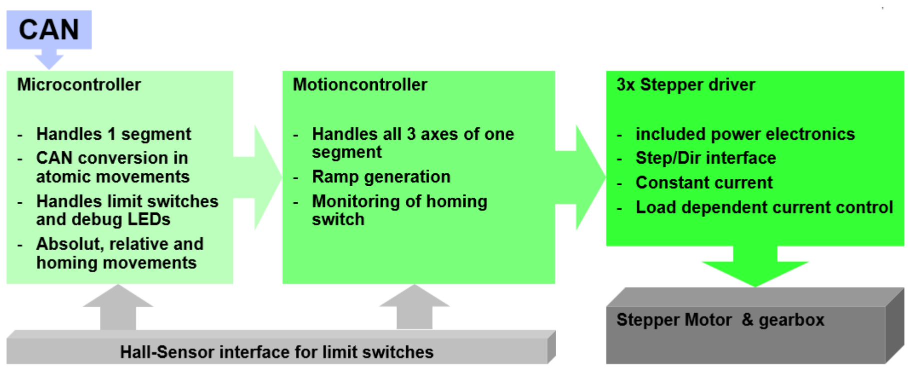

Figure 4. CPU block schematic.

By design, the new SCS2 system is able to drive all three axes at once and trigger their moves simultaneously. Hence the SCS weaknesses number (I) to (III) are inherently solved by the SCS2.

(D) CAN Bus: SCS2 relies on the new decentralized CAN-based instrument control tool-kit (DECANIC), developed by the University Observatory Munich (USM/LMU)[a]. Using state-of-the-art CAN bus allows for much faster communication than the outdated RS232. SCS2 is able to transmit worst case commands (longest possible message) within 0.4 ms. Given this, the communication time for the full array of all 273 axes is typically less than 100 ms. Compared to the nearly 10 s communication time required by the RS232 network, this is roughly a factor of 100x better which allows for a fast feedback loop on the mirror control. The CAN bus further allows the CPU to not only report on the status of each axis, it offers enough communication bandwidth for a sophisticated error report and handling system. This allows the high-level computer and the operator to maintain full knowledge over the entire array status. Given these improvements, the CAN bus approach perfectly addresses the old SCS weaknesses (IV) and (V).

(E) SMOCO: The Segment Motion Controller (SMOCO) acronym represents the actual PCB on which we place four individual segment CPUs. The PCB has a standard form factor of 10cm x 16cm and is shaped to fit into a standard 19 rack assembly. Use of state-of-the-art components made it possible to fit the functionality of 12 axes of motion onto this small footprint.

