X-ray systems and on-line optimization

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Mathematics and industrial applications

Applied mathematics becomes increasingly important

- digital control (flexibility during operation, flexibility for modifications, more complex controllers realizable, lower price)
- image processing (new applications, on-line processing)
- estimation of quantities, measurement (on-line processing, faster processing, more complex modelling)
- optimization in logistics (big data processing)

Drivers for mathematics in industry

- Increasing computing power
- Sophisticated hardware programming capabilities (FPGA, HW/SW-codesign)
- Simulation techniques, methods and tools
- Rapid control prototyping techniques and tools (code generation)

Mathematics is becoming important for SMEs

- Evolution from Mechanics, through Electronics and Software to Mathematics
- Basic disciplines are still needed, but focus shifts
- Computing platforms, sensors, actuators, become commodities, mathematics gives the individual "touch" (competitive advantage).
- Impact is relevant not only for big companies, but even (or maybe in particular) for SMESs

Zumbach In Numbers

Swiss Quality Precision Engineering At Your Disposal

For nearly 60 years in the world market

Worldwide 11 own companies

Worldwide more than 40 sales and service stations

More than 200 employees

8 different measurement technologies for best results

Worldwide, more than 100‘000 running systems

Worldwide Customer Service

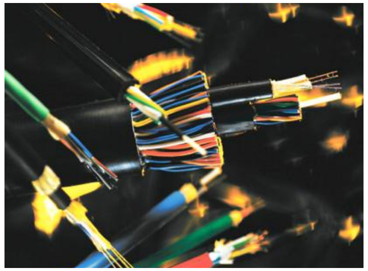
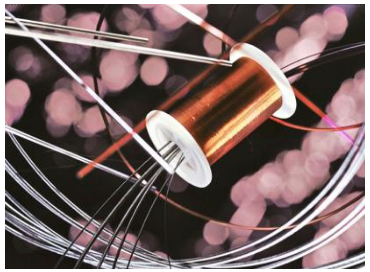
Always Close To You Wherever You Are

Quality And Innovation
Worldwide Competence Leader

- Leading manufacturer of in-line measuring, monitoring and control systems
- Pioneer in in-line measurement systems, based on various technologies
- Large number of international patents and trademarks
- Manufacturing and R&D centers in Switzerland and the US
- Expert sales and customer support from international subsidiaries with fully equipped service and spare part facilities
- Platform blog.zumbach.com with monthly publications to topics of the on-line measurement

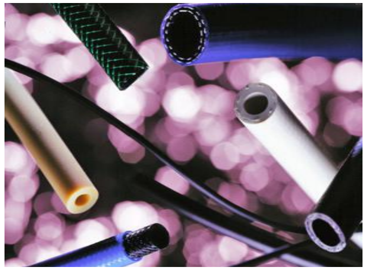
Partnership With Customers
Systems Tailored To Different Industries

Wire and Cable

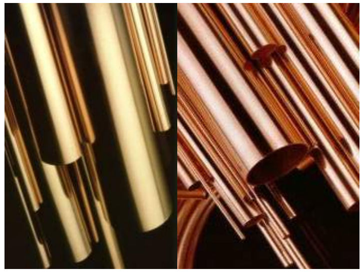



Fibre Optic and Glass

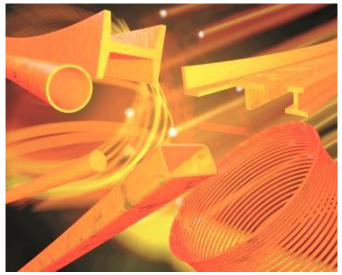

Plastics and rubber




Non-ferrous

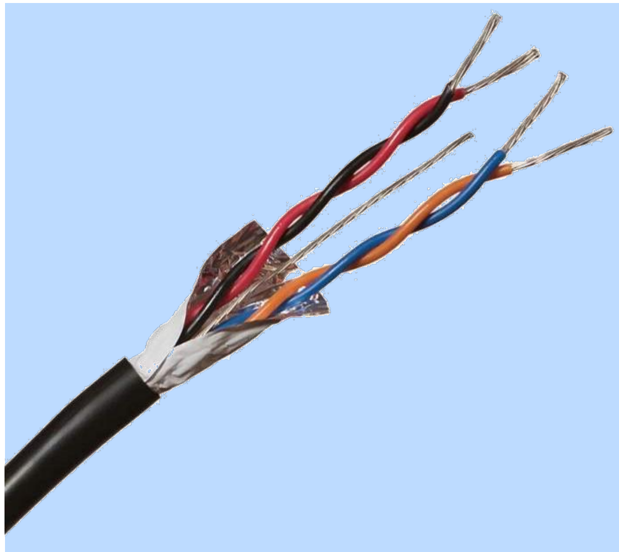


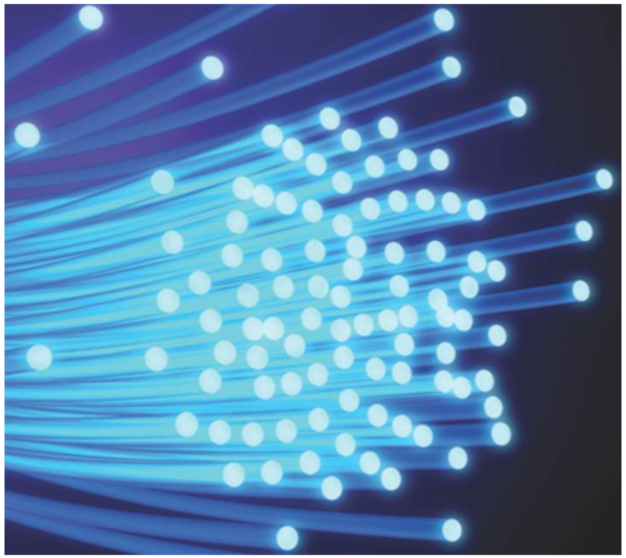

Steel and Metal

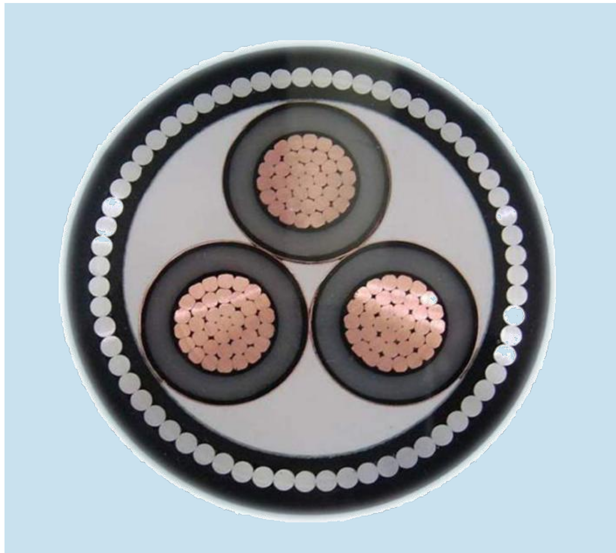



All extruded Products:

- Telecommunication and data cables
- Fibre optic cables
- Energy and control cables
- Magnet wire
- Fine wire
- Low, Medium, High voltage cables

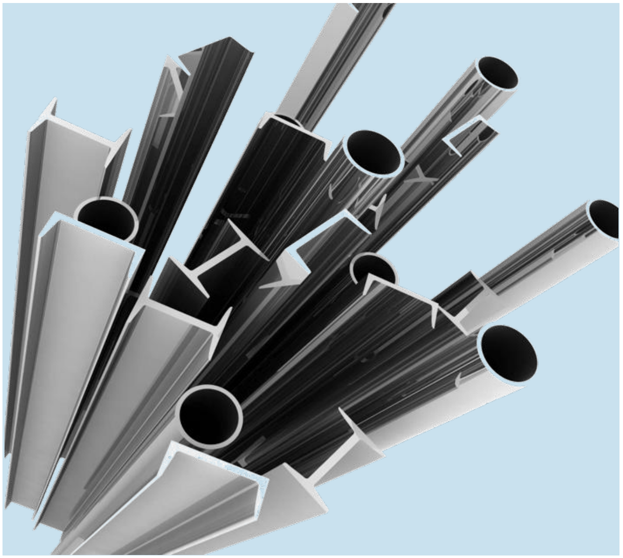
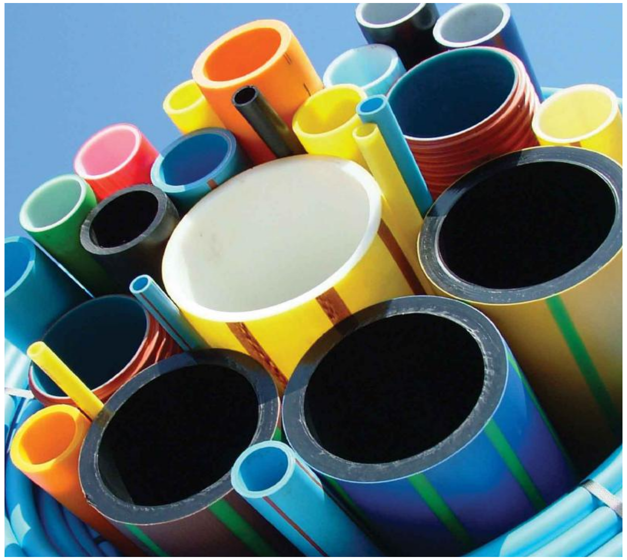






