Application Constraints in the Design of an Automatic Reading Device for Analog Display Instruments[*]

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Abstract

An analysis system design based on experience with a successful application in the field of inspection and calibration of an analog display measuring instrument is presented in this paper. First the measuring instrument is divided into its primitiva, defining the a priori known parameter of the primitiva: shape, relative position and size. According to the shape of the primitiva pattern recognition algorithms are used to detect the primitiva in intensity images. These independent detection algorithms are then grouped into a detecting order in respect to efficiency. Following a discussion of the general design of the detecting algorithm, specific constraints of the application and the industrial environment are considered in order to refine the general design to an applicable and efficient device by modifying both hardware and software configuration depending on the given constraints. Finally, results of the implementation of the algorithm and the constructed image acquisition device are discussed.

1 Introduction

Machines with analog control instruments are still used in industrial production lines and these measuring instruments have to be monitored by factory workers instead of by an automated process monitoring system. Furthermore, analog instruments are often used in places where a continuous power supply is not ensured or too expensive. The calibration of analog display instruments can be automated by using an automatic reading mechanism which is both safer and cheaper.

Reading a measuring instrument means detecting the position of scales and pointers in the intensity image to determine the value the measuring instrument displays. The design of an automated reading process for an industrial application requires that we consider not only pattern recognition algorithms for solving the problem but also several constraints which are given by the industrial partner and the industrial working process.

In this paper the general recognition theory for many different types of measuring instruments shown in [8] is extended and described in more detail, considering both industrial constraints and the fact that no redesign of the working process should be necessary if, for example, another measuring instrument is used, or if the pointers have different colors, or if the illumination conditions differ, or if the measuring instrument is rotated or if other changes occur. To reach this goal, the primitiva of the measuring instruments and the application constraints have to be determined (Section 2). According to the shape of the primitiva, pattern recognition algorithms to detect the primitiva are tested and integrated into a specific detection algorithm (section 3). However, before the detection process can take place, the important step of image acquisition and illumination must be carried out (section 4). The final development stage adapts the working process to the constraints given by the industrial environment (section 5). The paper concludes with a discussion of the results.

2 Primitiva and constraints

Pointers, scales and lettering elements are the primitiva of an analog measuring instrument (Fig. 1).

A **pointer** can have any symmetric shape with a medial axis such as a triangle, a rectangle or a combination of both. Pointers that rotate have a circle at their center of rotation. The shape is defined by a bitmap, containing one half of the shape and the medial axis.

The shape of a **scale** depends on the motion of the pointer. The shape of a rotating pointer is a **circle** or a **circular arc**. Pointers moving straight usually have rectangular scales. Scale captions are considered as part of the scale.

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[*] This work was supported by the Austrian National Fonds für die gewerbliche Wirtschaft under grant Z13/9934.

0-8186-6410-X/94 $4.00 © 1994 IEEE

There are other layout elements of a measuring unit that carry information about the measurement and the global orientation, classified as **lettering** (e.g. ÖRG in Fig. 1). This includes all forms of writing such as unit information, company name, firm's symbol, etc.

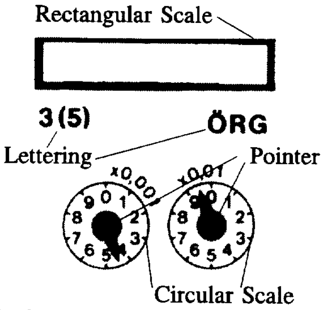


Fig. 1 Elements of a measuring instrument

One constituent is implicitly given with any measuring instrument - the measurement space. It defines what unit and what value the **measuring unit**, consisting of a scale and a pointer, displays and at what sample rate the displayed value can be read. The measuring space also defines the absolute measuring value the **measuring instrument** displays, as a combination of all measuring units. Note that we assume that one measuring instrument can measure only one physical unit.

