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Fully automatic mass laboratory from 1 mg up to 50 kg – Robots perform high precision mass determination

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Abstract:

In order to meet the requirements for a state-of-the-art metrology institute and in an endeavour to build a fully automatic mass laboratory, the Austrian Federal Office of Metrology and Surveying (BEV) has developed and realized in cooperation with Sartorius AG in Goettingen and the Vienna University of Technology three different handling systems for automatic testing weights on high-precision mass comparators.

Fully automatic System for alternating weights on mass comparators with different weighing capacity have been realized; one from 1 mg up to 10 g, one from 10 g up to 1 kg an the third one from 1kg up to 20 (50) kg using two comparators. The resulting load alternator "robot" holds between ten and eighty test weights and a corresponding number of reference Standard weights. All weights are transported without pallets. The Systems are based on Computer control and linear drive trains, and are used at the BEV to disseminate mass and for the calibration and verification of weights.

Keywords: mass laboratory, automatic system

Initial situation

In 2003, the BEV had a rather unsatisfactorily situation about available equipment in the mass laboratory. There was a new CC1000S-L comparator from Sartorius with a 4-weight load alternator (resolution 1 µg) for the dissemination of mass in the range from 100 g up to 1 kg. For the lower range of the mass scale the BEV have had one aging 4g mass comparator scale (resolution 0.1 µg), one traditional 100g mass comparator (resolution 1 µg) and a standard 100 g balance for the dissemination of mass and for calibrating and adjusting small weights up to 100g. For the range above 1 kg there was only a C10000S mass comparator (resolution 10 µg) with a 2-weight load alternator and a conventional 30-kg mass comparator for comparing 20-kg weights (resolution 10 mg) available. With the exception of the mass comparators including the changer all weights were positioned manually.

Fig. 1: Three handling systems implemented at the BEV: left: Handling system for micro weights and below: The handling system for medium weights at the BEV. On the right: The handling system up to 20 kg

In order to meet the appropriate standards for a National Metrology Institute respectively to meet the requirements for a state-of-the-art mass laboratory, it was necessary to build up new equipment. When considering the requirements for the dissemination of mass and the expected number of weight calibrations to be handled, traditional mass comparators did not appear to be sufficient for the job. Moreover to be able to offer high precision mass determination it was self-evident to build up automatic systems. Due the circumstances that for the intended requirement of the BEV there have not been really fitting handling systems on the market there was the decision to built up a own system

Introduction

The objective of the BEV was to develop and realize handling systems for loading and alternating weights on high-precision mass comparators. The overall process includes retrieving weights of 1 mg up to 20 kg from a repository unit, determining the load's center of gravity for correct positioning, and placing loads on the mass comparator in sequence. Each completed measurement routine encompasses a comparison of test weights to reference standard weights. The systems have to suffice all requirements, in view of the strict demands placed on the dissemination of mass standards and the number of weight calibrations expected to be performed at the BEV

Building on years of excellent cooperation, the BEV and the Institute of Production Engineering (IFT) of the Vienna University of Technology, together with Sartorius AG in Goettingen, have realized these three projects.

In the range from 1 mg up to 10 g a robot performs high-precision mass determination on weights

A development of the BEV realize a handling system to supply a new high precision mass comparator with weights. Weights from 1 mg to 10 g are retrieved from a magazine and then placed on the mass comparator. Each completed measurement routine comprises a comparison of test weights to reference weights.

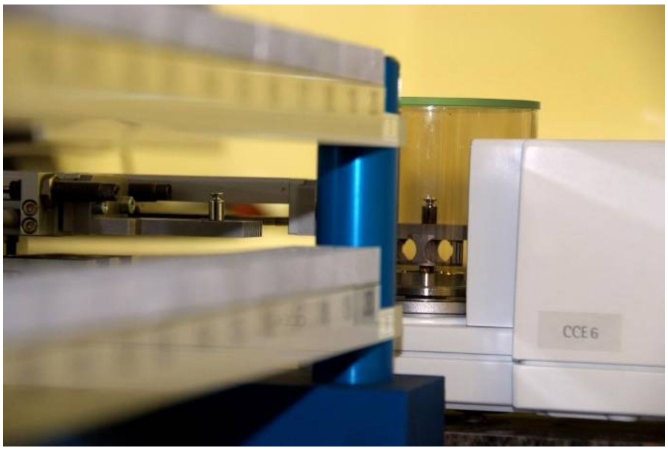

Fig. 2: The three main parts of the handling system for micro weights: The magazine in the foreground, weight carrier on the left and the balance on the right