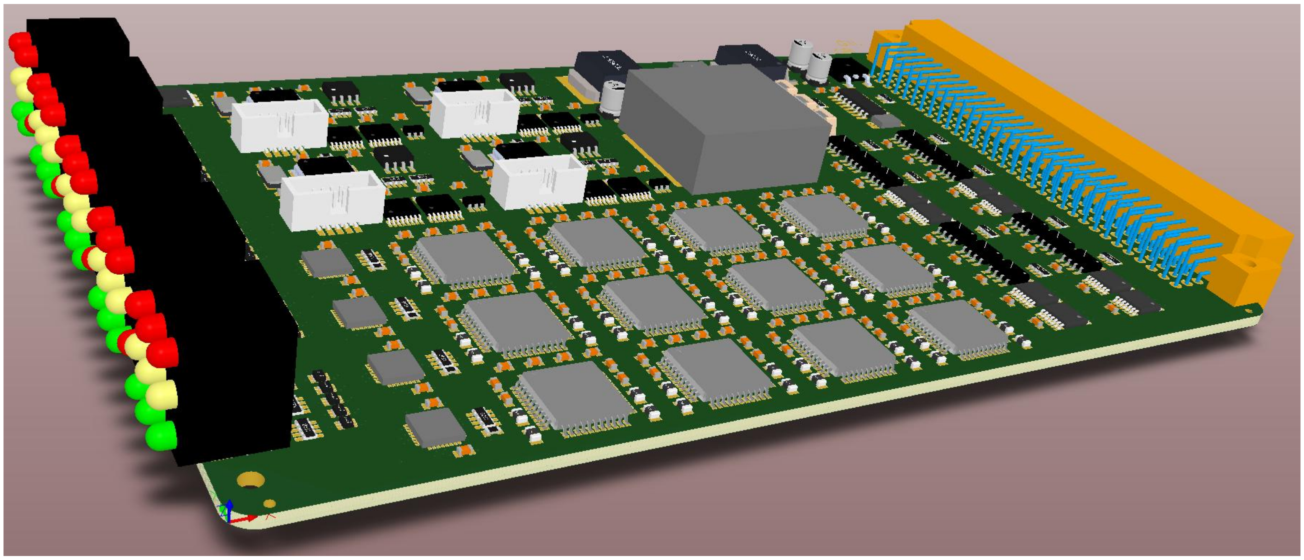

Figure 5. 3D design of the SMOCO PCB.

SMOCO characteristics			
⊙	Input circuitry for 2 hall effect sensors per axis	⊙	4 segment motion control (12 axes total)
⊙	3 step, on-PCB power supply	⊙	Front panel status LED interface (Figure 6)
⊙	nominal ≈ 1 W waste heat per SMOCO	⊙	Individual flashing interface per CPU

Most of the components of the SMOCO logic and embedded motion control circuitry are taken directly from the USM DECANIC system. At its heart, the system is a u-controller based CPU capable of interfacing various extension modules such as a stepper driver, digital I/O, and/or resolver circuitry. This design allows for it to be fit onto very small footprints, which can either be located directly by the controlled hardware or fit into a control cabinet requiring minimal space. In either configuration, its energy efficiency (nominal of 1W of waste heat per SMOCO) allows it to operate the smart individual controllers with little to no cooling required. Due to its modular hardware and low-level software design, the system is scalable from a 20 axes solution to the nearly 300 axes solution required for HETs segment control. The actual code with each CPU is almost identical and will run equally well on all 91 segment CPUs. The CAN bus keeps all these nodes connected simultaneously to the host computer.

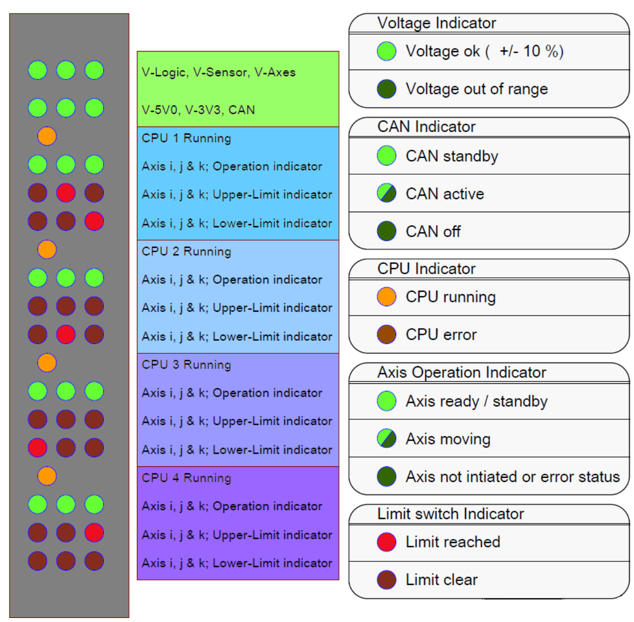

Figure 6. Front panel SMOCO status LED set.

