Trials and limits of automation: Experiences from the Zimmerwald well characterized and fully automated SLR-system

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Abstract. *Requirements for the automation of an SLR system may stem from different applications. In Zimmerwald the main goals are in particular the automation of the routine ILRS observations, the Space Debris observations, the interleaved SLR and optical observations, as well as experimental measurements (e.g. time transfer, multi-static space debris observations, etc.). An overview will be provided on the different components related to automation, including the hardware, the hardware independent and hardware dependent software parts, and safety related issues.*

Different strategies of automation are shown for two of our measurements systems. Firstly for the ZIMLAT legacy SLR system which is by now 20 years old and requires replacement of old hardware and electronics components and porting of software onto new operating systems and computer hardware. Secondly we will present the development of a new measurement system, originally designed for space debris observation, based on completely new hardware (telescope and mount). This system is currently validated and its tracking performance for LEO objects is being optimized and characterized.

Introduction - Hardware Communication Layout

The entire SLR system consists of different aged components of the last two decades. There are several serial devices: microDAC remote IO relays, microLynx motion controllers of optical tables, ModBus based digital and analogue remote IOs, computer terminal based IO of the PC keyboard and monitor (To save space, one will find all corresponding figures in the accompanying presentation [Lauber 2016]). All the well-known serial busses, RS232 etc. are used here. Today, these serial devices are operated through a terminal server IP port. The station computer - the overall controlling PC - acts completely as a TCP/IP server. Finally, all the devices are accessed via the TCP/IP based switch server. There are three special hardware frontends: the telescope PC, the data acquisition PC and the laser PC. Every of these PCs acts as a server for the particular hardware [Gurtner 2006].

In order to maintain operation of these systems in the future, it is important to have less Operating System (OS) dependencies like Graphical User Interfaces (GUI). If a new OS on a new PC runs the old GUI this might not always work because the GUI forces the user to use features of the entire OS. For our devices, usually simple byte protocols like ModBus have been used. These protocols survive long times due to their simplicity. E.g. inefficient systems convert text into a graphics format already at a server and send it to a client. Compared to a system where the text to graphic conversion takes place at the client, the former system needs more data rate on the data channel and has the dependency of the transfer (here graphics) format. The first might be overcome by increasing hardware speed but the second usually breaks portability in the future.

Automated Devices

Currently, there are 165 automated devices on the LAN. Only some are discussed here. The system can be parametrized very well into specific system states for different purposes. For every

SLR system feature, there is at least one device which allows controlling and monitoring the feature [Gurtner 2008].

There are very simple read-only devices like a humidity sensor outputting milli amperes which are converted to voltage in a remote IO device which also samples this voltage into a numerical value which in turn is transmitted on request through a simple bus protocol on a serial interface.

Other types of very simple devices are the read-and-write but digital on/off devices like relays switching the laser shutter to open or close. A lot of components can be switched on and off. E.g. for bi-static experiments [Kirchner 2013], the Fabry-Pérot can be moved out of the receiving path in order to allow passing the slightly different laser wavelength from the other SLR station.

There is less but much more difficult read/write devices like the matching lens drive. Because the telescope tube is not compensated for temperature and gravity effects at all, by design, the matching lens drive has been put into the optical path to compensate for these effects. The matching lens drive moves the lens a micrometer resolution over a full range of many centimetres to the calculated position. The encoder values of the current drive position are read out. This feedback loop is integrated into the system on a hardware close software layer.

In the receiving path before the stop pulse detector, a variable neutral density (VND) filter is also acting as an attenuator of the incoming beam. The voltage given to the stepper motor is written to a device on the serial bus. In a feedback loop, the return rate (ratio of the number of detected hits and outgoing pulses) of the detector is kept at 10%. This feedback loop goes up to the higher software level. So, it is not totally real-time but it is near real-time.