Specifications and objective

The objective, was to design and build an automatic handling system for weights with a mass of between 1 mg and 10 g. The specification included the use of weights in the form of both wires and flat polygonal sheets and without a weight transportation unit. The load alternator should guarantee the application of several weights at once (groups of weights on loading), namely for the dissemination of mass up to 10 g but also for calibrating special weights. In doing so it would be necessary to place at least four complete sets of weights of up to 10 g in the alternator magazine. Control should take place via an external control unit and should allow any desired programmable alternation of all weights in the magazine. The control programme should contain at least one standard programme for fully automatic calibration (comparison of weights) in accordance with the relevant operating instructions. After introducing the weights into the magazine they should be assigned to their positions by means of software. The placing of the weights on to the mass comparator, the mass comparison and the return of the weights to the magazine should take place automatically. The weights would thus be picked up directly (without weight transportation units).

Also this system should have several suitable control and monitoring devices to prevent double loading of magazine slots or the scale in addition to other types of damage and errors. Furthermore, the handling system should be designed in such a way as to exclude the possibility of compromising the measurement.

The handling system should also be designed to be suitable for operating with a variety of mass comparators.

Concept

The handling system has an adjustable axis that moves the transport unit horizontally. With a concept differing a little bit to that of the big robot this small one should have only two weight carrier units on the loading station (loading station) extended and retracted pneumatically. The reason for this is the greater number of standards weights; these weights are also storaged in the magazine.

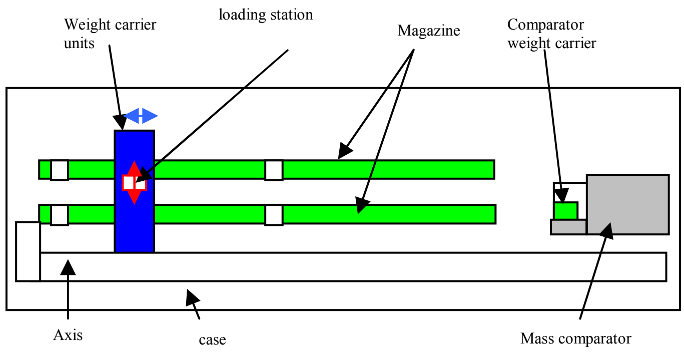

Fig. 3: The basic concept

The loading station is designed in such a way that the two weight carrier units can be extended separately and raised simultaneously. The vertical movement of the weight carriers is carried out pneumatically. The complete control of the system is based on a personal computer solution and takes place via digital inputs and outputs. The linear axis has a servo drive. The dimensions of the complete handling system were restricted to a maximum of 2000 mm x 800 mm x 800 mm thus making the handling system suitable to fit on a conventional weighing table.

Method of operation

The weights – 1mg to 10g – or groups of weights are introduced by hand into the correct magazine slot and the weight data is entered into the control PC. The same procedure is also follows for the reference weights.

The comparison measurement now takes place, whereby the loading station retrieves one weight and one reference weight from the magazine and places these alternately on the scale. This comparison measurement can now be repeated as often as necessary and in any desired sequence. When the measurement routine has been completed the loading station places the tested weight and the reference weight back into their corresponding slots in the magazine.

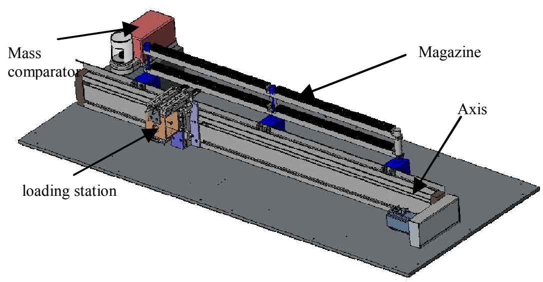

Fig. 4: Design overview

System design

The system was designed on a linear basis due to the positive experience gained from the previous system and easy, universal manageability - but also for production cost reasons. This makes it possible to use a controlled axis e.g. by a servo drive. All other movements are pneumatically driven. The magazine capacity has been designed at 80 slots on two levels, which may be loaded with reference weights and test weights as desired.

