

# Machine vision and ultrasonic supported measuring and monitoring concept for economical quality enhancement in small batch production

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**Abstract** – In order to handle production processes and product quality in small batch production, flexible measuring and inspection systems, which can be automated, are required. The integration of such systems into machine tools represents a profitable approach. The general advantages of inline measuring systems are described in this contribution. Subsequently the article demonstrates two exemplary applications in the areas of geometry inspection and material testing. Therefore an image-processing-based machine vision system and an changeable ultrasonic sensor are employed.

**Keywords:** Inline measuring system, ultrasound, machine vision, image processing, geometry inspection, part position, workpiece alignment

## 1. INTRODUCTION

The manufacturing of modern goods demands an increasing number of product variants which leads to smaller batch sizes. As a result, especially in the area of quality control, a reorganisation of checking and monitoring concepts is vital. Fixed measurement systems cannot cope with the increasingly flexible production processes. Particularly for goods made of high-value raw materials, with a high added value during production or safety-relevant components, material testing has gained further importance, next to geometry checking.

In this abstract multiple monitoring and measuring concepts are presented, which are based on flexible machine-integrated image processing systems or an ultrasonic probe for a standardised tool holder respectively. These inline-systems show up groundbreaking possibilities to increase product quality, reduce error rates and thus contribute to the total profitability of manufacturing companies.

## 2. INLINE MEASURING SYSTEMS

### *2.1. Advantages of machine-integrated measuring*

For early identification of the development of workpiece-specific quality characteristics and feedback of analysis results in small production-related quality control cycles, measures within the quality assurance have to be performed “inline” (e.g. in the production line). In contrast to large batch or mass production, small batch manufacturing processes need innovative and far more flexible measuring concepts that can be easily adapted to various new measuring tasks.

In doing so, the direct integration of efficiently planned measuring procedures in production processes reveals unused potentials in manifold applications. In the sector of millcutting many of these measuring functions can be basically realised with machine-integrated touch probes which can be automatically applied into the spindle. Today this functionality is only used for the accurate setting of the machine’s zero point and the alignment-calibration of the raw part’s coordinate system, previous to the actual milling process. In case of automated material testing in small batch manufacturing, there are generally no production-related concepts existent. Most systems are manually operated or used in cost-intensive, laboratory-like test facilities.

In the following, the most important advantages of machine-integrated measuring systems are listed:

- realisation of process-related quality control cycles,
- reduction of set-up time by using one chucking and existing CAD and NC data respectively
- elimination of adjustment mistakes,
- lower costs for clamping devices,
- lower costs for other measuring devices,
- use of high precision axis-integrated position sensors in times of machine overcapacity
- omission of separate test facilities

### *2.2. Machine vision supported process control*

Today the automation rate in modern production companies has reached a high level. Especially the available automation concepts for the volume production can be considered very sophisticated and capable. However, they usually premise constant, repeatable or at least predictable boundary conditions. In particular applications in the field of metal cutting as well as hot or cold chipless metal forming demand a reliable and reproducible clamping in order to ensure a smooth and accurate procedure. Depending on the automation level, work holding devices such as jigs and fixtures constitute a cost driver that cannot be neglected. In the small batch and single item production these costs cannot be passed to the customer if the production is supposed to remain competitive. The reason is the large proportion of the fixture investment concerning the total production costs. New and intelligent concepts have to be employed here.

Especially in the field of small batch sizes with a high variant diversity, decreasingly predictable disturbing influences add to the problem. A comparatively high deal of manual activities can be observed here (e.g. insertion and clamping of parts in the workspace of machine tools, levelling of the part and customising of the machine coordinate

system in order to correct the NC processing program, selection of the machining programs etc.). Therefore it is quite likely that errors and production disruptions occur due to the interaction of human activities and automated processes.

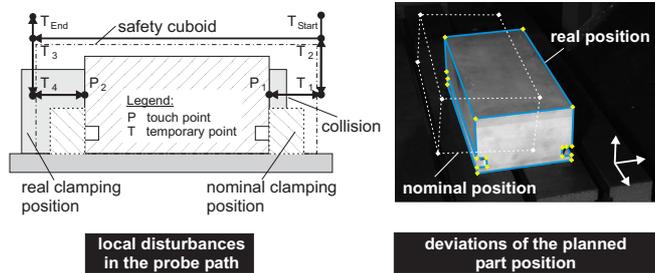


Fig. 1. Typical causes for breakdowns in semi-automated operations

Fig. 1 shows two examples that represent typical causes for breakdowns in semi-automated operations: on the left wrong clamping devices were used and differ geometrically from those defined within the process planning. On the right a raw part is pictured whose actual position differs from the nominal position that is expected by the NC processing program.