Besides the primitiva, several constraints are given by the industrial working process and the industrial partner. The most important of these are **computation time, accuracy, extendability** to other instruments, and **cost**. Therefore it is necessary to find an optimal balance between these constraints.

3 Detection algorithms

In the following we report our experience with several methods for detecting basic primitiva. The kind of elements to be looked for are circles, rectangles and pointers. Therefore, algorithms for detecting these shapes were tested and combined in order to be able to detect the primitiva in the image and to read the value the measuring instrument displays. The primitva's relative parameters, such as relative size, relative position on the instrument and valence, have to be known a priori to detect them. These parameters form the vocabulary and the relations between the primitiva, the grammar of a description language which can be used by the analysis process to make hypotheses about the position of the primitiva and to verify them. The general recognition theory for several types of analog measuring instruments is shown in [8].

For an industrial application like quality control in the manufacturing process this general recognition process has to be adapted for a very limited number of different types while taking industrial and economic constraints into account. In this section we describe the algorithms used for primitiva detection and the analysis process used for this specific application where only one type of measuring instrument is used.

3.1 Circular scale detection

To detect circular, arc- shaped scales in the intensity image, we use a detection method based on the Hough transformation [7,10]. The Hough method [6] is extended to circle detection by Duda and Hart [4] and extended by Ballard and Brown by using the gradients [3]. The detection process has the following steps:

Edge detection: The local derivatives in the x and y direction are computed and form the gradient;

Hough transform: Circle centers are clusters in the accumulator space;

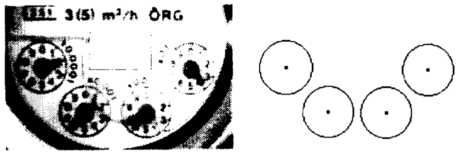
Peak enhancement: The accumulator image is convolved with a 9x9 Laplacian-like peak filter as derived in [4];

Max finding: A procedure finds the center of the peak with a neighborhood operation.

The result of circle detection is a set of potential candidates for arcs and circles. The circular Hough transformation estimates the position and the radius of the circular arc or circle. To verify if the candidate is a circular arc or circle, the edge points of the supposed circle are counted along the circle. If the density of detected edge points on a sector of a certain angle is more than 70% of the circle points in the sector, this sector is accepted as a circular arc; if 70% of the circle sectors are accepted, the supposed center is a center of a circle.

Fig. 2 shows the result of detecting circles in intensity images. These circles are the scales of a measuring instrument with 4 circles and all of them were detected.

We carried out a test series with 50 different images of several measuring instruments of the same type. The images contained the measurement instruments (app. 4 inch x 4 inch) in different resolutions (from 100x100 pixels to 400x400 pixels) and under different lighting conditions. Approximately 80% of the circles were detected in the test series. In the images with high resolution (400x400 pixel), 100% of the circles were detected.



intensity image detected circles

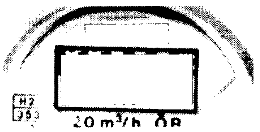
Fig. 2 Detected circles

3.2 Rectangular scale detection

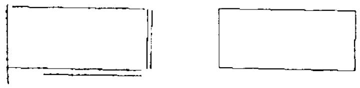
A rectangle consists of 4 straight lines, which we detect using an approach developed by Burns et. al. [2]. This algorithm groups pixels into line support regions of similar gradient orientation. The structure of the associated intensity surface is used to determine the location and properties of the edge. Four steps can be distinguished:

1. Group pixel in line support regions;
2. Approximate the intensity surface by a planar surface;
3. Extract attributes length, location, orientation;
4. Filter lines with certain length, location and orientation;

Steps 3 and 4 were changed from the original algorithm because our aim is to detect lines belonging to rectangles in the intensity image. Only three features given by the Burns algorithm are used, leaving long straight lines in the line set. An orientation histogram is computed and lines with 90° orientation difference are combined to form rectangles (Fig. 3).



intensity image



detected lines detected rectangle

Fig. 3 Detected rectangle

3.3 Pointer detection and verification

We tested two different methods for detecting the pointer in the scale area:

M1. Independent computation of gray level profiles along curves in the image plane: The intensity values are summarized along an axis and the center is supposed to be the location of the pointer. The mean intensity value of the pointer is computed in the center of the circle. Subsequently this mean intensity value is used to count pixels with similar intensities in the angle histogram.