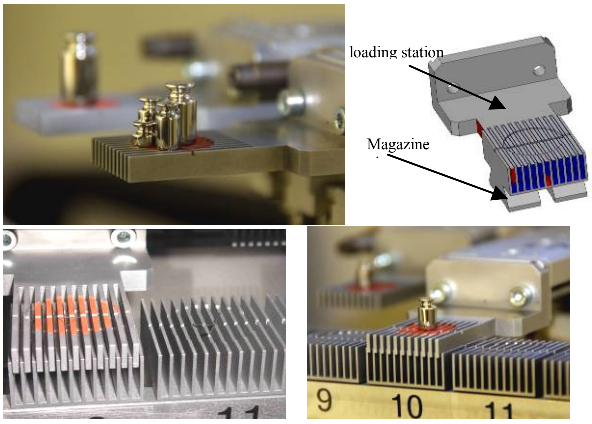

Fig. 5: Weight carrier – design and reality (carrying a group of weights (10 g), a 1 mg and 2 mg wire weights and a 5 g weight)(from the left).

The heart of the system is the pneumatically actuated loading station which can be driven easily to four vertical and two by two horizontal positions. A comb-type grabber system was installed in order to meet the design requirement that weights should always be picked up without the aid of a transportation unit. However, in order to be able to use 1 mg weights, the required tolerances between magazine and finger grabber are extremely tight. This means that the grabber must be able to position itself at any point with an accuracy of better than 0.05 mm. This is guaranteed by means of a servo-driven precision spindle along the entire movement path of 1800 mm.

The pneumatic drive provides “total” positionability due to the mechanical end stop at both end positions and the absence of interference from electromagnetic fields. By contrast, the use of electrical actuators to realise the lifting movements would only be possible at higher cost and greater complexity. The system is controlled by a personal computer which communicates with the DC-servo controller via Profibus-DP. This is a very safe, proven industrial solution.

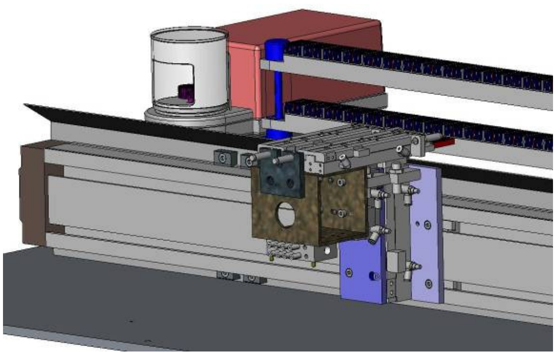

Fig. 6: Loading station with pneumatic drive.

The whole system stands on a granite plate, while the comparator itself is mounted on an additional granite slab. In order to prevent disturbing environmental effects, the comparator has a wind shield which closes during measurement. In addition, the whole system is housed in a protective enclosure which is detached from the measurement unit. Both the control and power electronics were placed outside the enclosure in order to keep the effects of thermically induced currents to a minimum. The whole system is constructed mainly from non-magnetic and/or antistatic materials to prevent disturbances from magnetic fields.

The mass comparator which is used in the System is a modified Sartorius CCE6 mass comparator to 10 g maximum load which has a resolution of 0.1 µg. This was specially adapted by Sartorius for use in handling systems. In addition the weighing pan for weights was completely redesigned.

Fig. 7: Direct comparison of two sets of weights, on the right the pneumatic drive can bee seen

Test procedure

The weights are placed in the magazine slots. The identification number, nominal value and type of the weight (test or reference weight) are then entered into the software on the control PC and the corresponding magazine slot is allocated.

Preparation for measurement takes place by entering the preselected test routine, selecting the weights or entire magazine bank and the number of repeat measurements. After confirmation the handling system automatically retrieves the individual weights from the magazine and the measurement is processed. All weights are prepared at the same time. The coordination of the weights of different nominal values and the substitution weights internal to the mass comparator – as well as the measurements themselves – take place automatically. On completion of the test routine the weights are removed from the magazine slots and the corresponding data are deleted from the database. Reference weights can remain in the magazine.