(F) CAVE: While the old SCS controllers needed to be located directly behind their associated mirror segments, the SCS2 SMOCO is designed to handle the actuators remotely. Consequently, all SMOCOs are located within the Common Actuator Vectorization Entity (CAVE). CAVE is designed to fit into a 19 rack. Conveniently, HET has a 19 rack in an insulated, co-rotating cabinet placed on the structure behind the main mirror known to the HET team as the IGLOO. The IGLOO contains the network, power and cooling systems required to support the CAVE and associated SMOCO assemblies. Placing SCS2 inside the IGLOO was a request from the technical staff from both an ease of maintenance standpoint as well as a way to improve optical seeing by controlling waste heat released under the primary mirror. Extensive measurements revealed that the old SCS controllers released upwards of 1.000 kW of waste heat directly into the optical path of the telescope. In comparison, all of the SCS2 SMOCOs release approximately 30W in worst-case scenarios. Additionally, this heat is released into the insulated and temperature-controller IGLOO where it can be exhausted outside of the dome away from the optical path. This is a huge advantage over the old SCS and solves the aforementioned weakness (VI). Figure 7 presents our current 3D CAVE design and illustrates its minimal footprint for a design that handles nearly 300 axes.

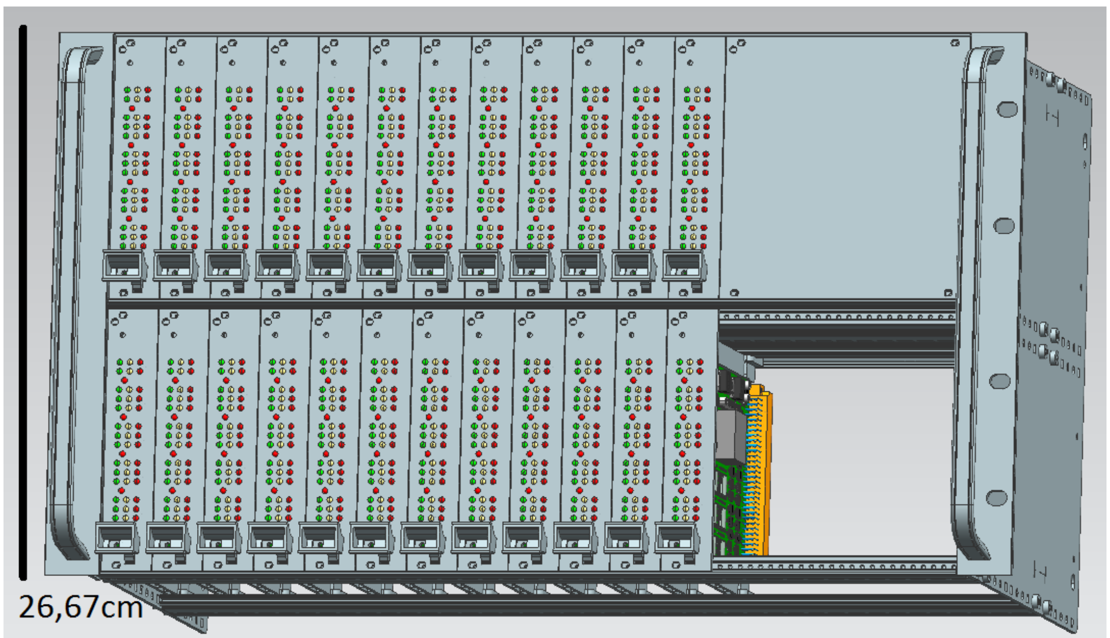

Figure 7. 3D design of the CAVE 19" rack assembly.

(G) Power supplies: While the power supplies also contribute to the heat budget of the system, their affects can be ignored since the supplies for the SCS system were already located within the IGLOO. SCS2 utilizes three separate power supply systems. First and foremost is the 24Vdc power supply system for the actuator stepper motors. This system consists of multiple 24 Vdc supplies run in parallel banks to provide the capability of delivering a minimum of 70A required to move all axes simultaneously. The second power supply system is a single 24 Vdc supply which drive the closed current loops for the hall-effect limit sensors within the actuators. In contrast to the SCS 5V TTL signals, SCS2 uses 24V-5mA closed-current loops to compensate for the long (up to 15m) cable lengths from the CAVE to the actuators. This leads to a worst-case consumption of 3A but solves the EMI-induced limit switch triggering problems of the old SCS. The third and final system is a 12 Vdc logic power supply that is utilized to power the CPUs and associated circuitry. While the actual voltages used on the SMOCO PCB are 5V for CAN communication and 3.3V for the u-controller, 12 V is used as a robust solution to drive the whole SMOCO array within the CAVE with each SMOCE containing DC-to-DC supplies to provide the appropriate voltage levels internally.