Both types of disturbances lead to a void measurement reading or even collision when the workpiece's position is measured automatically with a 3D touch probe for machine tools (fig. 2).



Fig. 2. Illustration of a 3D touch probe for machine tools

**Purposes:**

- Setting of workpiece zero points
- Setting of workpiece alignment
- Component size measurement and automatic correction

In order to antagonize most possible disturbing influences, a control and monitoring system – based on industrial image processing – has been developed at the WZL in Aachen, Germany (fig. 3). This so-called machine vision system assigns the capability to the machine tool to systematically detect situations that differ from the nominal one and to induce correcting measures.

The core of the software prototype, the 3D workpiece calibration, depends on a contour based 3D image processing. It disburdens the machine operator by conducting the time-consuming alignment procedure.

The machine vision system also provides a possible solution to production intermittent measurements of geometric object features by reducing interferences and auxiliary process time. An integrated system, for example, can monitor and support the production intermittent tactile measuring process and optimise the touch probing reliability and speed.

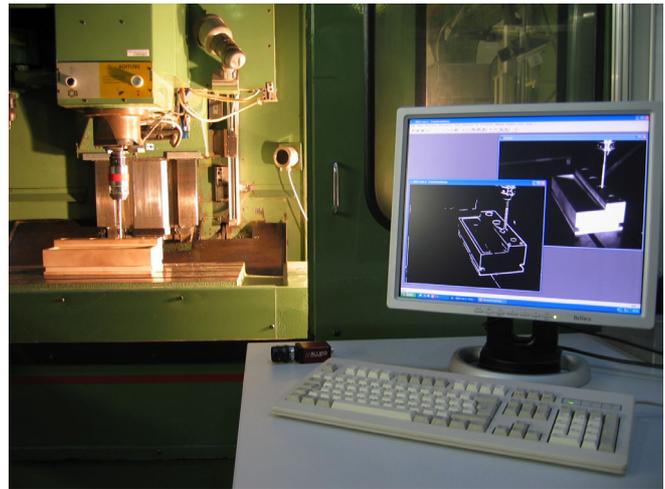


Fig. 3. Test bench for machine vision applications

*2.2.1. Challenges of industrial image processing and possibilities for the optimisation of automated machine vision systems*

A particular challenge for image processing solutions is the reflection characteristic of light on metallic surfaces. In small batch production alternating surface appearances and geometries have to be handled as well. Furthermore, the image scene is widely fixed by the production environment, so that it cannot be adapted to the specific demands of a dependable image processing. An appropriate machine vision system has to be flexible and robust in order to extract object features safely and reproducibly. Fixed parameters for a confined spectrum of features and tasks, like they are common today, do not meet these requirements.

In order to accommodate demand of high flexibility and automation without any precognition of relevant information about the image scene, a contour based multiple image processing step has been developed. The optimisation criteria is the migration affinity of edges or pseudo edges. Thus a false interpretation of the image, induced by shadows and reflections, can be prevented. Only this procedure allows subsequently a comparison of contours and vertices of the CAD model with the determined coordinates of the real contours. The functionality of the image processing approach for both challenges

- machine vision supported workpiece allocation and
- machine vision optimised touch probing for process intermittent quality control

is based on the following steps [1]:

1. Adequate filters eliminate objectionable surface textures and highlight gray tone bounds (steep gray tone gradients at object edges within the acquired images).
2. For the object allocation the segmentation disassociates the workpiece from the image scenes and conditions them for the following steps by using appropriate algorithms.
3. The developed “multiple image processing” assigns those contours, that have been verified through multiple images of the series, to an optimised contour image (fig. 4). Thus disturbing contours are suppressed as far as possible and real outlines are displayed nearly closed.

4. The last step of the registration of geometric elements is the feature extraction. Here workpiece vertices are determined fault-tolerantly.