During start-up of the SLR observation program loop, many of these devices are set up and a lot of them are regulated in real time over the satellite pass. In order to operate the system seamlessly, all these devices have to have a very long life time, or should have a long mean time between failure (MTBF), respectively. In case of a hardware failure, it should be easily possible to replace the hardware part by a replacement part. Due to the easiness of the system interfaces concerning both hardware and software slight adaptations should enable the fully functional replacement of an old degenerated hardware part.

Software Maintenance

The current software comprises about 300.000 Fortran77 source code lines. Most of the source code is under revision control. There are two philosophies for system improvement: Upgrading the old system in order to maintain automation, or writing new software which automates new things, e.g. tumbling/Envisat satellite data processing. The design rules are clear: The software should need less effort to be maintained in future. This can be achieved by following clear standards like ANSI, POSIX etc. from Unix-like OSs. In general, such software should be easily expandable. Linux and open software is your friend here.

E.g. due to historical reasons, the user interface is computer terminal based (VT220) [Gurtner 2002]. One can login to the station control PC and use the VT220 frontends. There is dedicated remote screen which shows a lot of information of the running system, e.g. the telescope pointing offsets in arc seconds from the predictions. Using a terminal emulator application on a smartphone (there are many available), one can move the screen into it.

The terminal emulator also allows using hotkeys to remotely control the station (from the smartphone!). E.g. if the system did not yet recognize the clouds at the current telescope position, one can command the system to move to the next satellite by typing the hotkey 'n' into the terminal emulator within the smartphone. Herewith, it had been shown that the SLR system station can be controlled remotely by a wireless smartphone wherever GSM contact is available.

Software Porting
The available source code is "legacy code" and chances that it contains major errors are minor. If the code can be maintained the system stability can be maintained too. The following formulation implements this idea. The old source code has been developed under MS-DOS. For today's development, Linux OS is preferred. Currently, two PCs run DOS and the accompanying executables. The software interfaces are VT220 protocol, TCP/IP network protocol (for the station control PC only one X11 application (pgplot) for residuals), and byte code protocols (e.g. ModBus) network. The main hardware interfaces are Enhanced Parallel Port (EPP) and Industry Standard Architecture (ISA). Additionally, video graphics has been used but only text has been represented. Fortunately, in this case the video graphics hardware adapter can be re-engineered using the Linux ncurses library. For this, a small software wrapper has been written which maps the calls of the libraries. If the terminal runs within an X11 xterm, only 1 byte is transmitted per character.

PC Hardware Maintenance and Porting
The motivation is to have hardware redundancy in case of any hardware malfunction. The ways described here assume that the hardware system design should be maintained and so, no new hardware system capabilities be build up. The result is to replace single components only one by one where possible. Within this development frame, there are again two possibilities: Preserving the OS and "upgrading" the OS. For the first possibility, preserving the OS, there is only one kind of PC hardware maintenance. In this case hard- and software is cloned wherever possible. The telescope PC hardware has been completely cloned, the hard disks have been copied and checked. The data acquisition PC hardware has been almost cloned. In contrast to the telescope PC, the DAQ-PC allows for upgrading the motherboard and the backplane. Due to these hardware differences, the old DOS and the executables will not run under this new motherboard. The station control PC has been set up as a virtual machine. This was possible only because this machine acts as a network server only. When the network adapter was ported to the new hardware environment, everything was running immediately. The laser software has been ported to a new embedded controller PC by copying the files completely onto the new PC which runs a newer MS-Windows. The laser program from the manufacturer runs a proprietary version of LabView, a GUI executable which is OS dependent. The second possibility - especially applied for the DAQ-PC - is "upgrading" the OS from DOS to Linux which means one has to port the software. The most important interfaces to port here are the ISA bus and the memory regions. How this can be done in detail is described in the Linux Device Driver manuals e.g. chapter Communicating with hardware of [Corbet 2005]. For short, the Linux kernel has to be informed about the memory regions which are allowed to be accessed by a running program. The implementation can be done in the kernel or in the user space. The first tests in user space were successful but not everything has been tested yet. Last interesting tests come up now in the real environment. In principle, problems with timing restrictions can arise. But we do not expect them in this case. In order to enable the real environment tests and to be able to switch quickly between the development and the operational system, an electrical adaption using a rebuild printed circuit board has to be setup and checked. For uploading a program to the telescope motion controller unit (PMAC), a firmware program under DOS is required. Because the source code of this firmware program is not yet open, a dos emulator runs this firmware.