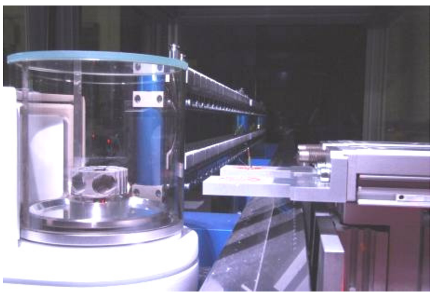

Fig. 8: The CCE 6 *weight carrier*

Due to continuous logging of all programme steps and movements it is possible to request the position of a weight at any time – even in the event of a complete system crash.

The recording of the ambient parameters for the determination of air density is automatically documented for each weight measurement. The documentation relating to the measurements and the calibration certificate of the measured weight are printed out as the result.

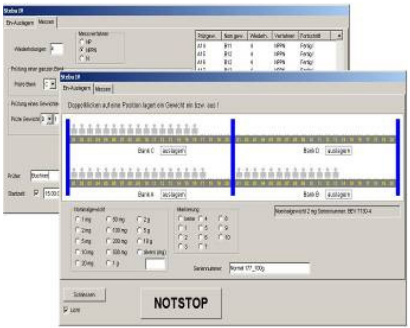

Fig. 9: Input form for weights of the software.

Measurement results

In order to validate the system, starting in Summer 2006 onwards measurement sequences were carried out using already calibrated BEV weights. The BEV also conducted internal comparison measurements using alternative procedures for mass determination. Previously a special calibration of the mass comparator and the development of the test software were necessary. After placing the weights in position, measurements were taken at intervals of 500 ms and with a series of measurement results of environment parameters documented.

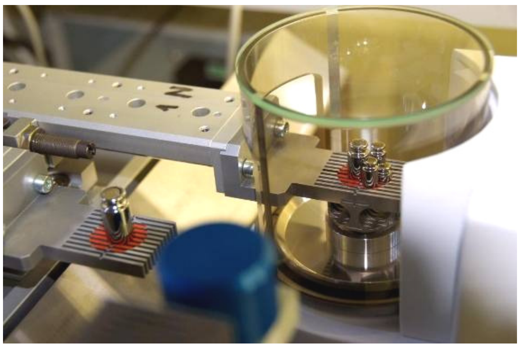

Fig. 10: Direct comparison of two weights or with a group of weights.

Messung vom		23.12.2006	17:29:27										
Prüfer:	Buchner												
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Korrekturfaktoren:													
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17:32:18	P	-0,02681	0,00003	22,89	45,49	1,013	Startindex=6	-0,02688	-0,0268	-0,0268	-0,0268	-0,0268	-0,0268
17:34:02	P	-0,02973	0,00021	22,89	45,49	1,0131	Startindex=6	-0,03002	-0,0299	-0,0298	-0,02968	-0,02957	-0,02938
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18:10:33	N	-0,00231	0,00002	22,89	45,54	1,0132	Startindex=6	-0,0023	-0,0023	-0,0023	-0,0023	-0,0023	-0,00235

Fig. 11: example: typical result of a 10 g weight: one ABBA sequence

The measurements recorded are averaged into “measurement blocks” and taken for further analysis. For the purpose of evaluation of the mass comparator, several measurements are carried out on E1 and E2 sets of weights and evaluated in measurement cycles of 10 ABBA or RTTR (Reference - Test - Test – Reference, i.e. the sequence in which the weights are alternately weighed). This includes comparison with weights with a nominal value from 1 mg to 10 g. The standard deviations of the average values obtained were less than 0.2 µg for the weights used. The repeatability of the average values of the measurement results was for the measurement cycles less than 0.1 µg for the smaller weights and less than 0.2 µg for the larger weights.

The system was installed at BEV in Autumn 2006 for the dissemination of mass in the range up to 10 g as well as for internal and external calibrations and verifications of weights.