M2. Multiresolution computation: This method is based on dividing the scale area into sectors and computing the weighted deviation from mean. This deviation gives a probability for the position of the pointer in a sector. Coupled pointers have a special feature: the previous pointer defines the position of the following pointer as shown in Fig.4. The pointer displaying the lower valence (e.g. 1) defines the position of the pointer displaying the higher valence (e.g. 10). If the lower pointer displays 0 for instance, the pointer with the higher valence has only a limited number of possible positions as shown in Fig. 4a. If the lower pointer displays 5 for instance, the pointer with the higher valence has again a different, limited number of possible positions (Fig. 4b). Every measuring unit contributes one digit to the number to be measured. The reading of the values indicated by the pointer position starts with the lowest valence. This strategy is characterized by low error propagation.

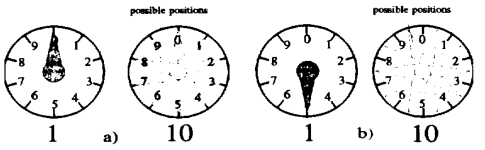


Fig. 4 Reduced search space

Let $\bar{e}_i$ denote the measurement value and e_i the correct value. If the reading error for e_{i+1} is $|\bar{e}_{i+1} - e_{i+1}| < \delta$, the reading error for the next valence is: $|\bar{e}_i - e_i| = |\frac{\bar{e}_{i+1}}{u_{i+1}} - \frac{e_{i+1}}{u_{i+1}}| < \frac{\delta}{u_{i+1}}$ For the unit of the next valence $u_{i+1} > 1$ holds (e.g. 10 in Fig.4), therefore the error of the lower valence has a small propagation and has little influence on measurement determination.

The second method was applied to the special type of measuring instrument used by our industrial partner. Fig. 5 shows the result of the pointer detection. The upper half shows the intensity images of the pointers and the lower half the results of the applied analysis algorithm. Note that the computed value is always the previous value on the scale if the pointer has not yet passed the scale value. For example, one might think the computation has led to incorrect results, because the rightmost pointer displays the value 2 and the computed value is 1. In reality the pointer has not yet passed the value 2, because the pointer with the lower valence displays 9.

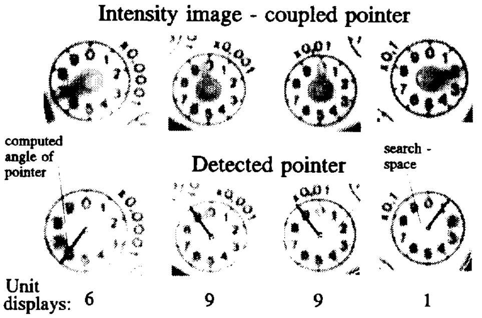


Fig. 5 Detected coupled pointers (0.1996)

3.4 Lettering

The detection of lettering elements has two different purposes. Lettering elements can be taken to check and verify the type and orientation of the measuring instrument. In this case the lettering element is postulated in a certain position and orientation in the image and checked by computing the correlation coefficient between the window found in the intensity image and the bitmap of the lettering element. The computed correlation coefficient defines the similarity between the detected area and the generic area and gives a probability for a match.

3.5 Detection strategy

This section briefly describes the steps of the analysis process. In order to simplify the diagram, Fig. 6 does not show the interaction of all processing steps with the parameters of the a priori given primitives (like size and relative position) and error treatment. If an error occurs in any processing step, the analysis process is stopped.

Image acquisition: Image acquisition is the first important step in the analysis process. Details of hardware and lighting conditions are described in the following section.