All extruded Products:

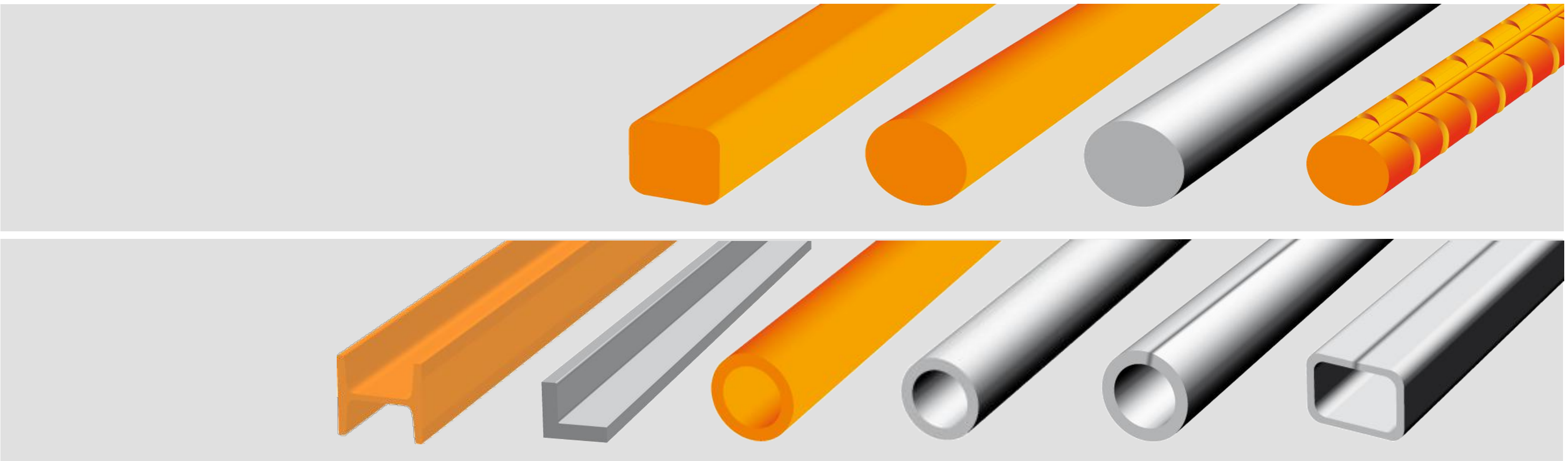
- Tubing
- Medical tubing / catheters
- Hoses
- Profiles

Steel And Metal Industry
Typical Products/Processes

Hot rolling:
- Bar, rod
- Profiles and seamless pipe
- Welded pipe
- QC (NDT)

Cold processes such as:
- Peeling
- Grinding
- Bending
- Polishing etc.



Laser / Optics
Dimension measurement with shadow principle

Ultrasonic
Eccentricity / Wall thickness

Inductive + Laser
Eccentricity / Diameter / Ovality

Spark test
Isolation test with high voltage

X-rays
Cross section measurement (3 layers)

Linear Sensor
(Multi-colour LED sources)
Diameter / Ovality

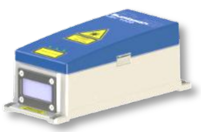
Laser light section technique / Image processing
Profile and shape measurement

Light section technique / Image processing
Quality surface monitoring

Technologies – For Each Application The Best Solution

Completing the Product Line of Industrial Equipment

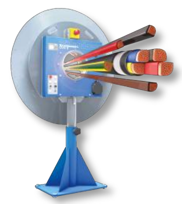
Capacitance Measuring Systems
Including Fast Fourier Transform / Structural Return Loss Software



LSV
Speed and Length Measurement

WST TEMPMASTER
Conductor Preheaters

AUTAC
Temperature Control Sensors



DVW / DVO
Oscillating Measuring Devices for Width/Height and Sector Cables

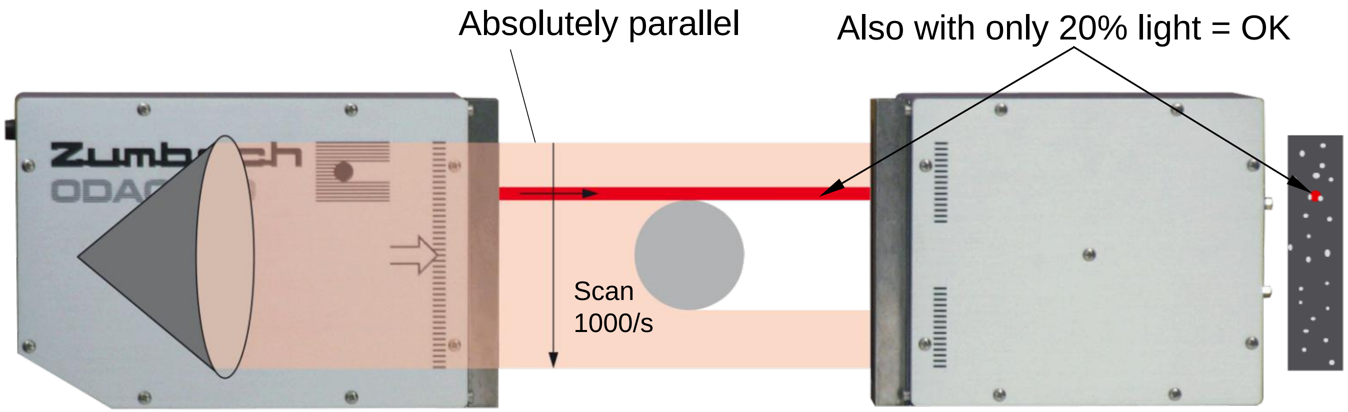
CALIBRATOR SP
Checking Device for periodic Verification and Calibration of Spark Testers

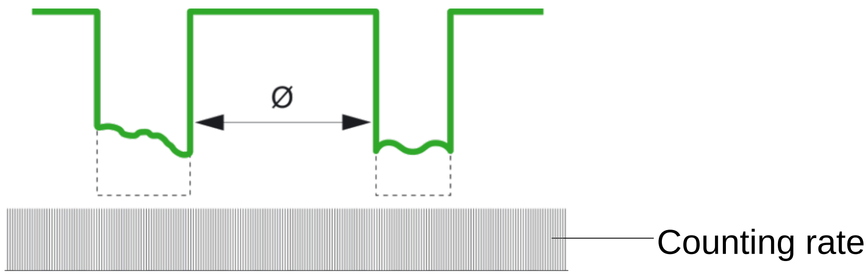
Surface Quality
Inspection Systems with Machine Vision / CCD Cameras