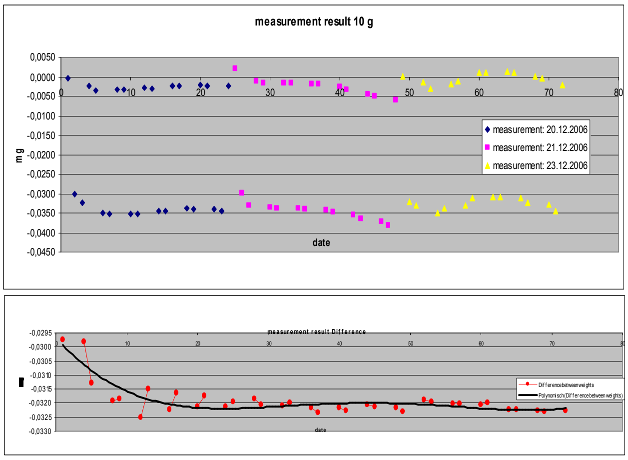

Fig. 12: example: typical result of a 10 g weight tree ABBA sequences over tree days. The repeatability is better than 0,2 µg; the thermostatisising process on the beginning can be seen

The second robot performs high-precision mass determination on weights in the range from 10 g up to 1 kg

The last target in the area of mass measurement was to fill the gap, in the most accuracy range of the mass scale between 10 g and 1 kg. Therefore the BEV has developed a further handling system to supply a high precision 1 kg mass comparator with weights. Weights from 10 g to 1 kg are retrieved from a magazine and then placed on the mass comparator. Like at the other systems a measurement routine is completed, when a comparison of test weights to reference weights have been carried out.

Fig. 13: The three main parts of the handling system: The magazine, weight carrier in the middle and the balance in the background on the right

Specifications, objective and Concept

The aim was to design and build an automatic handling system for weights on equal terms as the handling system for the micro weights i.e. the mass of between 1 mg and 10 g. The load alternator should guarantee the application of several weights at once (groups of weights on loading), namely for the dissemination of mass up to 1 kg but also for calibrating special weights. The number of alternator magazine places should be in the size of at least four complete sets of weights from 10g up to 1 kg. Due to the excellent experience with the performance of the other facilities the same control mechanism and procedure also the program should be used. Also this system should have the suitable control and monitoring devices to prevent double loading of magazine slots or the scale in addition to other types of damage and errors. Furthermore, the handling system should be designed in such a way as to exclude the possibility of compromising the measurement.

The concept for the realisation is the same as the system for the micro weights. There are only two significant differences: on one hand due the size of the weights there are only 40 magazine places and on the other hand the weights are placed below the mass comparator wile they are measured.

Fig. 14: The weight carrier puts 500 g from the magazine

Method of operation

All test weights and reference weights from 10 g to 1 kg or groups of weights are introduced by hand into the correct magazine slot and the weight data is entered into the control PC. For pre- centering the weights in the magazine, a stencil is used for bringing in the weights. The comparison measurement procedure and the calculation is the same as it is used at the other system.

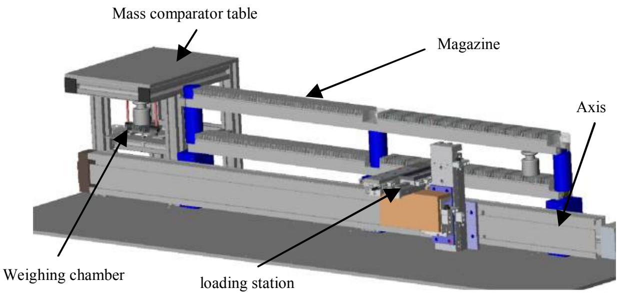

Fig. 15: Design overview; view from the back

System design and Test procedure

Due to the positive experience gained from the previous system the system was designed on the same linear basis that is easy, universal and well manageable. All other movements are also pneumatically driven. The magazine capacity was designated at 40 slots on two levels, which may be loaded with reference weights and test weights as desired.

Fig. 16: forty magazine places with the pneumatic lift and the weight carrier putting up a weight.

The pneumatically actuated loading station can be driven to four vertical and two by two horizontal positions. A comb-type grabber system was installed in order to meet the design The system is controlled by a personal computer which communicates with the DC-servo controller via Profibus-DP. This is a very safe, proven industrial solution.

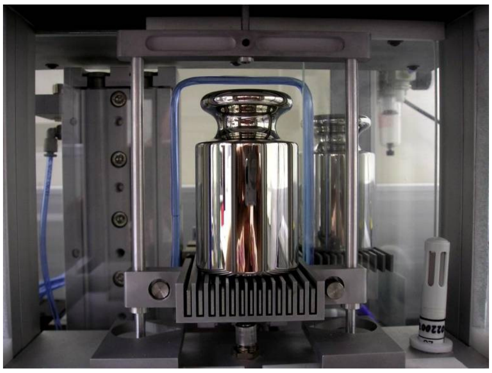

Fig. 17: The CC 1000S-L weight carrier with a 1000 g weight in the weighing chamber; below the weight holder a “brake” to avoid pendulation can be seen.