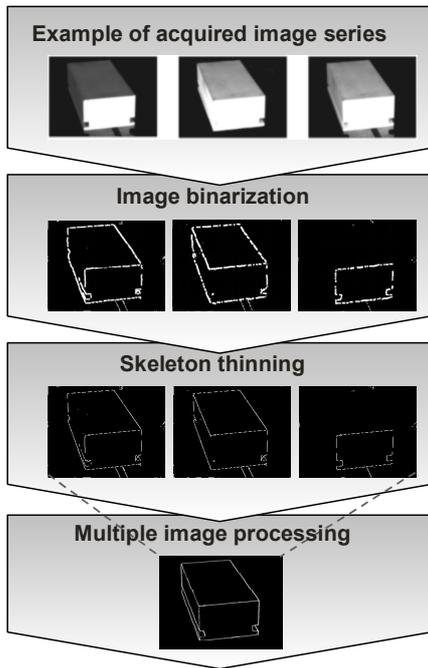


Fig. 4. Functional principle of the implemented "multiple image processing"

### 2.2.2. Iterative CAD matching to determine the positional deviation

For the detection of the part position an iterative CAD matching is carried out subsequently. For the CAD model an estimated initial position is assumed which usually corresponds to the nominal position. The distances between object and model features are minimised iteratively by manipulating the model calculatively using rotational and parallel translational movements. The absolute value of the displacement and rotation represents the displacement of the workpiece in regard to the nominal position (cp. fig. 1, right).

A popular method for registering a model to a 3D data set is the iterative closest point algorithm (ICP) applied in various vision systems using 3D sensors. The ICP algorithm is an iterative procedure with each iteration consisting of two steps. In the first one, closest neighbouring points are put into correspondence, while keeping the current object pose fixed. The second step updates the current registration by least squares minimization of the displacement of matched point pairs (fig. 5). It can be shown that the iteration converges to a minimum of residual error.

As the ICP algorithm is robust and efficient in practise, its principle was combined with a 3D to 2D correspondence operator that is robust with respect to occlusions to obtain an improved 3D to 2D registration performance [2].

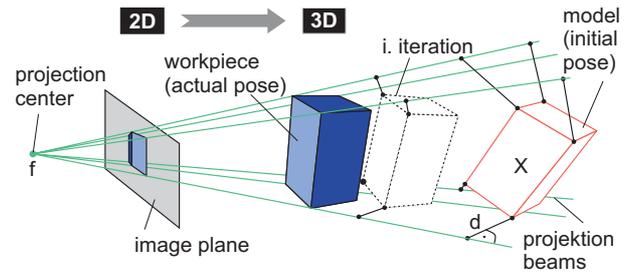


Fig. 5. Matching of the real part geometry with the corresponding CAD model

Subsequently this so-called IIPM algorithm (iterative inverse perspective matching) was further enhanced in such a way, that not every feature has to be identified through the image processing chain. On the other hand the algorithm is robust enough to handle possible image points which were accidentally identified as part vertices. In this way wrong feature correspondences between the real object and the CAD model are deleted. No extensive and time-consuming determination of hidden features has to be carried out.

The rough pose (position and orientation) that was educed by the matching process is then used as a correction value for the NC measuring program generated in the test planning. Using the correction value, the tactile fine probing can be executed safer and more efficiently (fig. 6). Collisions between the touch probe and clamping devices or the workpiece as well as void probings can be prevented and minimum initial safety distances between the probe and the object can be realized.

The aim of the machine vision supported touch probe monitoring is on the one hand to adapt dynamically each single touch point in order to measure geometries with local shape deviants. On the other hand the parameters for NC positions (stop positions, temporary positions and traverse positions) can be generated automatically by the software prototype in a way that a quick and collision free access to every touch point can be assured [1, 3].