Limits of Automation
This section should only describe some examples which can be automated only very hardly. Because the telescope has been designed for dual use [Gurtner 2006], for geodetic (path length

true) and astronomical (image true) use, all alignments have to fit both purposes simultaneously. The telescope is of a Ritchey-Chrétien (RC) design. The main and secondary mirror adjustment is demanding and has been already made years ago on stars and not been touched since then. Some alignments have to fit co-axial and others have to fit eccentrically ([Lauber 2016] on page Limits of Automation, see images Adjustment laser and Beam alignment). Three main cases for alignment exist: For the astronomic use, the cameras on the image de-rotating platform (axis 3) have to receive the images through the optics correctly. For the SLR use, the outgoing laser beam must point correctly to the satellite and the returning photons must focus correctly into the detector. Here, an outgoing laser pulse has to leave the telescope eccentrically on a circle around the mirror 2. An adjustment laser has been placed at different locations within the telescope, the laser focus has been checked on different screens within the optical path, some mirrors have been re-adjusted accordingly and the tertiary mirror has been mechanical re-fixed.
Within the laser, the pulse synthesis has to be optimized for high outgoing energy in one pulse. For this, the fine thread screws of the cavity mirror and the Pockels cell for tilting them have to be turned manually very carefully. The above is operations are difficult to automate.
There are also other tasks one would like to automate which are theoretical possible but are difficult or risky or ineffective in case of rare tasks: Optics cleaning is done on demand or at least on a yearly basis. The high quality mirrors are cleaned manually. On failure, the devices fans, power supplies and batteries are replaced. Re-chargeable batteries are replaced on particular time cycles. The Fabry-Pérot adjustment is carried out on high earth orbit (HEO) satellites during night time using the entire running system including all software loops. The maser drift correction is applied manually by intension, because masers should run free for optimal performance. The applied corrections are derived from a long term time series. The drift control at the maser is applied by turning number hand wheels.

Night Tracking Camera
The development and implementation of the software of [Ploner 2013] continues. The main difference to older developments is the level of precision and the automation. Beside specifications like low noise, the data readout using digital interfaces has to work properly. The exposure is taken well after the laser outgoing pulse when afterglow of the optical components in the system is low enough. A light shade pipe is required just before the camera. In order to suppress photons from the outgoing laser beam reflected in the atmosphere, additional laser light filters have to be installed. Along with the obviously needed filter for main wavelength of the outgoing laser beam (in our case 532 nm), an additional filter in the infrared is needed to suppress spurious photons at primary laser wavelength of 1064 nm. If the laser is off one obtains a Gaussian distribution at minimal ADU (figure IR-Filtering, black line). If the laser is on one obtains a distribution centred at higher ADU (red line). If the laser is on and using this IR filter, the detected photons distribution shifts towards the minimal one if the laser is off (blue line). A communication socket within the main program loop has been already installed. The different software for image acquisition and processing exist already separately. The latter software components have to be put together, so, that they can be driven fully automatically. Because some software is written in different languages, wrappers have to be programmed. Some manual tests on a HEO satellite have been already successfully carried out.

Safety of Low Energy Tracking
In the meantime, there are several satellites having additional safety requirements. For example, the Sentinel-3A has very sensitive sensors and the intensity of the laser beam at the satellite has to be limited. The International Space Station (ISS) is manned and the requirement is eye-safety

for the crew if they use binoculars looking directly into the beam at the ISS. For fully automated systems, the hard requirement is to maintain safety limits all the time. Usually, Zimmerwald fires 10 mJ@100Hz but at 0.4 mJ we also successfully ranged to all LEO and Lageos satellites. In an experiment, it has been shown by [Kirchner 2016], that 15 uJ@2kHz are sufficient to get returns from HEO satellites. One approach here might be that stations should fire only at the very minimum required energy levels.
Currently in the software, all system settings depend on the satellite name only. A second software variable from another data channel like the Go/NoGo-Flag for such satellites should be available.