Measuring instrument detection: Because position and size of the measuring instrument in the image are not known a priori they have to be detected. The shape of the instrument to be detected (in our case) is circular, so we use circular scale detection for detecting the instrument in the image with regard to topological, radiometrical and geometrical features of the instrument. The result is the detection of the instrument, its center (origin of the object-centered coordinate system) and its image size.

Scale and pointer detection: The detection and localization of measuring unit primitiva is carried out in the limited area of the previously detected measuring instrument. First, all circular scales and the rectangular scale are looked for because they cover a larger area in the image than the pointers. Therefore scale detection (both circular and rectangular) is more robust than pointer detection. The search space for the corresponding pointer is restricted by the region defined by the detected scale (section 3.3). This analysis step supplies the specific position and size for all scales and pointers as well as the orientation of the instrument.

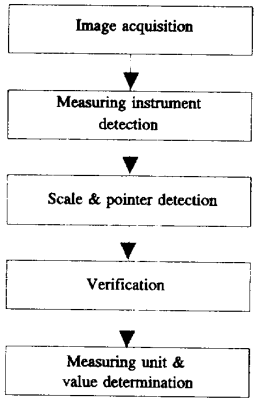


Fig. 6 Analysis process

Verification: Verification of the generated hypotheses about the size and the orientation of the measuring instrument is necessary. In order to answer the question "Are the measuring units in the right places on the measuring instrument ?", the detected measuring instrument is verified by checking the supposed position of the lettering elements in the image. This step also helps to avoid computation of measuring instruments that have similar size and primitiva but were not tested for automatic reading.

Measuring unit and value determination: The value for each measuring unit is determined by relating the position of the pointer to the orientation of the scale. The value for each measuring unit is the result of this processing step. The values of several measuring units are combined according to their valence into the measurement value of the instrument.

4 Image Acquisition and Illumination

One of the most important steps in the analysis process is image acquisition, because the quality of the images strongly influences the quality of the result. In order to ensure an accurate analysis, the image of the object should have high contrast and there should not be any shades or reflections in the image.

4.1 Image acquisition

There were 3 constraints for the image acquisition given by our industrial partner:

- low cost hardware
- pointers can move during image acquisition
- 12 inch maximum distance between camera and measuring instrument

To optimize resolution and the constraint of low hardware costs we used a commercial quality monochrome CCD camera Sony XC 75CE with a resolution of 752 x 582 pixel in connection with an suitable low cost monochrome framegrabber board.

To fulfill the second constraint of "moving pointers", the camera type with shutter option is used. The shutter speed can be selected from 1/125 to 1/10000 seconds. The maximum speed of the pointer is 15 revolutions per second and there are 10 different scale positions. A shutter speed of 1/250 was selected to ensure a minimum accuracy of ± 18 degrees of the position of the pointer in the image at a certain time. At lower pointer speed the accuracy of the pointer position is of course higher.

The maximum distance between measuring instrument and camera was set at 12 inch due to the industrial environment. Therefore we used a 0.3 inch C-mount lens of standard quality for the image acquisition. Lenses with a shorter focal length (0.2 inch and 0.25 inch) where tested but not selected because the distortion of the standard quality lenses was too high. The circular scales on the measuring instrument became elliptical and the circle detection did not operate without lens correction. In order to avoid camera calibration and lens correction an 0.3 inch lens was used for image acquisition.

4.2 Illumination

The industrial environment allows only two solutions for the illumination problem. Either complex preprocessing has to be done to adjust different illumination conditions in the factory or constant illumination is provided by a special illumination device designed for the special illumination problem [1]. We chose the second solution for two reasons: it helps to ensure correct reading and it can be implemented in our special environment.

Like most of the measuring instruments, our instrument is covered with a glass plate. As a result there are specific problems with specular light and shadows. With specular light a reading of the pointers is impossible because a highlight in the area of a pointer makes the pointer invisible and therefore unreadable. These highlights can be avoided if the angle between the light reflected on the glass plate and the optical axis of the camera is more than 30° as shown in Fig. 7.