USYS
Universal Data Acquisition, Processing and Display Units

Laser Scanning Principle

World-wide most used measuring principle





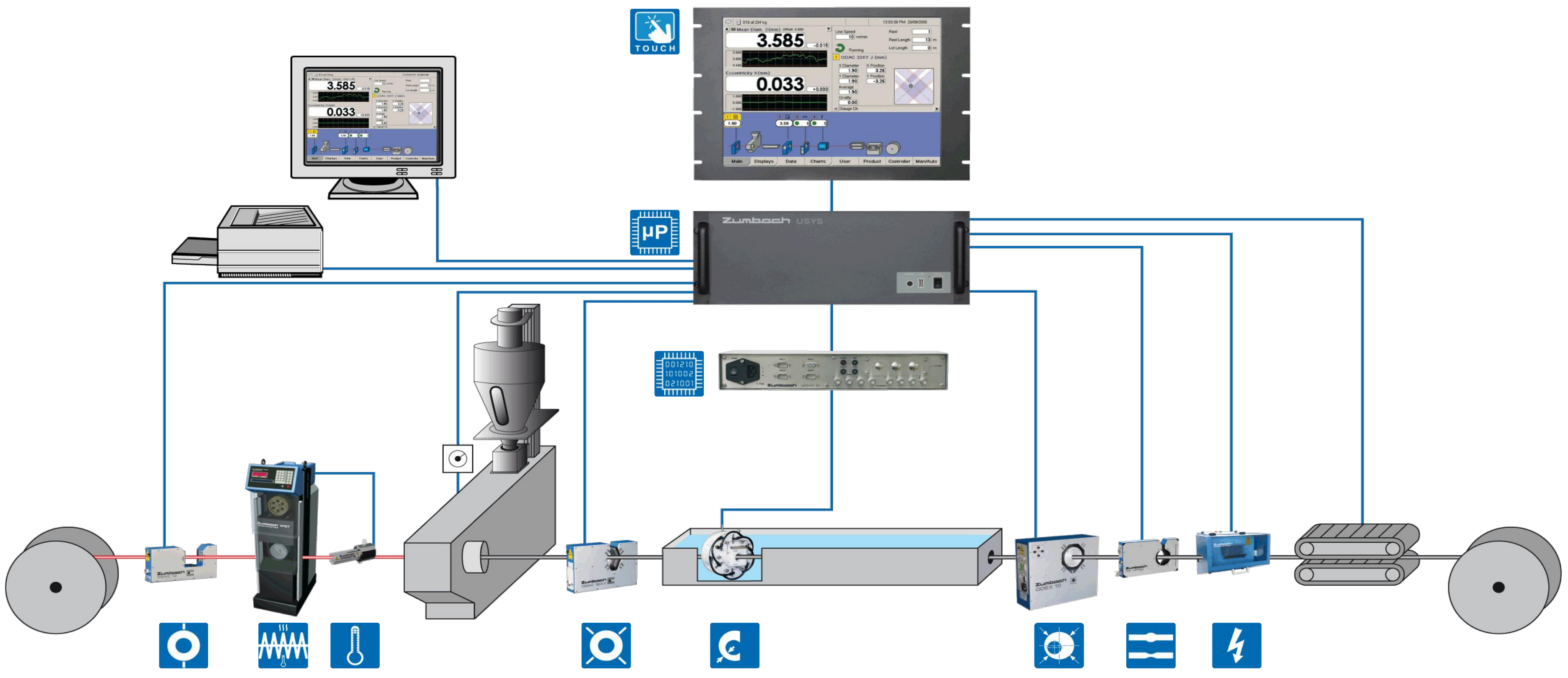
Measurement

- Very high accuracy (parallel/linear)
- Immune on dirt
- Immune on light variations
- Immune on vertical and horizontal movements

Resolution = 0.0001 mm (.000004 in.)
Rule of thumb for accuracy = 10 x resolution = 0.001 mm (.00004 in.)