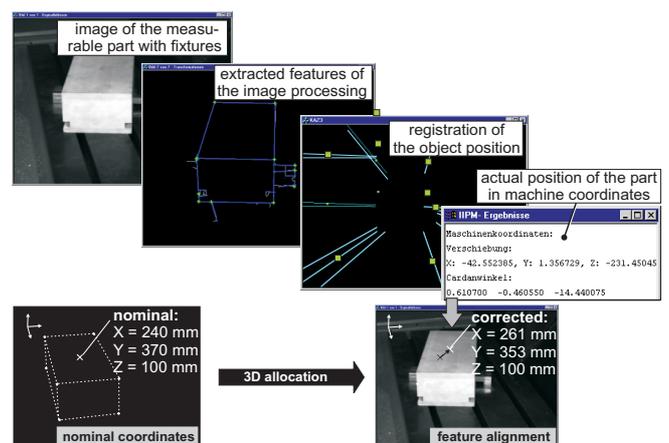


Fig. 6. Machine vision supported 3D workpiece allocation

### 2.3 Ultrasonic inline measurements

Besides geometry inspection, non-destructive material testing, especially of safety-relevant components, is of great significance. Thereby ultrasonic measuring is a reliable method which has been used for decades to characterise the interior texture and detect imperfections of manifold materials, such as inclusions, cracks or pores.

Ultrasound inspection systems use high frequency mechanical waves for non destructive inspection of the workpiece's interior. Basically two different techniques are commonly used: the through-transmission method, which relies on separate transmitter and receiver probes for sending and receiving the ultrasound pulses, and the impulse-echo method which only requires one switchable transceiver (fig. 7).

Due to the sensor setup, the impulse-echo technique evaluates the reflected ultrasound from spots within the workpiece, while through-transmission systems detect the impulse share passing through the material. Regarding conventional ultrasonic testing with fluid coupling, the impulse-echo technique is more widespread because of its easier usability with only one sensor. In fig. 7 an impulse-echo setup with a water jet probe is shown. In addition, this method also provides Time-Of-Flight (TOF) information of the echos reflected from within the part. If the sonic speed of the tested material is known, the depth position of voids or wall thicknesses can be measured precisely [4, 5].

Through-transmission ultrasound on the other side is rather used with high sound dampening materials or very large parts because the sound passes the workpiece only once. For some years the Through- and V-Transmission alignments are also used with special probes for air coupled ultrasonic testing, which is particularly relevant for the inspection of fibre reinforced plastics.

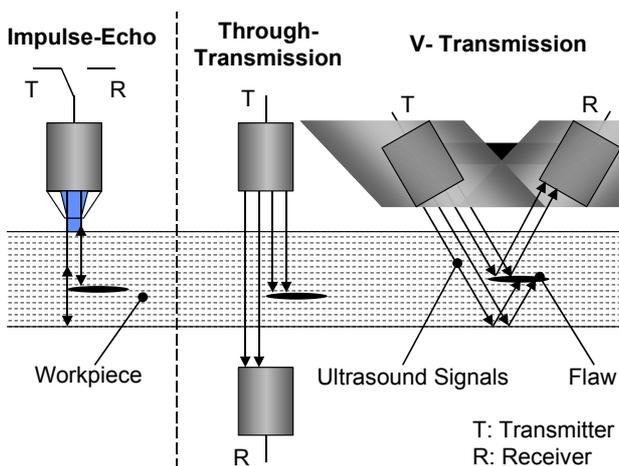


Fig. 7. Inline ultrasound working principles.

Within small batch production processes the application of ultrasound inspection techniques is often limited to time-consuming, manually operated measurements with restricted potential for further analysis and documentation.

### 2.3.1. Ultrasonic scans

Another important aspect of automated ultrasonic inspection is the automated recording and evaluation of the measurement results. For simple geometrical shapes, like cuboids or cylinders, it is possible to scan the surface back and forth or helical respectively. These ultrasonic measurements can be displayed as two dimensional images for a better survey. In general these images show plane cross sections of the workpiece. Most commonly used for the visualisation of scanned ultrasonic measurements are the so-called B- and C-scans. The B-scan shows a vertical cut view of the part, whereas the C-scan displays the interior texture in a certain depth parallel to the scanning plane [5].