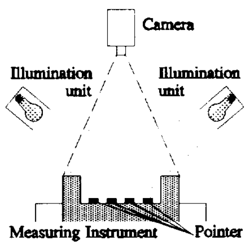


Fig. 7 Illumination avoiding highlights

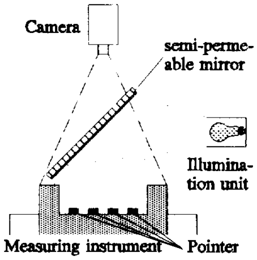


Fig. 8 Profile projection illumination

Another illumination problem that causes incorrect reading of the pointers results from the shadows produced by the pointers. Pointers always have to have some distance to the background in order to be moveable (in our case app. 0.1 inch). This distance produces shadows cast by the pointer and therefore ambiguities in the determination of the pointer's position. A result of this illumination configuration is shown in Fig. 10a where shadows cast by the pointers can been seen. For this reason and because of the special shape of our measuring instrument, the illumination- configuration shown in Fig. 7 cannot be used to illuminate the measuring instrument.

Another commonly used illumination method in industrial applications is called the profile- projection method, which uses a semipermeable mirror positioned at an angle of 45° to the optical axis of the camera to diffract the light on its specular side onto the surface of the object (Fig.9). The illumination direction is at an angle of 90° to the optical axis and is defracted in the direction of the optical axis. Subsequently the light is reflected from the object without producing shadows. The drawback of this configuration is that it works only if there is no glass plate on the measuring instrument. In our case the light was totally reflected by the glass plate as shown in Fig. 10b. Therefore we had to construct another

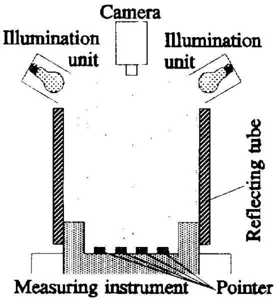


Fig. 9 Reflecting tube illumination configuration

illumination- configuration that overcomes the difficulties with specular lights and shadows. A homogeneous, diffuse illumination of the measuring instrument is necessary to obtain a good basis for further computation.

A tube with a diffuse, specular inner surface was affixed to the measuring instrument as shown in Fig. 9. This 6 inch high reflecting tube was illuminated by two lamps on the top of the tube with an illumination angle of app. 70° with respect to the optical axis of the camera. The surface of the tube defracts the incoming light diffusely onto the opposite side of the tube, there it is defracted once again and so on. The set- up of this illumination configuration turned out to be optimal in our tests because neither highlights nor shadows disturb image acquisition (Fig. 10c).

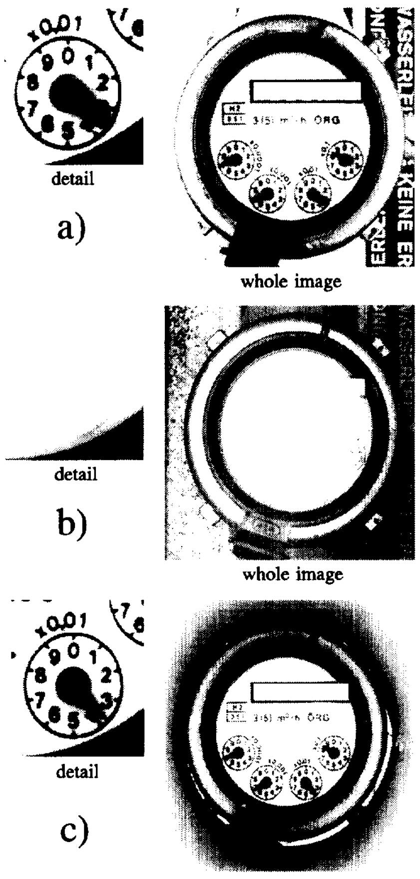


Fig. 10 a) highlight avoiding b) profile projection illumination c) reflecting tube

In our first test series in the industrial environment the tube was used even without the lamps, using the ambient light in the factory. It turned out that a correct result of the automatic reading process is given with a probability of more than 90%.