Example of cable Extrusion Line

Equipped with Measurement and Control Instruments

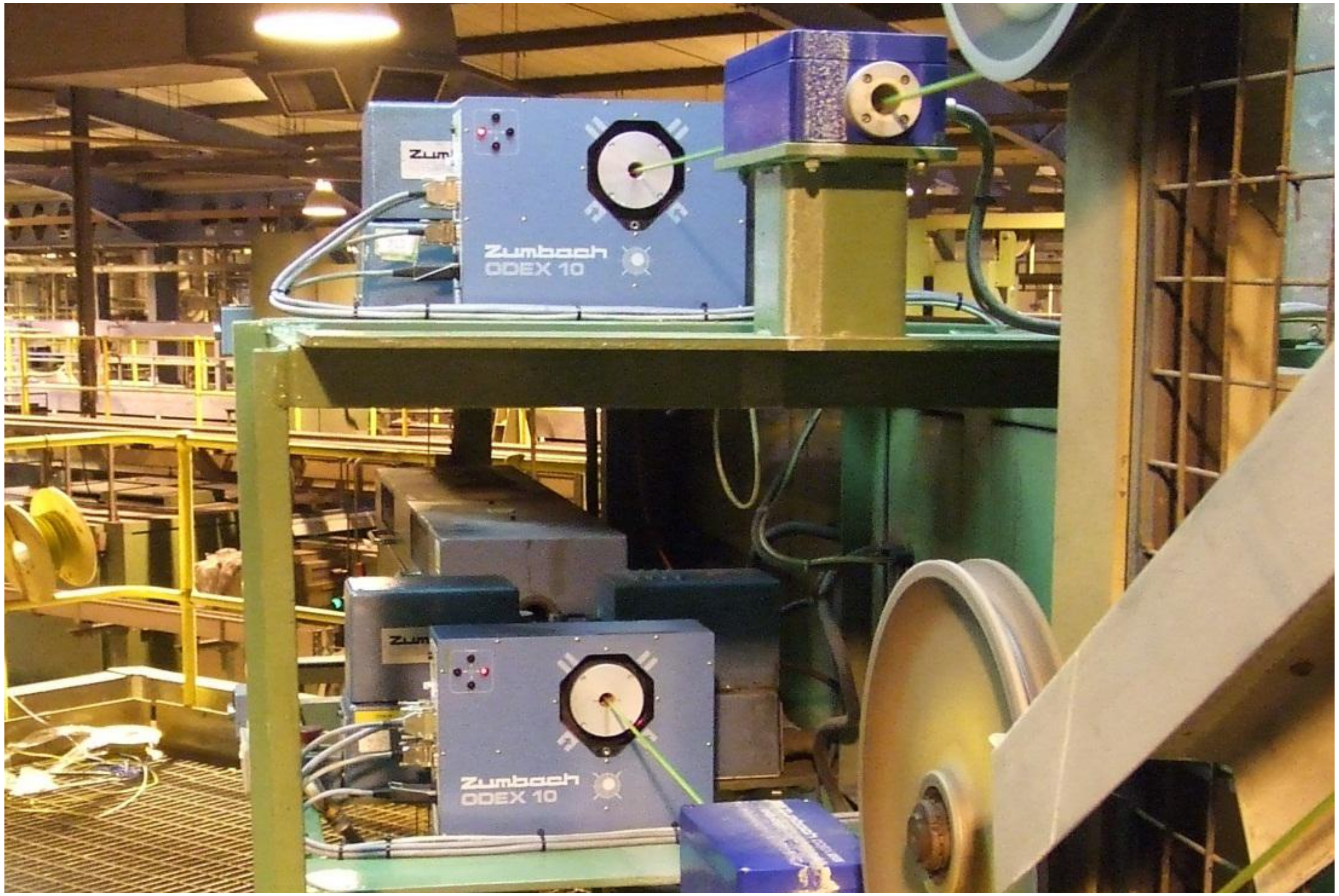


2 x ODAC® 152XY-J

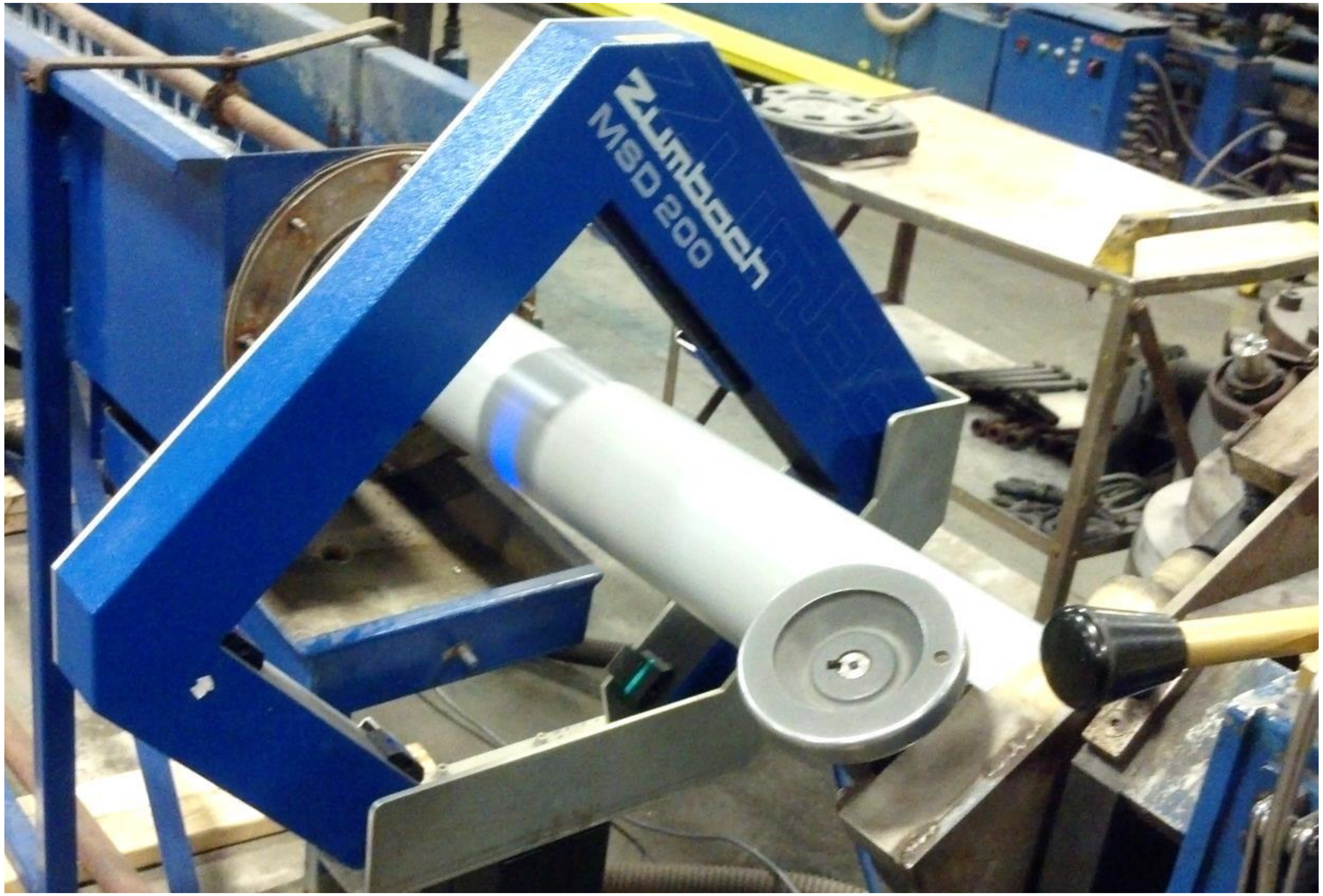
Laser-scanning measurement of outside diameter for power cables

ODEX® 10

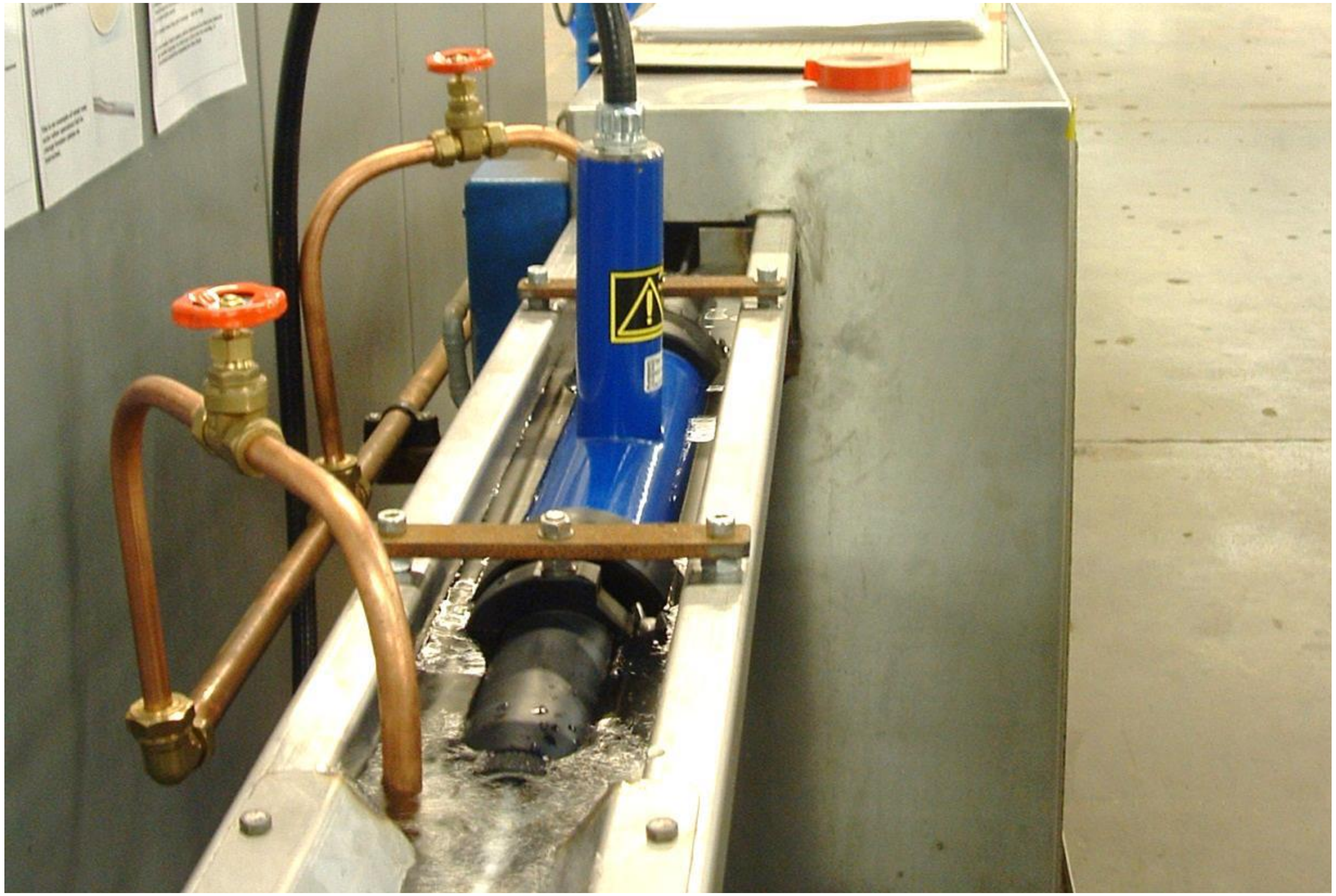
Eccentricity measurement system for communication cables