All power supplies are tied to a single C ground to avoid floating voltage levels. Furthermore, this ground level s used as a star point within the ground scheme to minimize electromagnetic interference.

4. SOFTWARE

The software side of the HET SCS2 project can be separated into three different parts. First, the low-level software inside the μ-controller (1). Second, the CAN communication layer between the low level μ-controller CPUs and the hosting high level software (2). And lastly the high-level control software itself (3).

(1) The low-level c-based μ-controller software allows for a comprehensive set of commands. Relative and absolute movement commands and designated homing procedures are implemented on the lowest level of the architecture. By implementing all logic on the μ-controller, which handles an individual axis, the communication between the host computer and the nodes is almost human readable. The code runs as a Real Time Operating System (RTOS) and starts one task per axis to handle. Three axes are operated more or less simultaneously and have access to the on board buses and resources based on mutual exclusion called mutex. This is a vital part of the RTOS and handles conflicting interrupts and hardware requests. Following is a excerpt of the functional commands embedded in the instruction set of the SMOCO CPU.

Instruction set excerpt

1	set absolute target	5	move to target	9	set $Axis_{Initialised}$	13	abort move
2	set relative target	6	move to lower limit	10	set $Vmax_{positioning}$	14	axis power On/OFF
3	request axis status	7	move to upper limit	11	set $Vmax_{homing}$	15	reset CPU
4	request limit status	8	start homing process	12	set $X_{Position}$	16	emergency stop

(2) The CAN bus is the communication back bone of the DECANIC system and proven to be EMI robust and capable of handling larger arrays of smart instrument control nodes.[3] A basic principle of the CAN bus topology is the fact that every connected node receives every message transmitted via the network. Each node has to acknowledge the information which consequently decreases the chance of an individual node misinterpreting the information. To avoid crowding the nodes with parsing unimportant information, a CAN message is built up of two parts. First the so called message-ID, which is either 11-Bits (standard mode) or in our case 29-Bits (extended mode) long. Both modes are industrial standard and supported by almost all available CAN bus products. DECANIC uses the message-ID as a 29-Bit field in which several informations are encoded.

28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	Bit Nr.	remark:
x	x	x																											28 . . 26	selects 8 possible prioritys
																													25 . . 20	Unassigned ID space
									x																				19	select ALL nodes
										x																			18	select ALL axis
																													17 and 16	Unassigned ID space
													x	x	x	x	x	x											15 . . 10	selcts ALL possible commands
																			x	x									9 and 8	selects motor axis[0..2]
																					x	x	x	x	x	x	x	x	7 . . 0	selects CAN node number

Figure 8. 29-Bit CAN message-ID bit mapping of SCS2.

CAN message ID sub structures

1	Priority bits allow emergency messages to be transmitted instantaneous on the network and also allow the host to keep bus control over the slave CPU nodes.* 8 Priority levels are implemented.
2	Bit 19 flags if a message is designated to all CPUs at once.
3	Bit 18 flags if a message is designated to all axes on the CPU.
4	Command bits allow for 64 individual commands as listed in the instruction set excerpt.
5	Bit 9 and 8 address the axis on the CPU which is affected by the command.
6	Finally Bits 7 till 0 open an address space for up to 255 nodes. In SCS2 one ID reflects the according mirror segment CPU.
7	Bits 25 till 20 and 17 till 16 are so far unassigned ID space.