The whole system is placed on a granite plate, while the comparator itself is mounted on a table. For the weights a position below the mass comparator was chosen. This eliminates off-center loading problems on the weigh cell. The measurement unit used is a modified Sartorius CC1000S-L mass comparator which has a resolution of 1 µg at a maximum load of 1 kg. The cell was specially adapted by Sartorius for use in this handling system and to fix the below weight holder. The specially developed comb-type grabber system makes it possible to insert the 10 g to 1 kg weights with no rearrangement required, and to position them precisely in the suspension device of the mass comparator.

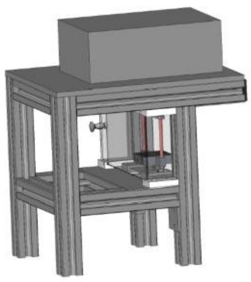

Fig. 18: right: CAD model: Mass comparator table with the below weighing chamber.

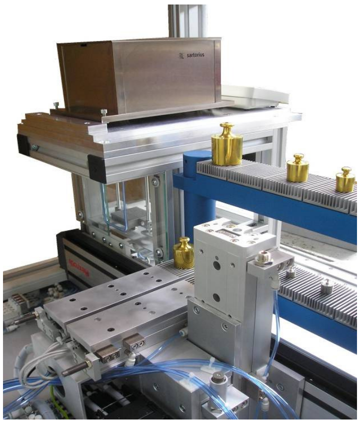

Fig. 19: Foreground: Loading station; Mass comparator table with the below weighing chamber in the background.

During handing over the weights and when the loading station is moving the hole suspension device of the mass comparator is fixed. So only a very small gap is allowed between the fingers of the comb-type grabber and the weight holder of the comparator. During the measurement the fixation is unfastened.
To prevent disturbing environmental effects, the weighing chamber has a class box - wind shield which closes during measurement. In addition, the whole system is housed in a protective enclosure, which is detached from the measurement unit. Like the others the whole system is constructed mainly from non-magnetic and/or antistatic materials to prevent disturbances from magnetic fields.

Building on the excellent experience the same evaluation logic and the same calculation procedure is used as in the smaller system.

Measurement results

In order to validate the system, at the present, furter measurement sequences are carried out using already calibrated BEV weights. The BEV also conducts internal comparison measurements using alternative procedures for mass determination.

For the purpose of evaluation the system, several measurements are carried out on E1 and E2 sets of weights and evaluated in measurement cycles of 10 ABBA. This includes comparisons with weights with a nominal value from 10 g to 1 kg. The first results bring excellent standard deviations and also the repeatabilities of the measurement results are remarkably.

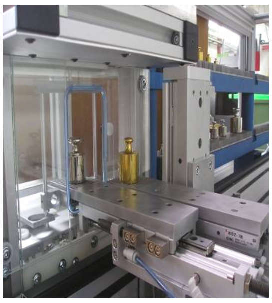

Fig. 20: Direct comparison of two 500 g weights (view from the back).

Fig. 21: Direct comparison of a 500 g weight with a group.

The system was installed at the BEV in March 2007 just like the others for the dissemination of mass in the range up to 1 kg as well for internal as for external calibrations and verifications of weights.

The third Robot performs high-precision mass determination on weights in the range from 1 kg up to 20 kg

Requirements and objectives

The objective was to design and manufacture an automatic load alternator (the "handling system" referred to in this report) for weights of up to 20 kg, for use with both bar weights and cylindrical knob weights. The handling system would have be capable of working with 20 kg consisting sets of 10-kg, 5 kg or smaller weights, as well as with 10 kg and 5 kg consisting sets of smaller weights. A further requirement was that the system hold up to 10 test weights and 2 reference standard weights in a changer magazine.

Fig. 22: The three main parts of the handling system: The magazine in the background on the right, weight carrier on the left and in the middle the balance

Furthermore, the handling system had to be designed to enable any type of mass comparator to be used and several different ones to be operated at a time and so it must be possible to enlarge the possible weighing range up to 50 kg .

