HYDROSTATIC LEVELLING SYSTEM GOING MOBILE

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Abstract

The LHC Collimator Survey Train has already shown that automated survey measurements in the LHC are technically feasible [1]. Nevertheless many constraints apply when making automated measurements in an accelerator environment. The research of adapted measurements techniques and strategies is an essential part in the development process of a new generation survey train. From the automation point of view, the measurements in the vertical plane are particularly challenging and one solution would be the use of a Hydrostatic Levelling System. They are frequently used in high precision monitoring applications but with a few compromises a mobile and very flexible version can be build. This paper describes the approach, development and tests of a mobile HLS which is able to cope with the constraints and boundary conditions given by the LHC.

INTRODUCTION

Hydrostatic Levelling Systems (HLS) are standard in high precision and long term monitoring applications. Depending on the used system and technology a precision of a few microns can be obtained. This is valid with stable conditions. Stabilized temperature or temperature compensation, controlled atmospheric pressure and vibration decoupling are making such precisions achievable. A mobile application will not fulfil these conditions -or- will loose its advantage of being mobile and flexible. A first prototype of a mobile HLS *(mHLS)* is showing that under the given conditions the precision of the *mHLS* is at least as good as the optical levelling. In addition, such a system is scalable with a minimum effect of the precision. Doubling the measurement distance will not double the errors. This makes a *mHLS* system a serious candidate for automated height measurements in the LHC tunnel.

SYSTEM DESCRIPTION

Different HLS technologies are available with different precisions and all of them have their advantages and drawbacks. Capacitive systems are sensitive to condensation or water on the electrode surfaces, tactile systems to water on the needle and floater based systems to the mechanical manipulation during a mobile use. Therefore the most promising system was an ultrasonic system with the transducer already emerged in water. Such a System was developed at DESY and used for years with good experience feedback [2]. DESY made one of their recent systems available for some tests at CERN.

Sensor Configuration

The ultrasonic system from DESY has a measurement range of ± 10mm which can be extended to a certain limit but taking into account a larger extrapolation from the reference piece. The height difference to be measured between two consecutive LHC magnets can reach up to 250mm, depending on the position in the ring. This is far beyond the range of a possible extension of the Ultrasonic HLS sensors. Therefore the sensors are supported by a vertical translation stage equipped with a high precision linear encoder. The sensors are kept with the initial range which is limiting the extrapolation factor and shifted vertically using the stages. Moreover this allows to position both pots using the theoretical height difference to have almost the same HLS readings which is reducing even more systematic errors. The majority of the height difference is measured with the optical scales and only the last fractions of a mm is measured using the HLS. The system is composed by:

- A vertical translation stage with build in motor controller.
- The composite measurement pot with reference piece and transducer.
- A high precision absolute optical scale.
- The measurement rack with electronics and power supplies.

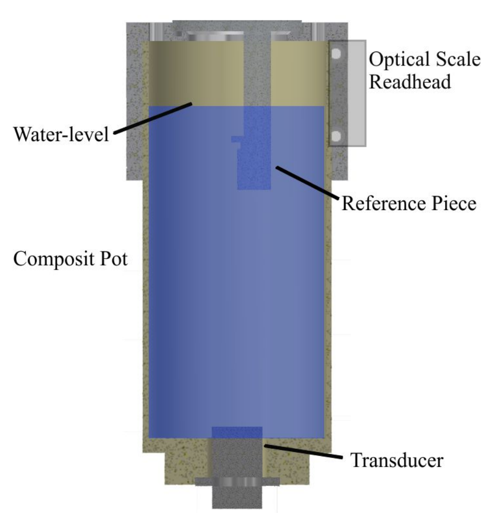

Figure 1: Section of measurement pot.

The translation table is a small and lightweight dovetail table with 250mmrange and build-in motor controller. The communication is based on a RS232 protocol. The controller provides relative positioning data using the stepper controller which is not precise enough to measure the vertical displacements. A Rensihaw RSLA encoder with an absolute optical scale is used to measure the vertical position of the HLS pots. The accuracy is given with ± 1µm/m and the communication is based on the *BiSS*-C Protocol. The scale is glued with a fixed point on the bottom of the sensor support while the read-head is directly attached to the support of the HLS reference piece. The composite pot and the transducer itself can therefore be dismounted without altering the system constants. A measurement is combined by a sensor constant (Hardware related offset of the scale and the lower reference surface of the sensor body) plus the reading of the optical scale plus the HLS reading. In order to avoid useless water movements or water spilling out during the system manipulation, a pinch valve is installed in the centre of the tube. This valve is normally closed and opened only for the measurements.