*The master-slave allocation is implemented via software. Each participating CAN node can in theory behave like a bus master. In practice slave messages will always start with at least one recessive bit.

In addition to this custom section, the message-ID also contains several bit fields in which security checks, bit stuffing information and many more CAN specific content is implemented. All of this is CAN standard and can be found in the according documentation.[4]

The second part of a CAN message are the optional data bits. It is noteworthy that a CAN message does not have to contain data bits at all. In some cases, receiving a command via the message-ID without any additional data is just fine. SCS2 makes use of this fact to provide acknowledgement information towards the host, by returning the command just with changed priority. Another example would be the host command to start all axes movements and initiate travel to their individual target positions. While the positions have to be transmitted individually and with the target position as data bits, the move trigger can be sent to all nodes at once with a single command without any optional data. This reduces the number of messages that need to be transmitted and it saves energy, since only one message needs to be parsed by all nodes and limits bus crowding to a minimum.

(3) In the SCS2 design, the CAN network resides only within within the CAVE assembly. It is accessed via the already mentioned CAN/Ethernet bridge, and the hosting computer need only open an Ethernet-based port connection.

(H) Control software: The high level SCS2 software will be almost identical to the old SCS software. As can be seen in figure 9, SCS controls the mirror array via a subset of 10 communication banks each based on RS232. This is necessary due to the very slow baud rates of this interface. The SCS software communicates via 10 Bank Control Demons (BCDs), each hosting a smaller number of controllers. As figure 9 illustrates, the old controllers can only handle two axes at a time, so three controllers share authority over two segments.

While everything from the BCDs to the actuators is redesigned, the remaining software structure is almost not affected by the upgrade. The SAMS and MARS diagnostic subsystems will communicate in the same manner as in SCS, so the systems precision will stay the same; however, the significant reduction in communication time and the ability to move all axes at once reduces the control loop time by almost a factor of two. While the GUI interface does not need to be changed, which further reduces the upgrade costs in terms of man power and risks.

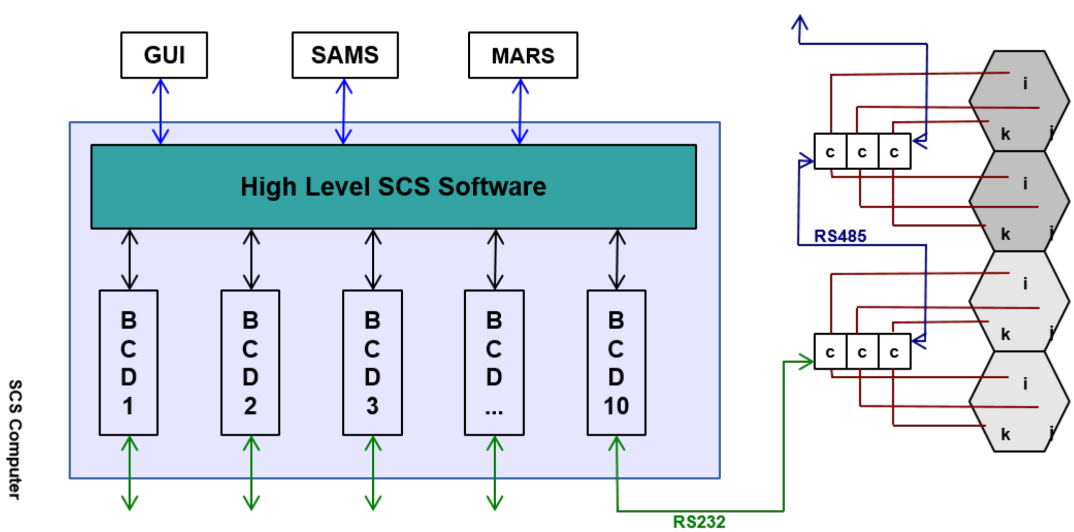

Figure 9. Block schematic of the SCS software.