MSD 200
Light shadow-based diameter measurement for tubes

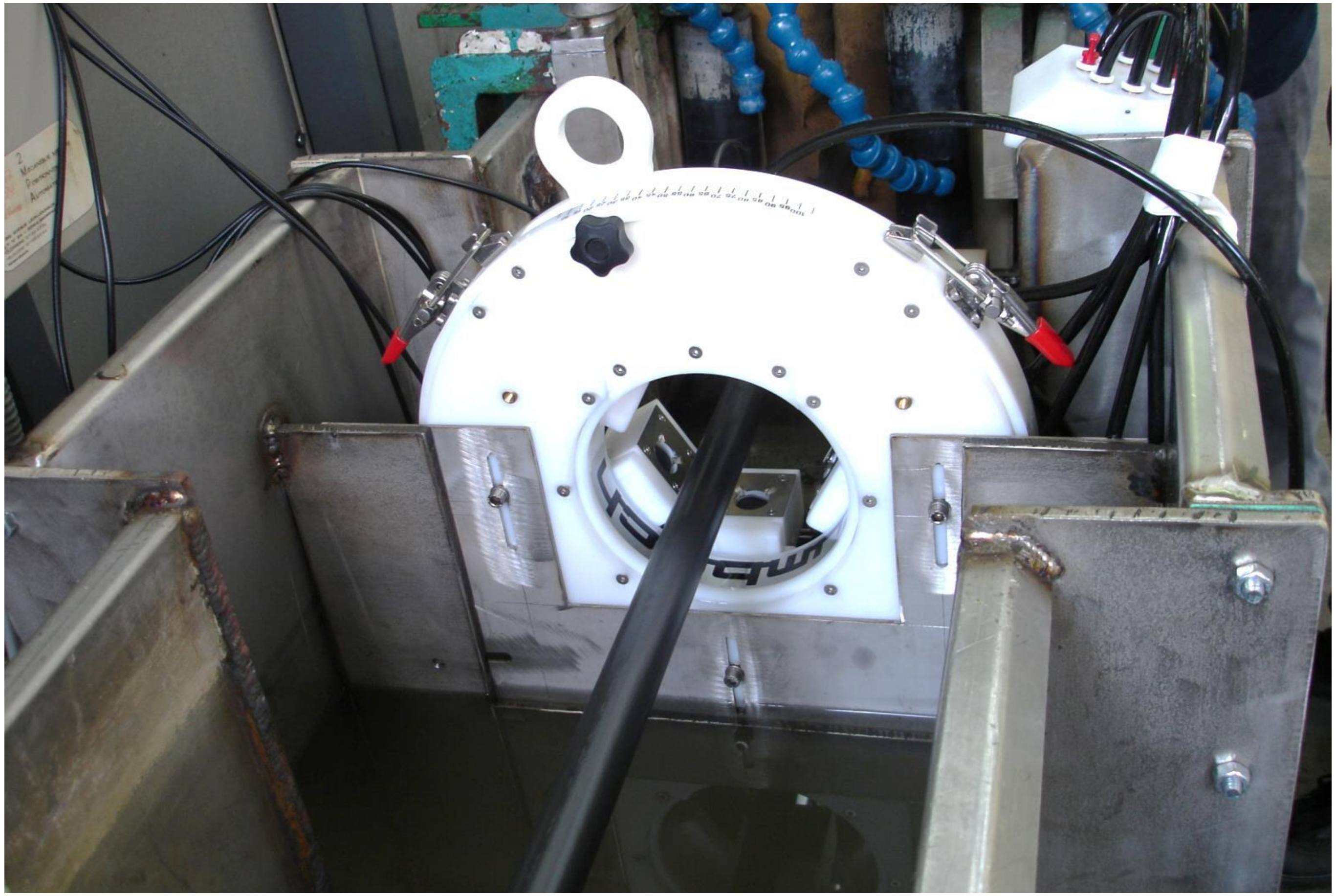


CAPAC®
Capacitance measurement for communication cables



UMAC® Z100-6K

Ultra-sound measurement syste for cable layer thickness measurement

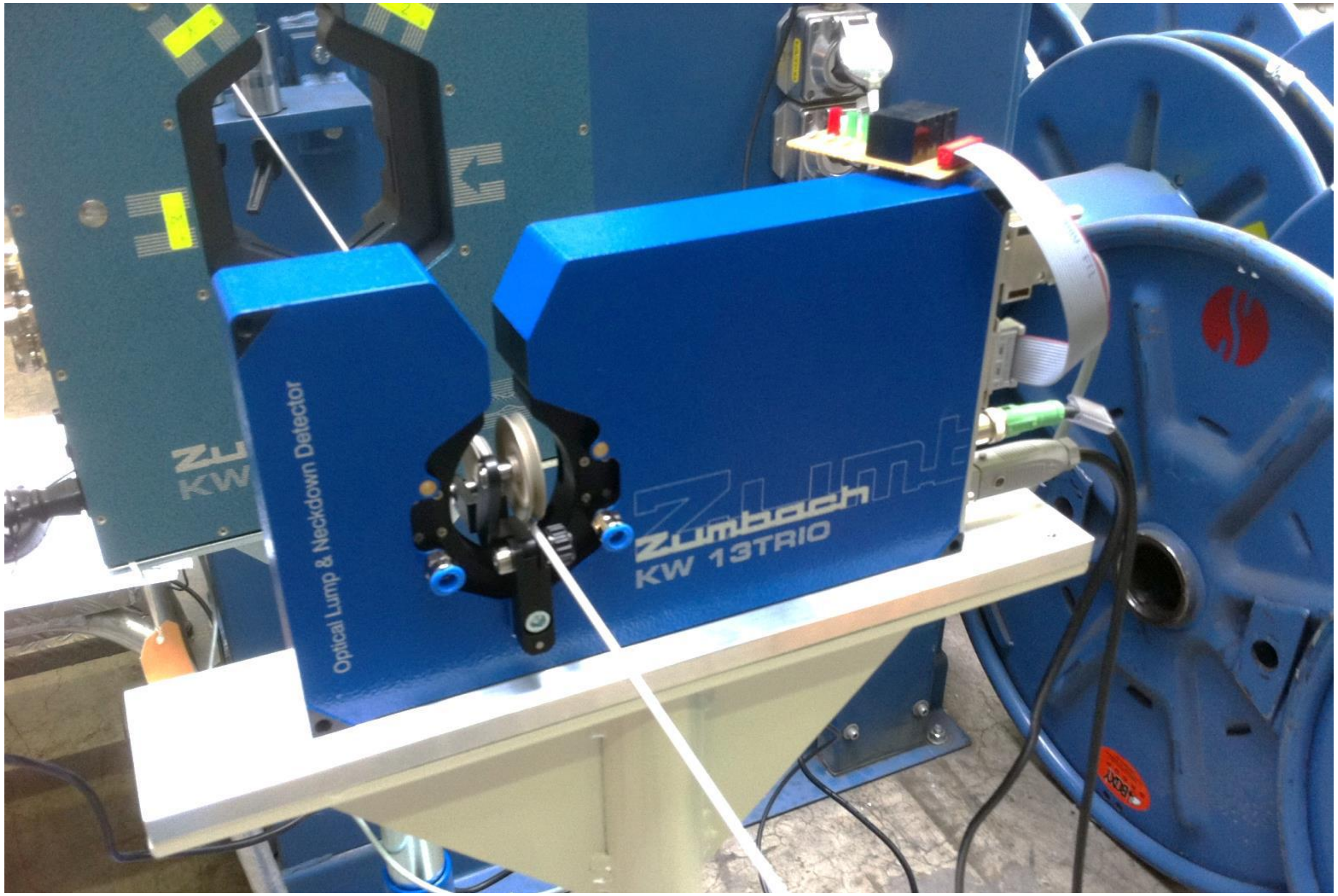


AST-L 15.50

High-voltage test system for the detection of insulation faults

KW 13TRIO

Lump and neck detection system for cable defects



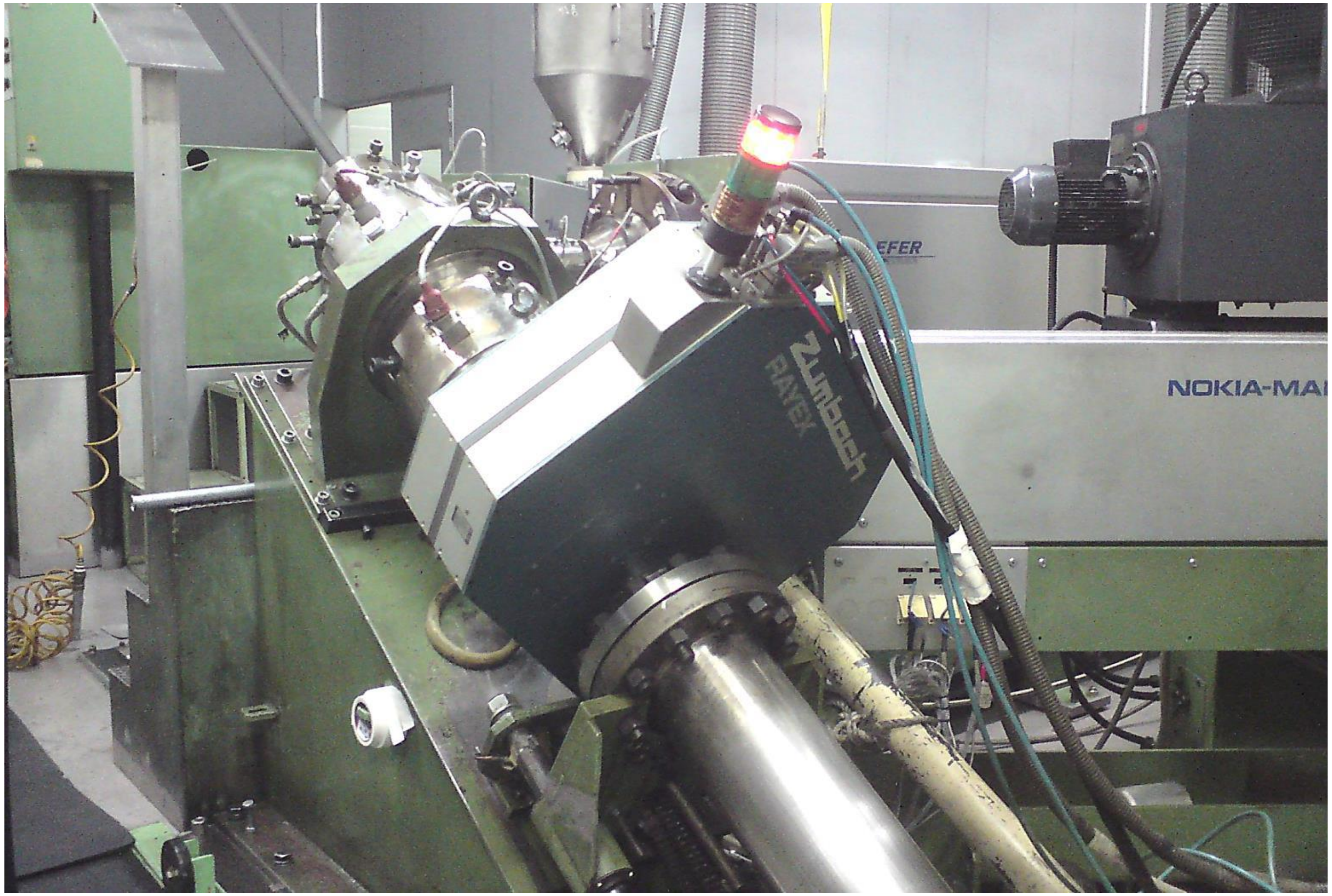
SIMAC® 63

Surface measurement system for the detection of defects in plastics products

Zumbach
SWISS PRIME MEASURING SINCE 1957

RAYEX® 220

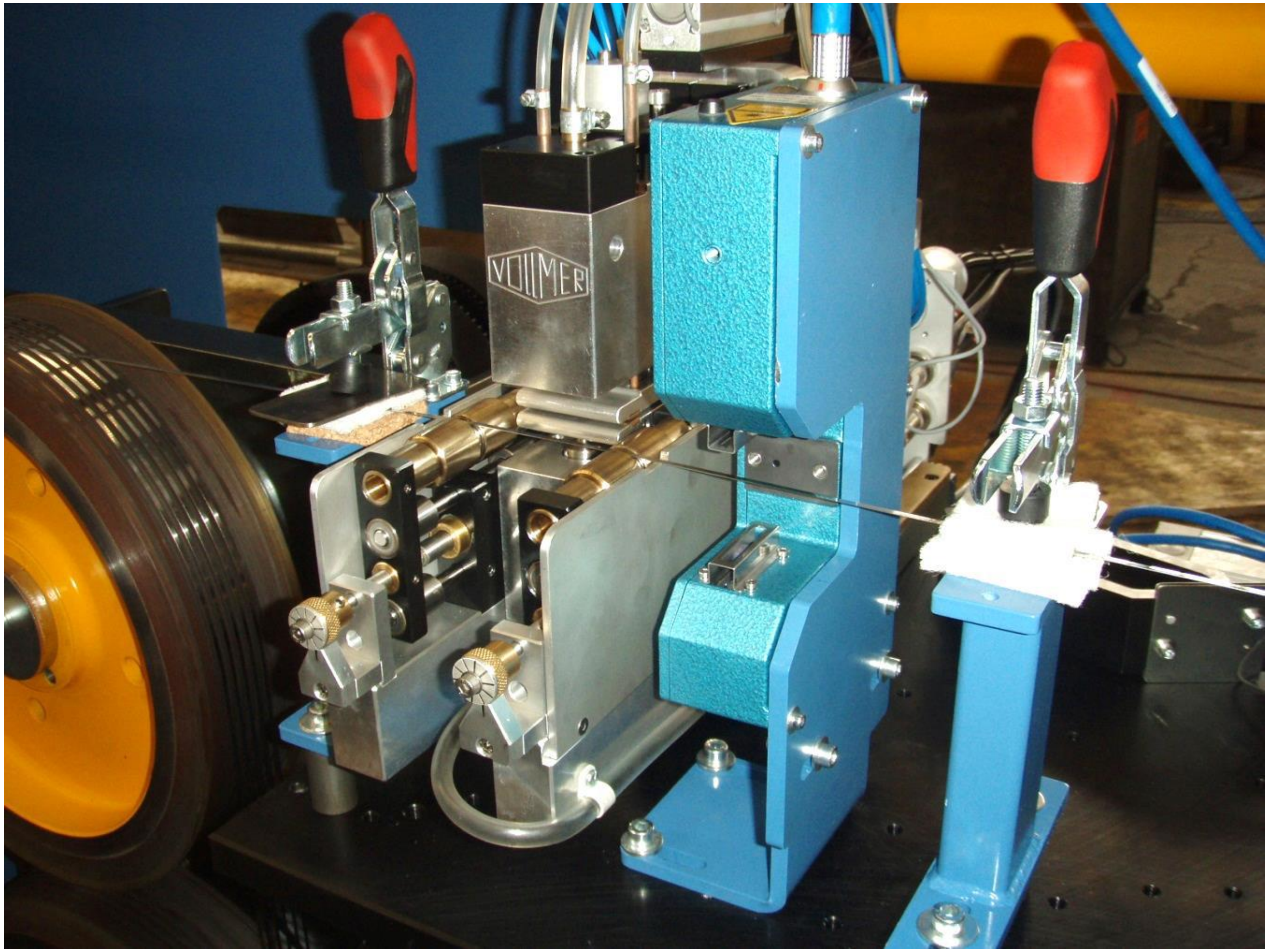
X-ray measurement syste for high-voltage cables