Figure 2: *mHLS* system on a Quadrupole.

Electronics

The needed electronics are installed in a 19 inch rack on a mobile platform so that it can be towed by the vehicles used in the LHC. The rack is housing:

- The two 12V 110Ah Batteries.
- The 24V mains power supply, UPS and charging circuit.
- The measurement crate with main and rec boards.
- The valve for the control of the water flow.
- The PXI with touch-screen.

The 24V UPS system is giving an autonomy of more than 10h continuous battery operation. The PXI chassis has been especially chosen for 24V operation and the mains power supply of the HLS measurement crate has been replaced by a custom build Version delivering the ±8V and 5V from the 24V UPS system.

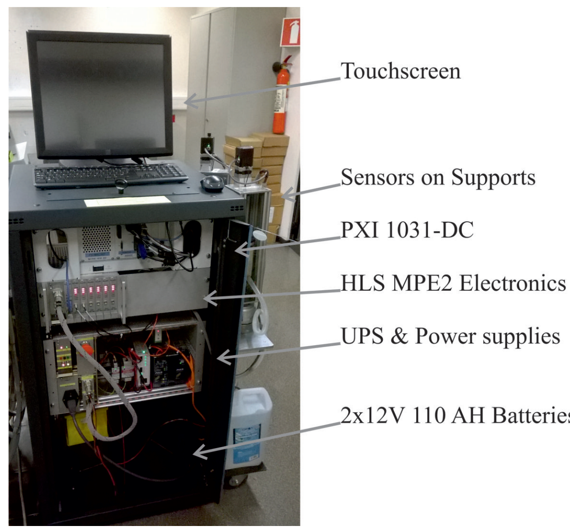

Figure 3: Mobile Measurement Rack.

CONSIDERATIONS

Fully filled, single pipe systems are not often used for geodetic and precise measurement applications due to their considerable drawbacks. Any differential pressure and temperature gradient in the vertical water column will lead to considerable errors on the measurements [2]. A half filled system is not an option for a mobile system as it requires a horizontal pipe installation. A two hose system would be an option to eliminate the differential pressure, but splash-water or condensation in the air tube will make the mobile use very difficult. In a first approach, the prototype is build without air tube and the pressure is balanced through a 2mmhole on the top of the composite pots.

Pressure differences

The difference of atmospheric pressure between the two sensor positions has been measured in the LHC and with the used instruments so far not measurable. The constant airflow of 0.6m/s in the LHC tunnel might however be a problem. First tests have shown

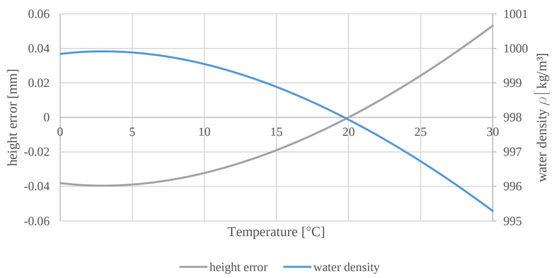

Figure 4: Water density as function of the temperature and corresponding height error for a water column of 50mm.

that the orientation of the sensors with respect to the airflow is changing the readings in the order of 60µm. The figure 5 is showing the sensor readings for different sensor orientations. Detailed measurements of the differential pressure inside the pots still need to be performed.

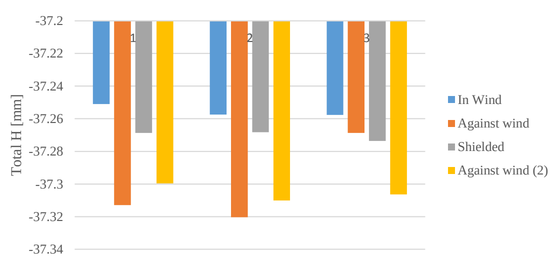

Figure 5: Height error due to sensor orientation.

Water density and temperature effects

The temperature effects must be divided into dilatation effects on the hardware itself like the body of the sensor, the optical scale and the reference piece, but also the density of the used water [3]. The effects on the hardware can -assuming a stable ambient temperature in the tunnel- be neglected in a first approach as they are the same for both sensors. For the ultrasonic measurement itself, the water density drops out of the formula due to the use of the reference piece. But the vertical water column is much bigger than in free water systems. A temperature difference of 5°C induces a height error of 1mm when using 1.2m water column height which is the case for the mobile system. A temperature difference at the pots and along the tube must be avoided or compensated. A temperature difference or gradient of the water column can be reduced by permanently circulating the water within the system. In addition it can be considered that the ambient temperature in the LHC is stable to 2°C along one day and the difference between the measurement position is smaller than 1°C.