Implementation for the European Laser Time Transfer (ELT) experiment

In order to allow comparisons between two tracked ISS passages at high precision, the frequency standard quartz has been replaced by a maser. To hit the 100 ns ISS detector gate, the time precision of our GPS-receiver (~100 ns) has to be improved. Two solutions are discussed respectively on the way: Upgrade the GPS-receiver or setting up of a link to the time and frequency laboratory METAS, located at a distance of about 8km (and referenced to a caesium fountain clock).
We checked our system specific implementation to identify problems. Our Riga event timers should have sufficient precision. So, we will proceed with the implementation of hard- and software to participate in the experiment. In our system everything for the LRO one-way laser ranging has been implemented. For ELT: Especially, the laser start epoch must be triggered and calibrated to ~10 ns to UTC which is much more demanding than for LRO. Full rate raw data files for two epochs (start and stop) are not yet supported; for LRO only the start epoch was needed. The micro switches at the divergence optics, a delay generation between the laser amplifier pumping and the pulses, and the ELT Laser Safety Assessment [Schreiber 2015] derived from [Schreiber 2013] are missing. Because of expected system changes, we were not yet able to calibrate our system using the external calibration device and to run the Calibration Test Procedure [Prochazka 2016].

New Systems

The other development philosophy is to develop a system from scratch. The following shows such a new system which has been implemented for space debris observation in the framework of the AIUB-DLR-SMARTnet project [Fiedler 2015]. It will not be used for SLR but from the first time this development has been carried out also under the perspective whether it can be used for SLR too. The motivation was to use the carbon fibre telescope tubes technology which has a higher stiffness, less weight and is much cheaper compared to stainless steel tubes. The equatorial mount was especially optimized for the space debris observations and might not be optimum for SLR.
Because of the new motion controller for the telescope motors, a first version of the software has been written. Only very minor source code has been imported from the old SLR system. To overcome different problems, Cubietruck Single Board Computers (SBCs) were integrated: The used FLI cameras have USB ports and USB cables have length restrictions. The SBCs act as a server which reads out the camera data and changes the physical data transmission from USB to Ethernet. PCs which should be put onto the telescope axis should also be very light weighted. Due to all these aspects, these very low power consuming SBCs have been chosen. Additional advantages are no mechanical parts, no active cooling/fan, no spinning drives (uses only flash/SSD memory) which ensures a low maintenance effort. After successful end-to end system tests, this telescope will be installed in South Africa and will be operated completely remotely.

For SLR, the satellite pointing has been evaluated already: It is at about one arc second precision. Because this development was only implemented for space debris, some needed features for SLR are still missing. There is, e.g., no sun avoidance implemented in software. Also, the timing requirements for SLR are at the one millisecond level which could not yet be achieved by this system. The motion controller does not yet slew to the target taking into account an additional timing constraint. The SLR motion controller used in our old system (PMAC) slews all axes always considering the timing constraint. This new mount currently carries a 20 cm ASA and a 50 cm Planewave telescope. The quality of the images is impressing compared to the one of the 1 meter SLR telescope. Of course for SLR, there are also path length considerations which have not been yet put into practice here. In the meantime, a similar system has been setup by [Kirchner 2016] partially based on this development - especially the one arc second pointing precision. Using this system, an un-calibrated SLR tracking to HEO satellites has been already realized.

Conclusion

There are very different views of automation. Here, we showed some very different perspectives. On the one hand, there is the automation of the legacy systems and what can be done to keep them running. On the other hand, there is the automation of newly designed systems. For the SLR system, also some different types of possibilities to keep such highly automated systems running were shown. In practice, the automation is frequently a combination of these types. As a not yet mentioned constraint, the manpower is usually limited and decides the way automation is put into practice.

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