PROFILEMASTER® PMM 80-4K
Profile measurement systems for drawn steel and non-ferrous profiles

ODAC® 16-30

Laser scanning measurement system for flat wire



3 x ODAC® 151J

Straightness measurement and monitoring system

STEELMASTER SMS 100-S6

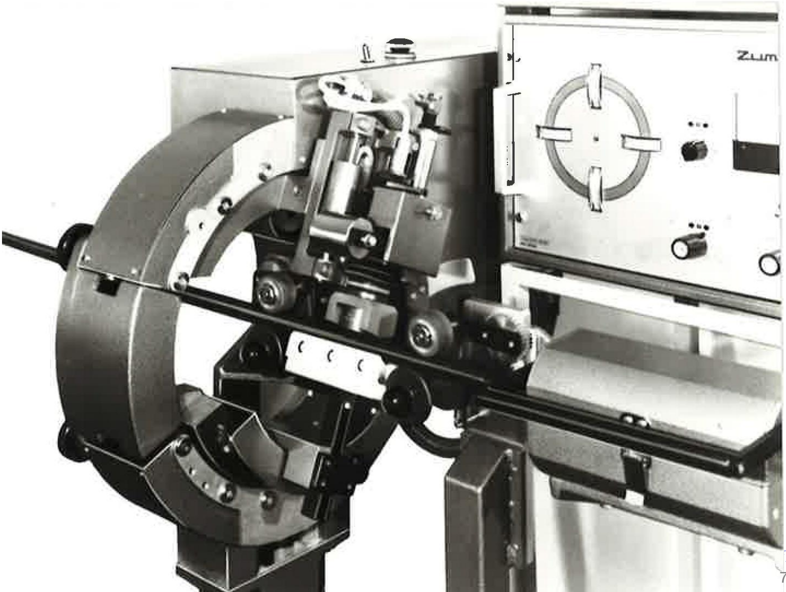
6-axes laser scanning measurement system for cold steel applications

PROFILEMASTER® SPS 400-S4

8-axes laser line triangulation system for hot steel application

Focus on mechanical design, 60's

Eccentricity measurement systems

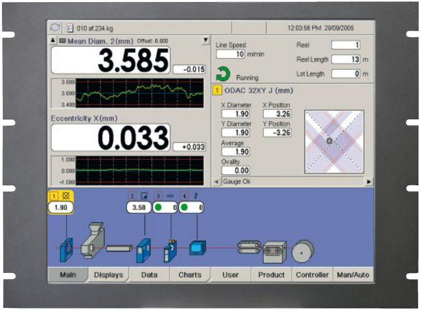


Focus on electronics design, 80's

Electronics for diameter processing

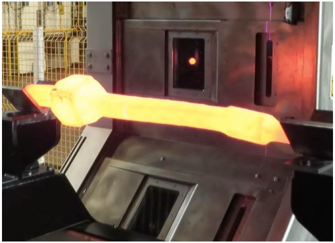
Focus on software design, 90'