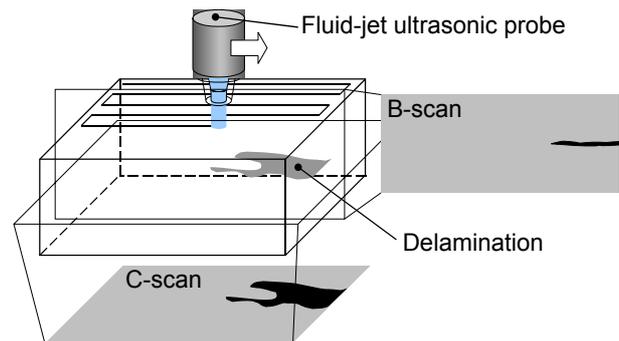


Fig. 8. Ultrasonic scan methods

In addition it is possible to save the ultrasonic measuring data of the whole volume of the part. The ultrasonic test stand at the WZL saves the ultrasonic signals of the single parts to a stack of B-Scans bitmaps without data loss. This format type has no impact on the quality of subsequently generated images but accelerates certain evaluations.

That followed a standard computer tomography (CT) software can be used to visualise the scanned volume in three dimensions, whereas the gray value of the voxels (volume pixel) shows the intensity of the ultrasonic echos. By saving all measuring data it is possible to generate and evaluate offline any desired cross section of the part. The 3D model can also be scaled according to the sonic speed of material and the measuring point density. Depending on the used CT software various geometric measurements can be performed virtually within the part's volume.

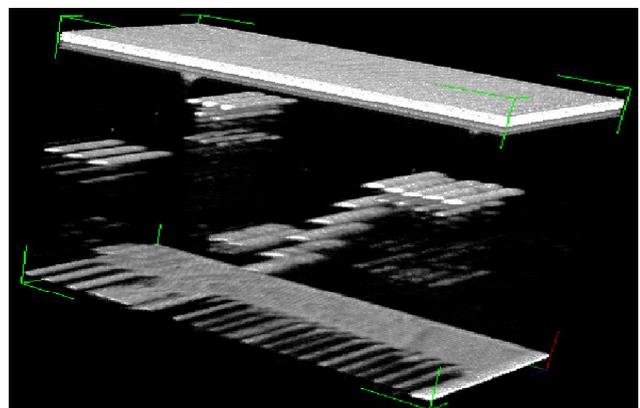


Fig. 9. 3D view of test part's interior

Fig. 9 shows a 3D view of an aluminium test block (50 x 50 x 80 mm) with differently sized blind holes. The part has been scanned back and forth from the top as shown in fig. 8, so the upper surface and its opposite side result in echos and turn also visible. Voxels with low echo significance have been blinded out to enhance the exposition of the blind hole echos. Beyond no additional processing of the measuring data has been applied.

### 2.3.2. Ultrasonic probe for milling machines

In order to fulfil the requisitions of increasing flexibility and inline deployment, a new automated changeable ultrasonic probe for milling machines, which is capable of scanning, has been developed at the WZL.

The sensor hardware is based on commercialised ultrasonic probes which use a fluid jet to launch ultrasound impulses into the workpiece. Because of its general availability in the machine tool, cooling lubricant is used as coupling fluid. The utilisation of air coupling ultrasonic probes in this sensor carrier is not possible yet because these sensors are solely used in through-transmission configurations within industrial material testing. The implementation of the transmitter and receiver in V-alignment is also restricted, due to the very limited space in the automatic tool changer (ATC).

Depending on the specification of the measuring task, different transducers can be mounted into the sensor interface by using various adapters. The sensor interface is based on a standardised HSK 63 tool holder (fig. 10). Therefore it is possible to store the entire ultrasonic sensor carrier in the ATC magazine of the milling machine.



Fig. 10. WZL Ultrasonic sensor tool

In order to realise fast, fully automated sensor changing cycles, a special interface for coupling the cooling lubricant on the one hand and the signal transmission on the other hand has been designed. During the actual milling process this connector with the signal wire and coolant tube is placed on a small bracket in the workspace. The connection

of the sensor and the measuring unit is controlled by a small NC program. The operation and signal-processing of the ultrasonic system can either be performed by an external computer or by integrating the ultrasonic hardware and software in the machine control.

During the measurement, the NC controlled milling machine's axes move the sensor across the workpiece's surface. For the prototype evaluation a 4 axes test stand has been originally been used to perform basic scanning tasks of plane surfaces or cylindrical shapes (fig. 9). For machine testing, the system was integrated in a 5 axes milling machine. This way, complex and scaled ultrasonic material tests can be carried out without setting up cost-intensive separate test facilities.