In contrast to the old SCS design as shown in figure 9, figure 11 points out the different approach of SCS2, to have all controllers on one single bus. As already mentioned, this allows the system to trigger various kinds of commands all via one single interface. During SCS2 system integration, SCS2 and SCS software will be run together. The high-level software will be updated as SCS2 hardware is installed to insure that the updated segments are disengaged from SCS BCDs and engaged in the CAN demon. This coexisting set up of both systems can be seen in figure 10.

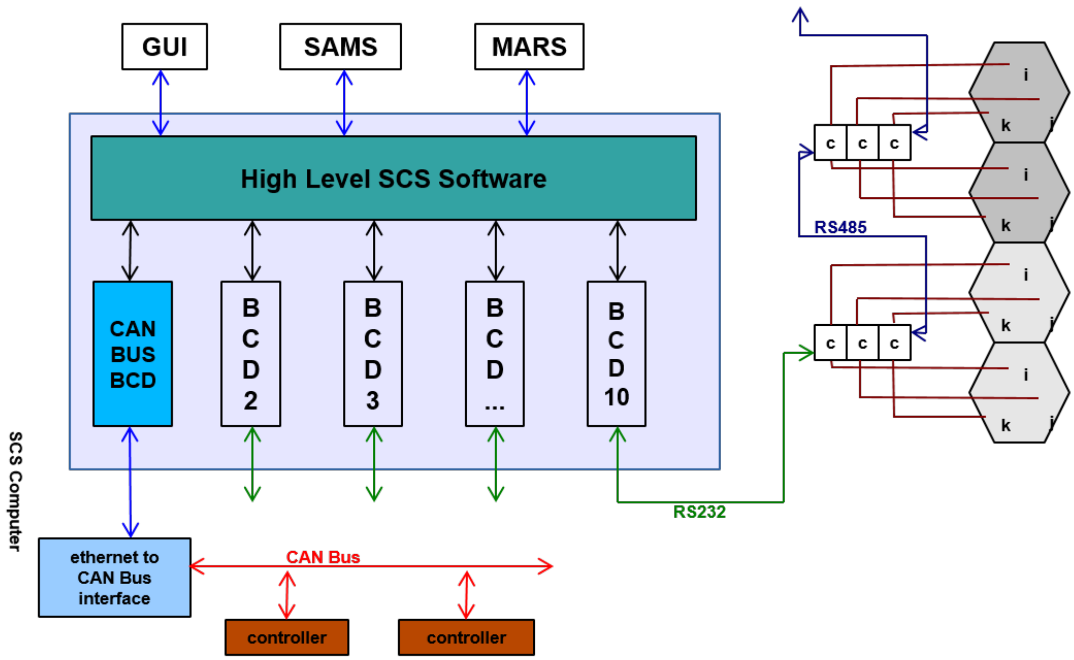

Figure 10. Block schematic of the coexisting SCS and SCS2 software.

Being able to integrate the new system in small steps, like one segment pair at a time, has the advantage of not causing any telescope downtime.