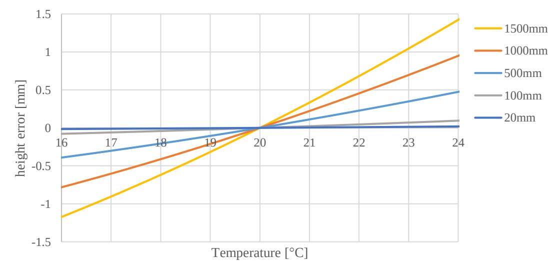

Figure 6: Height error for different water columns

CONTROL APPLICATION

The control application for the system faces several specific challenges. On a first stage, developing the individual drivers for the system main hardware and modules. Afterwards, integrating them under a higher level control under modular philosophy and incorporating data analytics and all types of auxiliary systems into the process flow. In order to better face these requirements, the development of the application was done under LabVIEW, taking full advantage of its core strengths: a rapid application development especially regarding the integration of exotic hardware while still providing high level control and data analytics functionalities. The application is deployed on a PXI chassis (8180) able to accommodate all the required communications protocols, namely USB for the Optical Scale, RS232 for the translation stage stepper motors and TCP/IP for the HLS sensor. This model also integrates a DC power supply model, a requirement for integration into the Survey train and for a mobile application.

Architectural Overview

The development of the application needs to be accomplished in a flexible, modular way, especially regarding the development of a novelty system whose components can easily change in the near future. For this reason, basing the architecture under an Object Oriented Programming (OOP) paradigm, we are able to provide a great deal of agility and flexibility to a rapidly evolving system. Synthetically, every major module represented can be replaced or expanded upon by simple inheritance, without any changes to the whole application infrastructure, granting it a measure of durability in itself. The figure 7 is a representation of the main application modules, complete with a short description of their functionalities.

Communication is carried out between the modules by a queue based message system. By using messages that are classes themselves, as opposed to more statically defined data types, we benefit from the same OOP derived advantages, leading to an agile and flexible communication network. Adding new messages or replacing existing ones is again acted

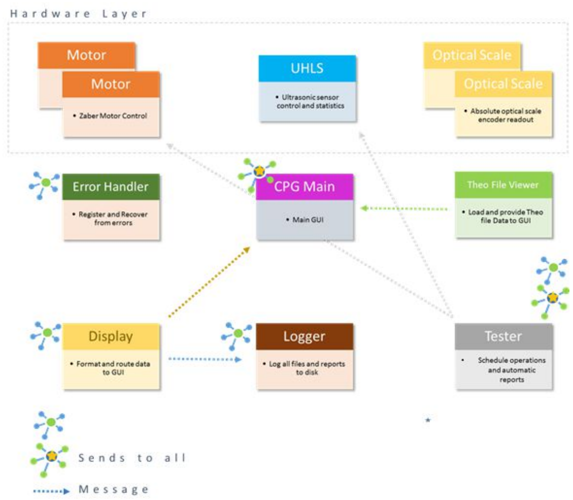

Figure 7: Programm Modules and messaging between them

out by simple inheritance from a parent 'Message' class. Ultimately, this means that messaging – and consequently system functionalities, can be expanded upon more readily and in a completely transparent way to the infrastructure mechanism that actually circulates the message objects. In this case, as the application follows a specific design pattern known as an Actor Framework based architecture, it concretely implements this mechanism via queues.

Using the Actor framework model in LabVIEW also accelerates OOP development by making use of the provided custom scripting. However, due to its very particular and distributed design characteristics, it requires explicit documentation regarding its functionalities. With a certain level of familiarity, one can take full advantage of the power of the framework in having a uniform, coherent and asynchronous messaging system for a dynamically set number of control modules.

Main UI

The root of the application represents the main UI the operator will interact with. It also launches the other modules as asynchronous, independent processes and issues their commands. It is entirely devoid of any processing or execution functionality that would overlap with the hierarchy of the other modules. This command loop also doubles as the display update one, by taking advantage of dynamic user events issued from the Display Module. The GUI was designed to be as intuitive as possible, moving and opening other windows as to better make use of the limited space in the touch-screen utilized by the operator.