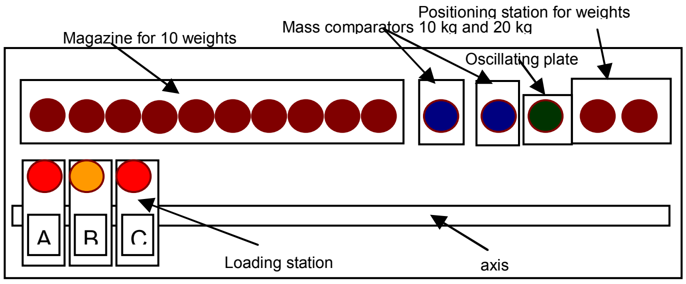

Fig. 23: Basic concept

The system should have an external control unit with options for user-definable programming of comparison routines for all weights in the magazine. The control program should also need to have at least one standard program for fully automatic calibration of weights (comparison of weights) in accordance with the applicable standard operating instructions, and a fully automatic system for inserting and centering the required weights. In other words, the weights should be placed on an insertion device, assigned a position in the changer magazine, automatically centered, and then inserted into the magazine. The placement of the weights on the mass comparator, the comparison, and the return of the weights to the magazine would also have to be fully automatic, and the weights should be lifted directly, without the aid of pallets.

The handling system should need a number of control and monitoring systems to prevent potentially damaging errors, such as double-loading of a magazine slot or of a mass comparator. The design of the handling system should have to rule out interference with the measuring process.

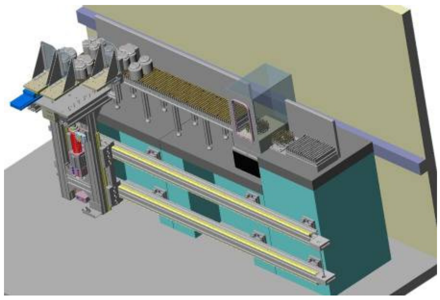

Fig. 24: CAD design overview

Design

The handling system has a positionable axis that moves the transport unit longitudinally. The loading station on the transport unit are extended and retracted by pneumatics. The transport unit is designed in such a way that the three receptacles – A, B and C – can be extended separately and raised simultaneously. As an added safety feature, a spring is provided for lifting the receptacles; weights are lowered pneumatically against the spring force. The system is designed for computer control, and the linear drive train has a motion controller with point-memory for precision control.

Fig. 25: Load platform with axes

Function

At the time weights of 20 kg max. are introduced into the system via the repository unit on the platform, and data concerning the weights are entered on the computer. The handling system retrieves a specified weight and places it on an oscillating plate to center the load. The weight is lifted and lowered repeatedly to adjust its center of gravity to a predefined position, after which the weight is inserted in the assigned magazine slot.

This preparatory weight positioning procedure is repeated until all of the required weights are in the magazine. A similar procedure is follows when positioning the reference standard weights, with the exception that these are placed on loading station A and C rather than in the magazine. The comparison sequence is as follows: loading station B retrieves a weight from the magazine, and this weight is compared to that on receptacle A or C by alternating the loads on the mass comparator in accordance with the appropriate measurement procedure (e.g., A-B-B-A). This comparison can be repeated, placing the weights on the mass comparator in any order, as often as desired. At the end of the measurement routine, the transport unit returns the test weight to the repository unit and retrieves the next weight to be tested.

Implementation

The mass comparator, the magazines and the repository unit are mounted on a granite slab with concrete pylons; the guides are installed on the front of the pylons. The axes are aligned with the load platform using adjustment plates. A stepper motor moves the longitudinal axis, and an error detection function has been integrated to ensure the highest possible safety of operation. The mechanical drive of the horizontal axis is operated by toothed belts using a gantry design. This drive has a brake that is set automatically when the drive comes to a halt, so the voltage can be switched off to prevent vibration or electrical interference during measurement.

The transport unit consists of a load platform that has a travel distance of about 50 mm. For optimum safety, upward movement is implemented using a spring; in the event of a failure in the pneumatics, the platform moves to the uppermost position. The platform is lowered pneumatically against the force of the spring. There are three positions on the platform; i.e., the loading station, from which weights can be transported off the platform. These receptacles are equipped with precision guides and are pneumatically driven. The control system runs on a commercially available personal computer (PC) that addresses the load alternator hardware over an I/O card. The predefined motion sequences and constant optical monitoring of the entire system ensure that weights cannot collide.