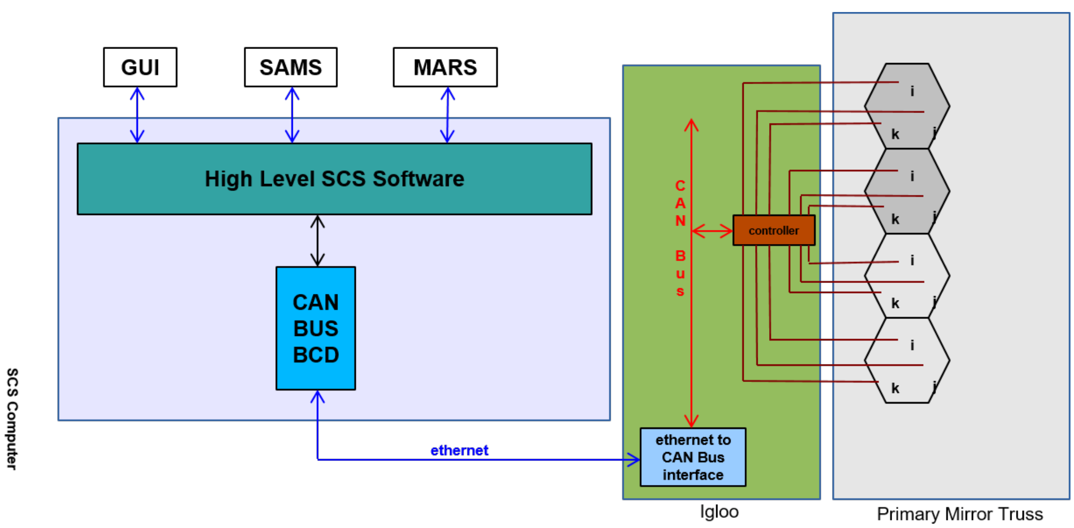

Figure 11. Block schematic of the SCS2 software.

As the comparison of figure 9 and figure 11 shows, only minor parts of the high-level software do have to be redesigned. Mainly, this entails a library which converts the high-level commands into the SMOCOs CAN instruction set commands. In HET terms, this code will be called CAN BUS BCD.

5. SUMMARY

The upgrade of the SCS towards SCS2 will allow the HET to maintain its main mirror shape better than before and reduce the amount of time needed to execute corrections on the mirrors' positions significantly.

As already investigated by Racine et al.[5] dome and especially mirror seeing can largely contribute to the overall seeing of the facility. While the HET dome design allows for very good airflow, its mirror seeing might have been affected by the large amount of waste heat from those old controllers. The amount of waste heat emitted into the optical beam will be reduced by at least 1000 W; therefore, we expect the local seeing to improve and hope to gain overall facility efficiency.