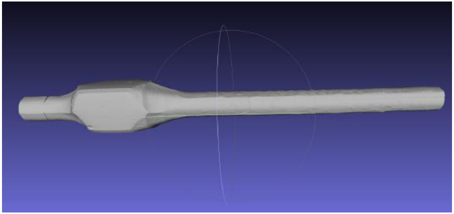
USYS computing system for fast data processing and higher-level functions



Focus on applied mathematics, today

SPS for the measurement of profile in hot steel applications





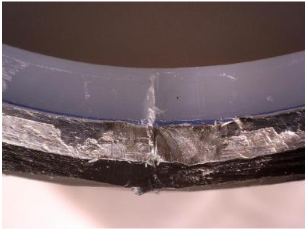
The RAYEX® S system

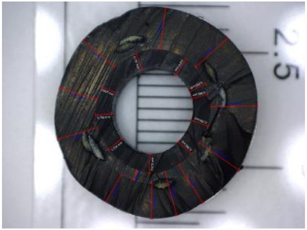
X-ray measurement system with two measurement axes

The applications

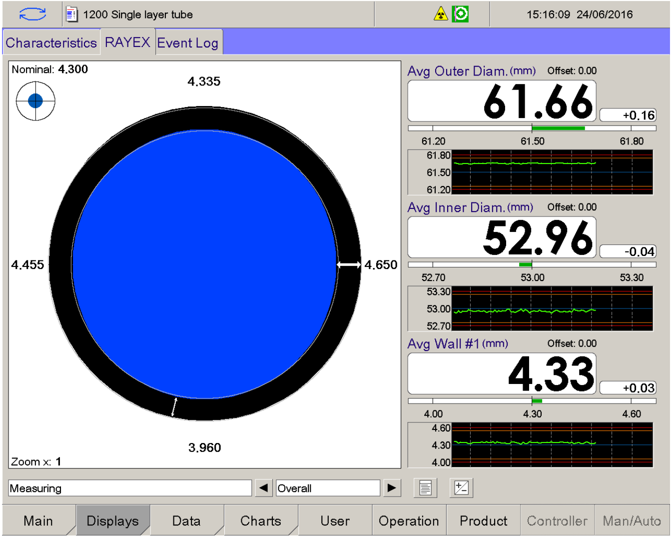
Layer thickness and eccentricity in

- hoses
- tubes
- cables (jacketing)



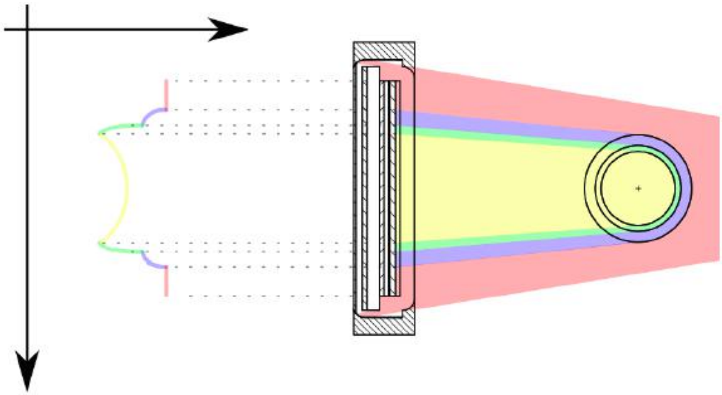


Processing and display of measured values



Measurement principle

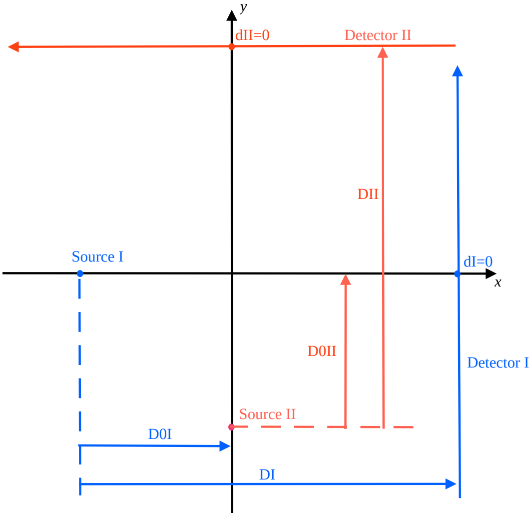
Projection of two fan beams on line sensors: example of a two layer tube



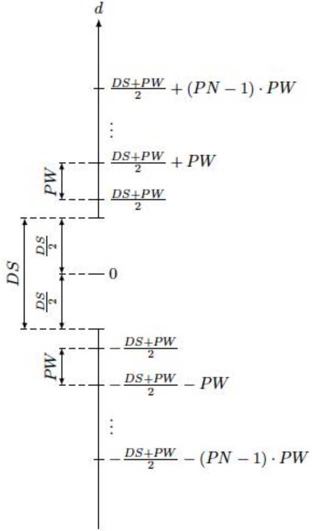
Specifications

- Accuracy 10 μm (pixel width 50μm!)
- Sample rate $>$ 10Hz
  - faster=more robust against object motions,
  - slower=lower emissions
- Measurement of thickness of multilayer tubes (up to 3 layers)
- Measurement of cable jackets
- Robustness of measurement

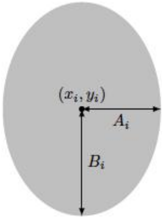
Axes


y
dII=0
Detector II
DII
Source I
dI=0
x
D0II
Detector I
Source II
D0I
DI

Detector geometry



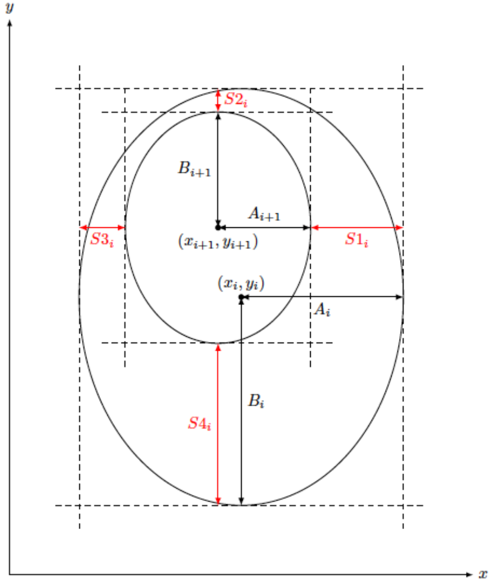
Device under test (DUT)



Chord length is

$$c_i(d) = \frac{2 \cdot A_i \cdot B_i}{a_x^2(d) \cdot A_i^2 + a_y^2(d) \cdot B_i^2} \cdot \sqrt{a_x^2(d) \cdot A_i^2 + a_y^2(d) \cdot B_i^2 - (b(d) + a_x(d) \cdot x_i + a_y(d) \cdot y_i)^2}$$

DUT with multiple layers



X-ray beam

Beer-Lambert absorption law: beam intensity decays exponentially with chord length in material:

$$I(d) = I_0(d) \cdot e^{-K_i \cdot c_i(d)}$$

or also

$$(Abs_i(d)) = \ln\left(\frac{I(d)}{I_0(d)}\right) = -K_i \cdot c_i(d)$$

and

$$Abs(d) = \sum_i -K_i \cdot c_i(d)$$

Detector sensivity

- Thermal noise causes signal to be roughly proportional to exposure time ($Dark$)
- Full exposure may present different levels for each sensor/pixel (Ref)

Given measurement signal Raw, the normalized relationship for the intensity is

$$e^{Abs(d)} = \frac{I(d)}{I_0(d)} = \frac{Raw(d) - Dark(d)}{Ref(d) - Dark(d)}$$

Kalman filter (KF)

Given is a linear system are state-equation and output equation

$$\begin{aligned} \boldsymbol{x}_k &= \boldsymbol{F} \cdot \boldsymbol{x}_{k-1} + \boldsymbol{G} \cdot \boldsymbol{u}_{k-1} + \boldsymbol{w}_{k-1} \\ \boldsymbol{y}_k &= \boldsymbol{H} \cdot \boldsymbol{x}_k + \boldsymbol{v}_k \end{aligned}$$

with state vector $\boldsymbol{x}_k$m, input $\boldsymbol{u}_k$ and output $\boldsymbol{y}_k$
State covariance matrix is

$$\mathbf{P}_k = \mathrm{Cov}\left(\boldsymbol{x}_k, \boldsymbol{x}_k\right) = \mathrm{E}\left(\left(\boldsymbol{x}_k - \hat{\boldsymbol{x}}_k\right) \cdot \left(\boldsymbol{x}_k - \hat{\boldsymbol{x}}_k\right)^{\mathsf{T}}\right)$$