To ensure a maximum echo contrast of the ultrasonic scans, the fluid jet has to impinge perpendicularly onto the part's surface. The definition of scanning lines can be achieved for complex parts with freeforms by using a CAD/CAM tool. To visualise the complete measuring data three dimensionally in an expedient way, various coordinate transformations have to be applied first which are currently under development at the WZL.

### 2.4 Applied machine-integrated measuring systems – machine vision and ultrasonic sensor

The combination of the different physical measuring principles described above provides the basis for a very flexible inspection system capable of performing complex measuring tasks. A possible multi sensor inline measuring process is shown in fig. 11.

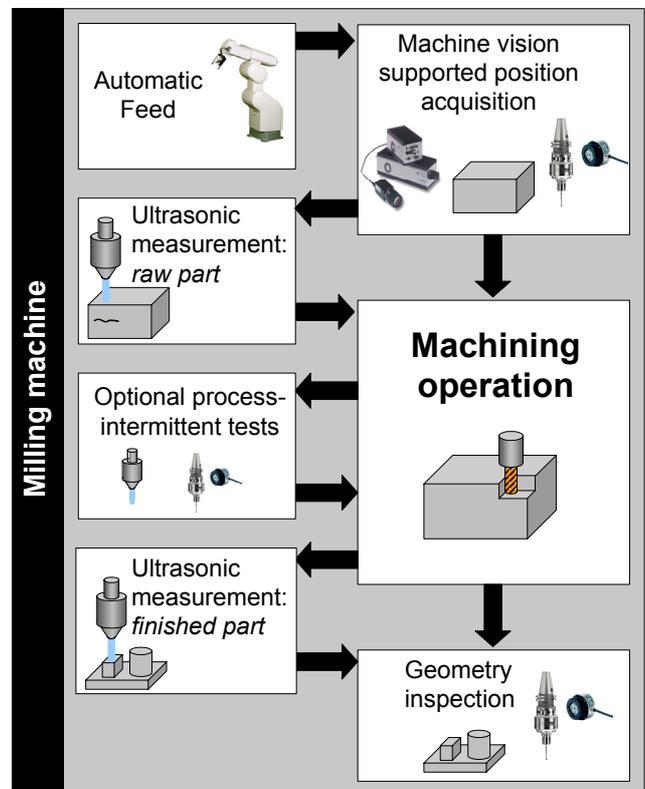


Fig. 11. Workflow of the two integrated inline measuring systems – machine vision and ultrasonic sensor

First of all the workpiece is fed to the machine chuck by an automated gripper system or manually. The workflow's next step is to acquire the exact position of the part so that the NC machining program can be aligned. In order to minimise the secondary process time, caused by the automated touch trigger probe, the machine vision system described in *section 2.2* is employed. Subsequently the ultrasonic raw part measurement can be applied optionally. This can be very profitable especially if expensive raw materials are used or if the raw part has experienced an extensive treatment before it was inserted into the machine and material flaws are likely to occur. Another reason for the assignment of this material testing technique is an interminable and therefore costly consequent chipping machining. Defective or security relevant unemployable raw parts can be rejected. Possible parts (fig. 12) for the pre-machining inspection can be cast iron blanks for crankcases, gearboxes, marine propellers or by build-up-welding refurbished extruder screws or turbine blades respectively.

After this the part is being processed. The machine integrated touch probe can be either used again at the end of the completion of critical features or after the complete machining of the workpiece.

The inline material inspection can be flexibly applied intermittently at any time during the process. An example for downstream testing with ultrasound is the measurement of section thicknesses close to ventilation and lubrication boreholes in cylinder-heads.



Fig. 12. Examples of predestined parts for the described inline measuring system

### 3. CONCLUSIONS

The herein mentioned machine-integrated measurement systems enable flexible and automated tests on workpieces to be accomplished in small batch production. Measurement tasks such as geometry inspection or material testing can be conducted easily inline. The results are fed back to reaction-time-minimised quality control cycles within the planning and controlling processes.

The machine-integration offers many advantages to the user, regarding fast characterisation and documentation of material and workpiece quality, testing times and spare additional test facilities.

In addition, after once setting up the automated measurement systems, inline quality inspection can be performed by the machine user without further qualification.

### 4. ACKNOWLEDGEMENTS

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