Display Module

To outsource the processing of the data that gets displayed to the user away from the module that actually generates the data, the data is routed through

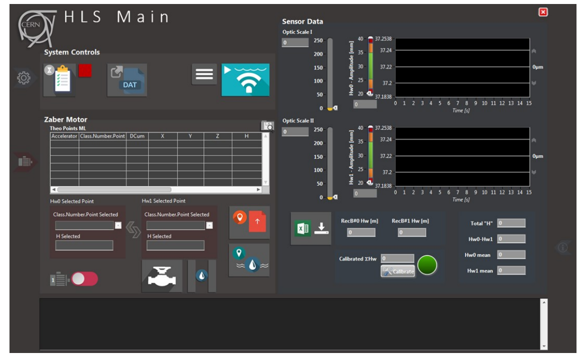

Figure 8: Main User Interface

the Display module for processing before being presented in the Main GUI. Therefore every module can produce its own data, regardless of the type, and send it under a "Display Data" type object queue to the Display Module, who will be in charge of forwarding and processing the data, if needed.

A particular functionality is the routing of data originating from the Optical Scales. Since there is no deterministic way of knowing which of the two actors will be initialized first – seeing as it depends on the USB port they are physically connected to. This makes them obviously vulnerable to eventual swapping. To make the interpretation of their data transparent, a function of the Display module is precisely aimed at switching the two appropriately before presenting it to the rest of the application.

OPERATION

The *mHLS* sensors are mounted on a standard fiducial interface (figure 2) and can be installed on the majority of the magnets and reference points. Both sensors are identical and can take the role of the lower or upper sensor. The rack is positioned roughly in the middle between the two points to be measured and the mHLS sensors are installed on the fiducials. The operator selects the corresponding fiducials from the Database using the interface and starts the measurements process. The pots are automatically moved to the theoretical height difference between the fiducials. The water valve is opened and the first measurement is initiated to control the communication between the sensors. A set of 20 individual acquisitions is done and if an inverse correlation of the measurements can be detected the test is validated and a water stabilisation message is given to the operator. The stabilisation of the system takes a maximum of 40 seconds and is followed by three measurements with 20 acquisitions each. For detailed tests, one sensor is then moved by 1mm and the measurements are repeated. The Operator can see and assess the curve and the associated statistics. An automatic statistical treatment is helping to validate the measurements.

Once approved, the valve is closed, the sensors are swapped, the motors adjust again the height difference and the second configuration is measured.
One sensor stays and the second one is put on the rack and moved forward to the next fiducial. This is changing the first orientation of the system at every measurement which helps reducing systematic errors further once the measurements will be done in one orientation only. For evaluation and test reasons the system is still semi-automatic. The measurement and validation process will be fully automated in the future and the operator will only be notified of the results and in case of problems.

TESTS

A series of laboratory tests have been made in order to validate the setup in terms of stability and precision. Stabilisation time, temperature influence and also the handling of the system were parts of the tests. The only test able to demonstrate if this system is really practicable for measurements in accelerators is the real use in the LHC. The winter shut-down 2015/2016 was used to make detailed levelling measurements of the sector 7-8 in the LHC along with the first tests of the *mHLS* system.

Labtests

The sensors have been installed in a network together with 3 Fogale Capacitive HLS sensors in the geodetic base laboratory at CERN. The tests conducted by Xiaoye He have shown a very good performance of the *mHLS* system [4]. We can conclude that the resolution is below 1μm and they agree within 5μm with the Fogale HLS sensors. The different mobile platform has therefore no influence on the performance of the sensors under stable conditions of a laboratory.

LHC Tests

The tests in the LHC have been made in order to address two different aspects. The first is the control of the system performance of the *mHLS* system under real conditions. The real tunnel environment with all accelerator components as well as real temperature and ventilation conditions. The second aspect is the handling of the system. The test should show if it is practicable, how much time a measurement campaign will take, the lifetime of the cables and components and also the installation in the rack which is towed by a tractor along the tunnel.

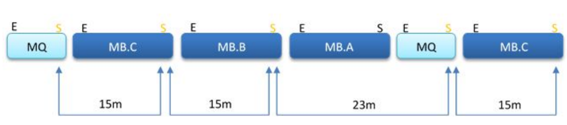

Figure 9: Measurement Sequence

The Tests have been made in the sector 7-8 of the LHC and at the same time as the standard optical levelling campaign in order to have recent data for comparisons. The measurement sequence is shown in figure 9 and was adapted to be coherent with the optical levelling measurements. The measurement systems have been switched on each point so that problems could be detected immediately. Each height difference was measured three times with 20 individual acquisitions in both configurations thus giving enough redundancy to evaluate the system. A number of verifications are done on the raw-data in order to control the measurements.