Fig. 26: measuring the test weight on the below weighing system. On the right there is the precentering plate.

To eliminate negative ambient influences, the mass comparator has a protective enclosure that shuts automatically as soon as a weight is positioned for measurement. Additionally, the load alternator system is encased in a barrier housing that is not in contact with the measuring device. Both, the control unit and the power electronics are installed outside the equipment housing to keep the effects of thermically induced currents to a minimum. Additionally, the system is made for the most part from non-magnetic and/or antistatic materials to preclude magnetic disturbances.

The measuring instrument are a Sartorius CC20000S-L (resolution 100 µg) and a Sartorius CC10000U-L mass comparator (resolution 10 µg) both specially adapted for this purpose by the manufacturer. Both mass comparators have been rebuilt for a weighing position below the mass comparator

Fig. 27: the below weighing system of the CC20000S-L; below the weight holder a “liquid brake” to avoid pendulation can be seen.

This eliminates off-center loading problems on the weigh cell. The specially developed load alternator makes it possible to insert the 1kg to 20kg weights with no rearrangement required, and to position them precisely in the suspension device of the mass comparator.

The system can be adapted to special ambient conditions and metrological requirements at any time. Several mass comparators can be used simultaneously with this system, which permits testing of a wide range of weights. Experiments have shown that weights from 1 kg to 50 kg can be transported by this conveyor. Since 2004 the handling system have worked with the CC20000S-L for 10 kg and 20 kg weights. At present, the BEV install a the second comparator in the system for the range from 1 kg to 10 kg.

Test sequence

Weights are stored on a positioning device in the repository unit. The identification number, nominal mass value and type of weight (i.e., test or reference standard weight) are entered in the controller PC. Once the input is confirmed, the weights are centered and inserted in the magazine.

Preparation for measurement includes entering the selected test routine, choosing the tests weights and defining the number of measurement repetitions. Once this input has been confirmed, the weights are centered and positioned automatically by the handling system and the measurements performed in sequence. The preparatory steps can be carried out for all test weights at one time. Coordination of weights with different nominal mass values and the two mass comparators and also the mass comparator’s internal substitution weight is automatic, as are the measurements. Once tested, weights are moved to the repository unit; a number of safety mechanisms have been integrated to make sure one weight is not mistaken for another. The result of each measurement series is a calibration certificate that is issued for the weight tested.

Fig. 28: Routine testing: measuring a 20-kg bar weight, a 20 kg block weight and a 10 kg bar weight(test weight); in the background are two 10-kg weights and two 5 kg weights (reference weight). A sensor with its opposing reflector foil for weight position determination and the automatic protective enclosure for the mass comparator can be seen clearly

Measurements and results

Series of measurements have been carried out at BEV since May 2004 to provide the required mathematical basis. In these measurements, weights values were measured and recorded at 250 ms intervals, together with data pertaining to various environmental parameters, and the results evaluated. To validate the system for observance of the BEV's legal requirements, approximately 1,000 individual measurements were performed during this phase, each consisting of ten A-B-B-A cycles, and evaluated. Comparisons were performed subsequently using weights with nominal mass values of 10 and 20 kg. After implementation of the system with the weighing position below the mass comparator, the standard deviation achieved for 20 kg mass comparator for the 10-kg weights between 0.04 mg and 0.10 mg; for the 20-kg weights, the standard deviation was between 0.05 mg and 0.12 mg. The repeatability of results was between 0.03 mg and 0.3 mg for the higher range

Since December 2004 the system with the CC20000S-L has been implemented at BEV for the dissemination of mass standards for a range up to 500 kg, as well as for internal and external calibrations and verifications of weights with nominal mass values of up to 20 kg. At the present the range form 1 kg up to 5 kg have been implemented

The BEV is currently implementing the additional weighing cell (CC10000U-L mass comparator) from Sartorius with a resolution of 1x 10^{-5} in the quality system of the BEV. Thus this the BEV will have completed its plan to fully automatize its mass laboratory. In future all measurements for calibration and adjustment and a large part of the measurements for the dissemination of mass will be carried out by the three “weighing robots”.