5 Tradeoffs

The general detection strategy presented in section 3.5 was first implemented in an experimental developing environment on a Unix platform with a series of test images taken under laboratory conditions to take advantage of fast prototyping with high computation power. After demonstrating the practability of the presented detection strategy, the working process had to be adapted to an industrial environment. Five main constraints have to be fulfilled for this application:

Speed: The reading of the pointer has to be performed in a previously defined time of max. 3 seconds/frame.

Cost: Due to industrial application and reselling strategies, the hardware cost had to be minimal.

Accuracy: Since the automatic reading is used for calibration and industrial process monitoring, reading accuracy plays an important role.

Reliability: The accuracy, the reliability has to be close to 100% to ensure correct calibration and monitoring.

Archivation: In order to fulfill the ISO 9001 quality inspection standard, all measurements have to be archived in image and numerical form together with further data of the measuring process such as time, date, serial number and the like.

The archivation constraints were taken care of by using JPEG data compression for image archiving [9] and a database. The rest of the constraints had to be considered in more detail because the automatic reading process should be integrated into an existing working process, in which the maximum computing time is set at 3 seconds per frame. This computation time was barely reached by using a SUN Sparc 10 workstation for which the hardware costs are already too high for our industrial partner. Therefore we made several tradeoffs between speed, costs, accuracy and reliability in order to achieve an optimal balance of the given constraints.

5.1 Speed versus number of free parameters

The reading process has three image acquisition parameters which allow a very general application of the

reading process to a given measuring instrument:
Size (s): The measuring instrument can have any size within the intensity image (of course there is a minimum size defined by resolution and reading accuracy). The change of the size is caused by the change of the distance between camera and measuring instrument.
Position (x,y): The measuring instrument can have any position in x and y direction within the image.
Orientation (o): The measuring instrument can have any orientation in respect to the camera orientation.

If all of these parameters are not fixed to a certain range, the reading process takes 3.7 seconds. Therefore a successive restriction of these parameters reduces the computation time while decreasing the generality. First the size of the measuring instrument is fixed in the analysis process. In this way, the search space of the circle detection (see section 3.1), detecting the measuring instrument is confined to a small number of possible radii (in respect of δs) and therefore performed with higher speed. This modification saved 20% of computation time and therefore the process fullfilled the time constraint but forced a fixed distance between camera and measuring instrument.

Due to a modification of the final image acquisition configuration it was possible to ensure the position of the measuring instrument on a nearly fixed place within the image, restricting the position parameters to $[x \pm \delta x, y \pm \delta y]$. Therefore a modification of the analysis process could be made by eliminating the processing step "measuring instrument detection", again saving 25% of the computation time. The fixed imaging geometry requires an accurate positioning of the camera or the measuring instrument and was obtained by designing an attachment including illumination units and camera.

5.2 Speed versus costs

Hardware costs play an important role in industrial applications if the system is to be widely used and be resellable. This led us to the decision for a standard PC 486 configuration instead of a workstation configuration, reducing the hardware cost by 80%. This cost reduction has the drawback of dramatically decreasing computation power. After converting the software onto the PC we measured a computation time of the analysis process of 20 seconds/frame, including scale and pointer detection, determination of orientation and measurement value.

As a consequence, the last free image acquisition parameter, orientation, had to be fixed. The fixation of orientation was possible by adapting the attachment device such that it can only be attached in a certain, mechanically fixed way. Subsequently the detection strategy was modified in the following way: only the left- and rightmost circular scales are looked for in the intensity image instead of all scales. The size of the search window is defined by the number of pixels representing the positioning error $x \pm \delta x$, $y \pm \delta y$ and the size of the circular scale (in our case δx and δy are 5% of the diameter of the circular scale). This fixation of the position reduces the search space down to 10% of the previous search area (the complete measuring instrument).