- The water communication of the pots is always checked before a measurement.
- A still stabilizing water column is identified using the correlation coefficient between the two sensors.
- A measurement is validated only if not more than 2 acquisitions are identified as blunders.
- The total amount of water needs to be constant.
- The three subsequent measurements must be in sufficient agreement.

The first value from interest is the zero offset of the system which has been determined with 1.18mm in the laboratory prior to the measurements. During the measurements the Zero offset was also 1.18mm but with a RMS of 44μm as shown in figure 10. There is no trend or drift visible so far but it is looking like a systematic and periodic influence. All measurements are done 3 times and the average is retained as final value. The RMS of the repeated acquisitions is in general well below 5μm with a few values reaching up to 10μm.

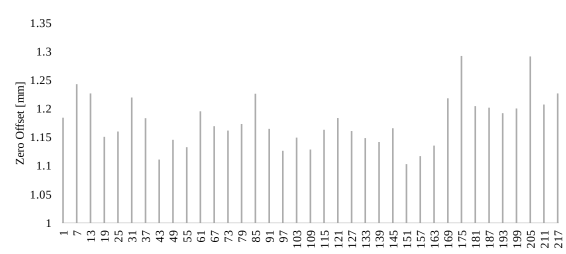

Figure 10: Variation of Zero Offset

The calculation of the levelling as a whole using the LGC software is showing a well centered and gaussian distribution of the residuals with an RMS of 41μm.

The determined height differences can now be compared with the ones determined by the optical levelling using a LEICA NA2. The figure 11 is showing the double differences along with the measured height differences. One can not see any influence of the actual height difference but the double differences are shifted by -60µm. Separating now the differences for the NA2 outward and return measurements is showing that the outward measurements are shifted by -90µm and the return measurements by -40µm. It was already suspected earlier that the direct levelling measurement are affected by a systematic error due to the tunnel ventilation and detailed tests are ongoing. With the present tests and data it is unclear if the *mHLS* is more or less affected than the optical levelling. But the direction of the differences and their magnitude are very promising for a potential correction.

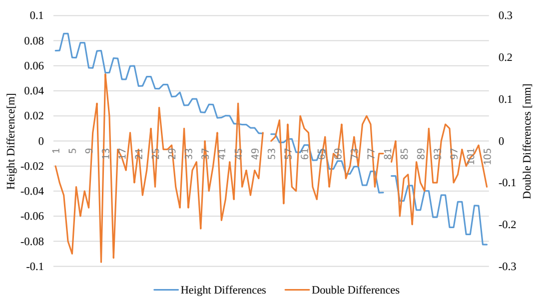

Figure 11: Double Differences and Height Differences

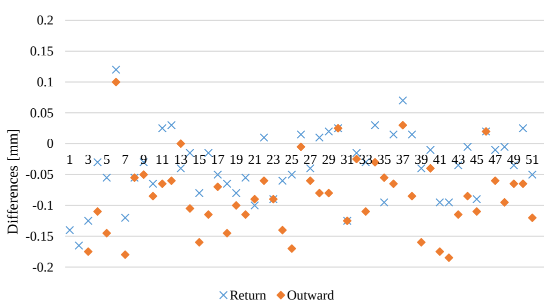

Figure 12: Differences between outward and return measurements compared with *mHLS*

CONCLUSION

The laboratory Tests have shown that the system in behaving as known from the previous tests and experience by DESY [2]. Even when used as single tube and open system with a 1.2m high water column. The use of the single silicon tube with 10mm inner diameter is attenuating the water movements and a stable state is reached in less than 40 seconds. The real conditions in the LHC tunnel have shown a non random variation of the zero offset which is most probably be linked to the pressure differences in the pots due to the ventilation or residual temperature effects. Further laboratory tests will clarify this.
The comparison with the optical levelling has shown that there is a difference between the outward and return measurements of the optical levelling campaign which was already suspected before. More measurements in different conditions and configurations will be needed to confirm this effect.

OUTLOOK

No show stoppers have been found so far and the development will continue with an improved prototype version. Points of improvements are the cables and tube protection. A further automation of the measurement and control process. Some detailed tests will be made on the differential pressure inside the pots due to the airflow in the tunnel. And the source of the systematic zero offset variation must be confirmed and mitigated. The integration of a combined gyro and accelerometer module MPU-6050 has already started and will allow the automated manipulation and verticalisation of the system using a robot. In parallel first tests are running covering the possible integration of this system on a train.

ACKNOWLEDGMENT

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