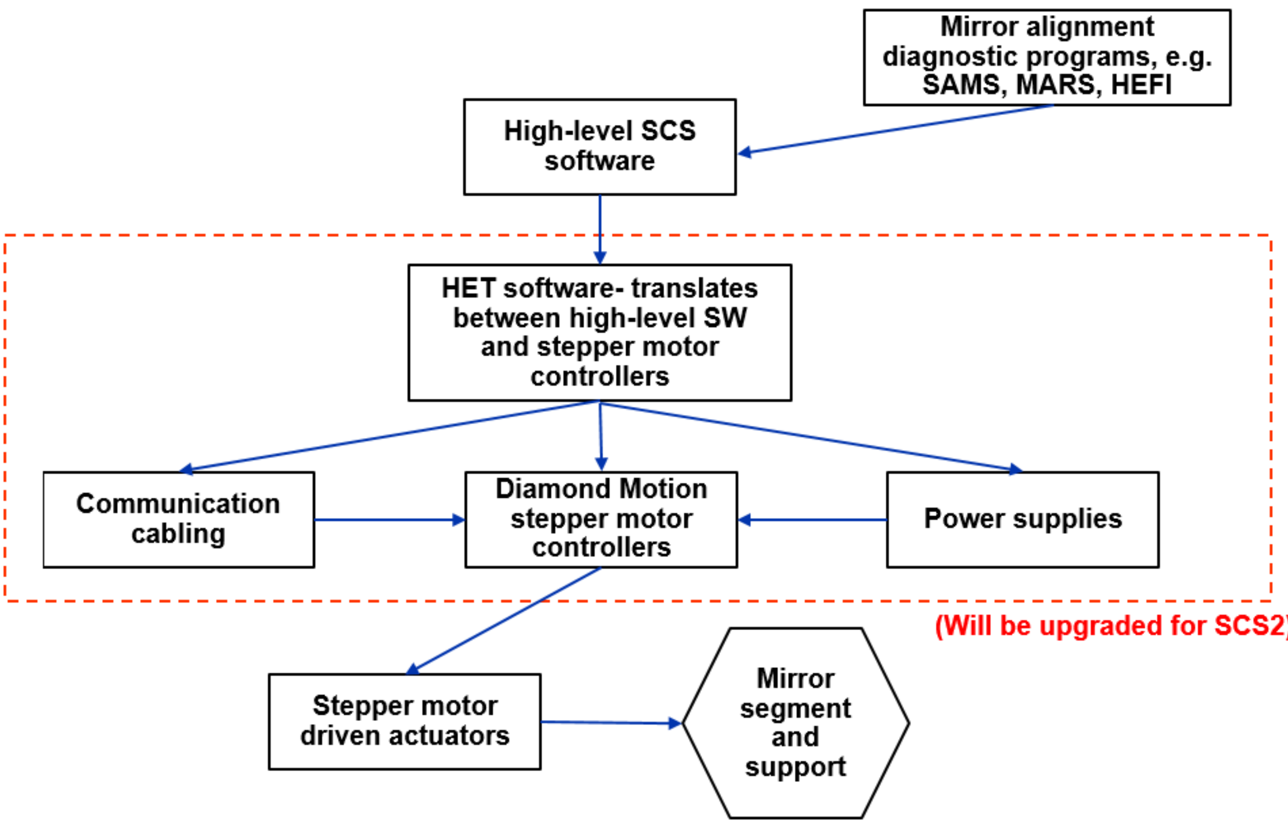

Figure 12. General SCS/SCS2 system diagram.

Project status: SCS2 is a rather young project and officially started in December 2015. While the need for a overhaul of the SCS has been obvious for a longer period of time and other opportunities have been researched in detail in 2015, it became clear that a cooperation of the University observatory Munich, the Max-Planck-Institut for extraterrestrial physics and the University of Texas at Austin with its HET staff is the most promising solution. Buying a complete system from a regular vendor would be extremely costly. A fair comparison between both options included not only the hardware costs but also the cost in terms of man power and a detailed risk analysis. After a quick and intense design phase in early 2016, the project has been externally reviewed by an international committee. Based on the experts' review results and experience, the HET board of directors approved the upgrade in May 2016.

As of May 2016, prototype SMOCO boards are in manufacturing and so far have fulfilled expectations. As already mentioned have most of the electrical circuitry been used for instrumentation at the Mount Wendelstein observatory close to Munich. This can be seen as a proof of concept.

The next big step is the series production of the actual SMOCO boards, once the prototypes pass all functional and quality checks. Subsequently, the manufacturing of the CAVE will be done. Shipping those two parts of the hardware to the HET is scheduled to happen in late 2016.

Integration: Given the fact that the HET staff is busy bringing the HET back into scientific mode, the preparations for the SCS2 upgrade do not have highest priority. Still, running the needed cabling into the mirror truss will be done on low priority from mid till late 2016. We expect to be able to start swapping mirror segments from SCS to SCS2 during the daytime in early 2017. After a short test phase, the entire main mirror segment array will be swapped to SCS2 and the old SCS will be dissembled. By taking these steps, the upgrade will not cause any downtime on the HET itself.

As the individual segments of the mirror are periodically swapped and re-coated, the glass and segment support pairs are moved to different locations in the array. While out of the array, the segment supports are realigned according to their next position, and this alignment is done within the HET mirror lab. Therefore SCS2 will have a small lab-based offspring, only consisting of one SMOCO board. Once the alignment has been reached, the high-level software reads the actuators positions from the mirror lab SMOCO board and assigns the according segment CPU within the CAVE set up with those positions from the mirror lab alignment. Afterwards, the overall mirror shape is fine-tuned by the regular system calibration in the beginning of the night, using the MARS and HEFI diagnostic sub-system.

ACKNOWLEDGMENTS

HET SCS2 is built in a close collaboration of the University of Munich's Observatory (USM), the Max-Planck-Institute for extraterrestrial physics (MPE) and the University of Texas at Austin's HET staff.

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