Out of the relative position of the centers of the two detected scales all other scale positions are computed before a simple verification and the pointer detection (see section 3.3) takes place. With this adaption to the detection strategy the computation time is within the desired 3 seconds per frame limit with the requested accuracy.

5.3 Speed versus accuracy and reliability

The tested accuracy of the general detection strategy is $\pm 3°$ determined by the given resolution of app. 500x500 pixels for the measuring instrument. This resulted in a computation time for the adapted reading process (all acquisition parameters fixed) of 4 seconds. Due to the use of coupled pointers with discrete positions and a graduation of 10 units in a circle in combination with low error propagation (see section 3.3), the minimum reading accuracy of the pointer angle detection is $\pm 18°$. This accuracy decreases the reliability and requires very stable illumination conditions in order for the position of the leftmost pointer to be read correctly. Therefore a tradeoff between accuracy and speed has to be made in order to ensure the requested reliability. Our tests demonstrated that an accuracy of $\pm 8°$ is the best tradeoff between speed and accuracy. This reading accuracy reduces the resolution to 300x300 pixels for the measuring instrument and led to a computation time of app. 2 seconds per frame which is within the time constraint.

5.4 Experimental results

The adapted algorithm was tested comprehensively with our PC configuration both under laboratory and industrial conditions. The position of **all elements** except the lettering was determined in the **requested time**, with the requested **accuracy** and **reliability**.

For the example in Fig. 11, the analysis process computed 0.8361 units. Note that the coupled pointer computation method is used, therefore pointers which have not passed a value on a scale completely are considered to display the previous value. The analysis process is tested with a test series of 200 frames under laboratory conditions. All of them were computed correctly.

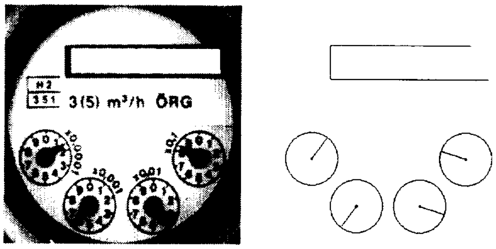


Fig. 11 Detected scales and pointers: 0.8361

During a test series (400 frames) conducted under industrial conditions without special illumination (the test series was conducted with the configuration in Fig. 9 but with ambient light instead of special illumination), the lack of light led to images of very low contrast, causing a rejection rate of 5% (20 frames were not computed because there was not enough contrast in the image to find the circular scales and hence the pointers). Although there was a rejection rate of 5%, the reliability of the reading process was 100% because images that could not be read were marked unreadable and stored for visual inspection by an operator. All of the computed measurements were correct.

6 Conclusion

In this paper we have presented a special application in the field of inspection and calibration of an analog display measuring instrument. A general approach was designed by dividing the measuring instrument into its primitiva and defining the a priori known parameter of the primitiva: shape, relative position, and size. According to the shape of the primitiva suitable pattern recognition algorithms were implemented and tested in order to detect these primitiva in the intensity image. After testing and refining the primitiva detection a general detection strategy was developed to solve the problem of reading the measuring instrument automatically. Instead of detecting primitiva independently, a detecting order was used to enhance efficiency. The last stage in the design of the analysis process refines the coarse analysis process by adding constraints generated by the specific application and the industrial environment, which are: **speed**, **cost**, **accuracy** and **reliability**.

This refinement influenced both the hardware and software configuration with respect to the given constraints and practicability. Therefore we have suggested a general approach for the solving of a specific problem and have refined this approach by adding constraints given by the specific application. These constraints are heavily interdependent and have therefore to be balanced in an optimal way in order to be applicable in an industrial process.

Acknowledgment

The authors want to thank Hannes Foettinger and Robert Brandner for their help during the adaption of the analysis process for industrial application.

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