Noise model

Process noise $\boldsymbol{w}_k$ and measurement noise $\boldsymbol{v}_k$ assumed to have zero mean normal distributions:

$$\boldsymbol{w}_k \sim \mathcal{N}\left(0, \mathbf{Q}_k\right)$$
$$\boldsymbol{v}_k \sim \mathcal{N}\left(0, \mathbf{R}_k\right)$$

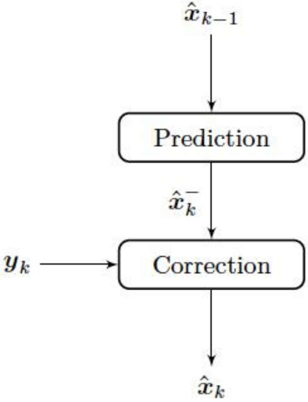
where $\mathbf{Q}_k$ is process noise covariance matrix, $\mathbf{R}_k$ measurement noise covariance matrix:

$$\mathbf{Q}_k = \mathrm{Cov}\left(\boldsymbol{w}_k, \boldsymbol{w}_k\right) = \mathrm{E}\left(\boldsymbol{w}_k \cdot \boldsymbol{w}_k^{\mathsf{T}}\right)$$
$$\mathbf{R}_k = \mathrm{Cov}\left(\boldsymbol{v}_k, \boldsymbol{v}_k\right) = \mathrm{E}\left(\boldsymbol{v}_k \cdot \boldsymbol{v}_k^{\mathsf{T}}\right)$$

KF filter steps

Two step estimation

- first estimation with prediction of new output based on model and on current input (pre-estimate)
- second estimation with correction of pre-estimate with current measurement value (post-estimate)



KF equations

Prediction

Predict State Estimate

$$\hat{\boldsymbol{x}}_k^- = \boldsymbol{F_{k-1}} \cdot \hat{\boldsymbol{x}}_{k-1} + G \cdot \boldsymbol{u}_{k-1}$$

Predict Error Covariance

$$\mathbf{P}_k^- = \mathbf{F}_{k-1} \cdot \mathbf{P}_{k-1} \cdot \mathbf{F}_{k-1}^\mathsf{T} + \mathbf{G}_{k-1} \cdot \mathbf{Q}_{k-1} \cdot \mathbf{G}_{k-1}^\mathsf{T}$$

Correction

Compute Kalman Gain

$$\mathbf{K}_k = \mathbf{P}_k^- \cdot \mathbf{H}_k^\mathsf{T} \cdot \left(\mathbf{H}_k \cdot \mathbf{P}_k^- \cdot \mathbf{H}_k^\mathsf{T} + \mathbf{V}_k \cdot \mathbf{R}_k \cdot \mathbf{V}_k^\mathsf{T}\right)^{-1}$$

Correct State Estimate

$$\hat{\boldsymbol{x}}_k = \hat{\boldsymbol{x}}_k^- + \mathbf{K}_k \cdot \left(\boldsymbol{y}_k - \cdot \mathbf{H}_k \cdot \hat{\boldsymbol{x}}_k^-\right)$$

Correct Error Covariance

$$\mathbf{P}_k = (\mathbf{I} - \mathbf{K}_k \cdot \mathbf{H}_k) \cdot \mathbf{P}_k^-$$

Kalman filter states

Linear state transformation: Layer thicknesses as state variables

$$\begin{aligned} S1_i &= A_i - A_{i+1} + x_i - x_{i+1} \\ S2_i &= B_i - B_{i+1} + y_i - y_{i+1} \\ S3_i &= A_i - A_{i+1} - x_i + x_{i+1} \\ S4_i &= B_i - B_{i+1} - y_i + y_{i+1} \end{aligned}$$

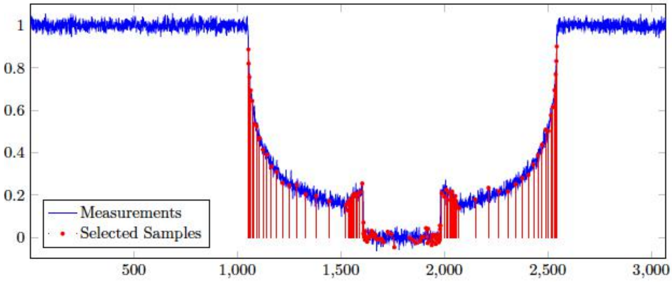
gives state

$$\boldsymbol{x} = [A_1, B_1, x_1, y_1, \boldsymbol{K}_{1,A,N}, S1_1, S2_1, S3_1, S4_1, \boldsymbol{K}_{2,A,N}, \ldots, \\ S1_{I-1}, S2_{I-1}, S3_{I-1}, S4_{I-1}, \boldsymbol{K}_{I,N}, \Delta x, \Delta y]$$

Sample measurement selection

Each CCD detector has two sets of 1536 pixels. Processing of 6144 pixels per sample is not practical.

⇒ Selection of representative pixels.



Software implementation

- Development under Scilab (Matlab-like tool) and Embarcadero with C++
- Run-time environment Windows PC
- Encapsulation of Scilab code in wrapper within C++-code
- Functionally equivalent implementation of Scilab algorithm in C++

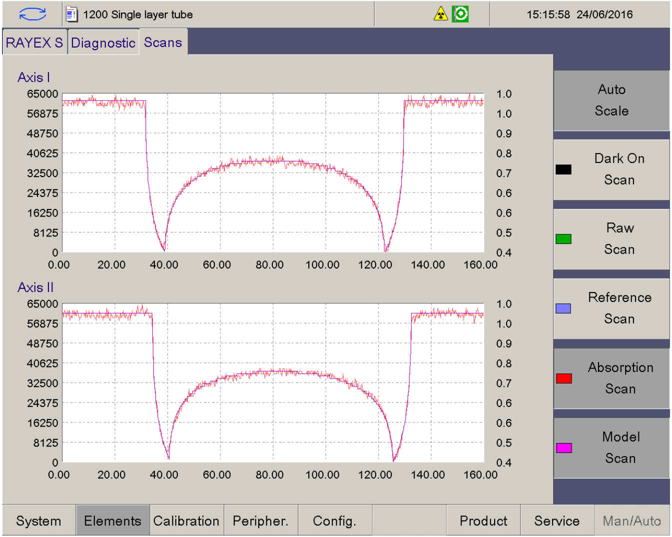
Other mathematical issues dealt with

- Calibration of device and detector geometry
- Detector offset drift to be compensated on-line
- Object motion considered in Kalman filter
- Limited stability of x-ray source intensitiy (still open issue)
- and more ...

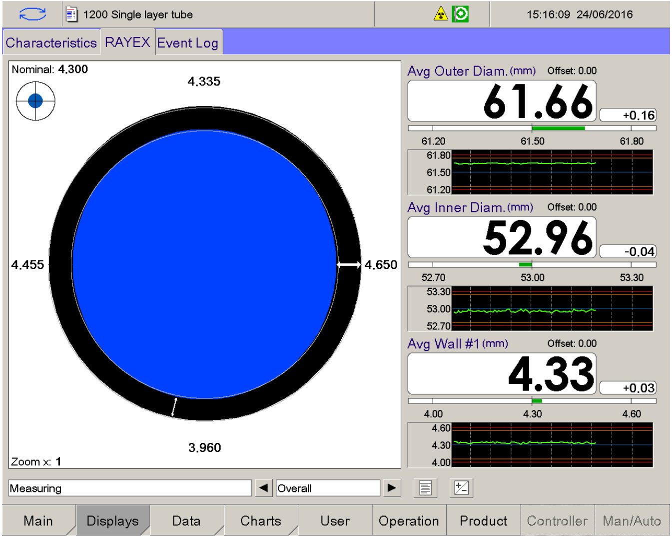
Challenges

- Computational requirement to be minimized (wish of highest possible measurement rate)
- Simple operation (e.g. user should not define starting values for state)
- Limited complexity allowed on site (e.g. for calibration)
- Relevant environment uncertaintes
- Strong object variability
- Non-ideal measurement process behavior (noise level drift, noise dynamics, material-dependent behavior)

Profile for diagnostics



Processing and display of measured values



Thank you for the attention!

Questions?