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USE-APPROPRIATE DESIGN OF AUTOMATED OPTICAL INSPECTION SYSTEMS FOR ROTATIONALLY SYMMETRIC PARTS

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ABSTRACT

Presently, there is still a lack of concepts and technical design guidelines for automated optical inspection systems for rotationally symmetric parts. This paper provides an approach to solve this problem and presents a design support method based on decision trees. In order to understand the capabilities a systematic review of state of the art in inspection methods has been achieved. Sub-problems are identified and systemized within the complex environment. Subsequently principal challenges and practical case applications on industrial products are described.

Index Terms – automated, optical inspection, imaging, quality assurance

1. INTRODUCTION

Nowadays, there is a consumer driven demand for products with a constant high quality even for low-cost products. Mastering the production processes parameters only cannot meet these goals. Additional measures like continuous automated inspection of production process and final products are in many cases the only way to achieve the quality requirements. Automated optical inspection plays a very important role in this area.

A rapid growing number of practical solutions for automated optical surface inspection, which provide a reliable quality control on parts with plane surface, are already available. Even in the case where the surface is slightly curved, solutions based on inexpensive components have been proven to be highly efficient. However, the optical surface inspection of cylindrical or other rotationally symmetric parts is quite challenging in industrial practice. These parts can be found in almost all sectors of industry such as automotive, electronics and food industry. Some typical examples are: shanks, screw heads, bushings, installation fittings, food packaging etc.

2. OBJECTIVES AND PROBLEM FORMULATION

2.1. **Objective**

This paper provides a systematic review of state of the art in inspection methods. A novel approach is the holistic view of the inspection task with a wide variety of possible solutions rather than a selective analysis of one solution. In order to perform the problem analysis, first of all sub-problems are identified and systemized within the complex environment of automated optical inspection. Subsequently principal challenges and a practical case study on an industrial product are described.

2.2. **Problem formulation**

Optical imaging of rotationally symmetric surfaces cannot be obtained from only one point of view with the aid of a single camera acquisition in a usual case. In fact, the surface has to be captured either in several images from different angles which are subsequently combined into one view or by using specially designed optical systems like mirrors and lenses. In particular, for shiny metallic surfaces, a careful selection and configuration of the imaging system requires special endeavors due to reflections. The implementation efforts for such inspection systems are often underestimated despite the high performance of current image processing methods. An inconsiderate comparison with the very powerful human vision and cognition often leads to lacking consideration of important boundary conditions for image acquisition and defect detection. Further the quality of the image data plays a key role for the performance and service capability of an inspection system. The goal should not be to acquire as much image data as possible, rather than as much as necessary for a given task. This implies in particular the selection and design of the inspection method, the imaging optical system as well as the lighting concept. The optimization of the imaging and lighting method should be targeted on providing the best possible contrast of the surface features which should be detected. In the subsequent step of image analysis the features can be recognized and reliably classified. Additionally, in a dynamic image acquisition the usual small surface defects have to be imaged with suitable short exposure time of the imaging sensor in order to avoid in-motion blur effects. This effect usually decreases the required contrast between the feature which should be detected and the flawless surface. In this context, the maximum brightness used of a lighting system is of significant importance.

The subsequently presented solutions for optical inspection of rotationally symmetric parts show that there are a wide variety of possible approaches existing for this problem. It could create the impression that due to the variety of solutions there is no need for further scientific work concerning this field of research. However especially the wide variety of established approaches for practical inspection tasks with rotationally symmetric parts poses a challenge to the person in charge. On the one hand, the best possible approach out of a wide variety of solutions has to be selected at first and on the other hand to have a suitable configuration and dimensioning within the selected approach must be provided as well. A systematic approach should support the system developer in the decision process. Through a systematic analysis of parameters and possible solutions a problem-oriented solution can be realized in a shorter development time.

3. SURVEY ON AVAILABLE INSPECTION METHODS

In the context of this work an extensive enquiry regarding the analysis of the various possibilities of the inspection of rotationally symmetric parts has been accomplished. These various concepts show a wide range of realization possibilities.

3.1. **Single camera with direct optical path**

Illustration assemblies with a single camera and a direct optic path are part of the basic approaches of the automated optical systems. Area scan cameras as well as line scan cameras can be employed.

3.1.1. Area scan cameras

In the simplest case the part to inspect can be observed radially by one camera only. In a single view only a section of the whole surface can be observed. To detect the whole surface the inspection area has to be changed. This often is realized by turning the part under test around its longitudinal axis in front of the camera. The turning is carried out step by step with a rotation angle matching the field of vision of the camera. As a result an image with several frames is generated. It represents the surface in multiple partial views. Due to the curvature of the surface of the part under test and associated distortion effects, usually more than two partial views are needed. The number of shots depends on the individual requirements of the inspection task.

This approach basically corresponds to the surface imaging with the aid of a line scan camera with a single difference that not only one line but a strip-shaped area of the object can be depicted by every single shot. A different approach to the surface scanning in front of the camera is proposed in [1].The test system consists essentially of an area scan camera, a directional illumination and a transparent pad for the part under test (Fig. 1).

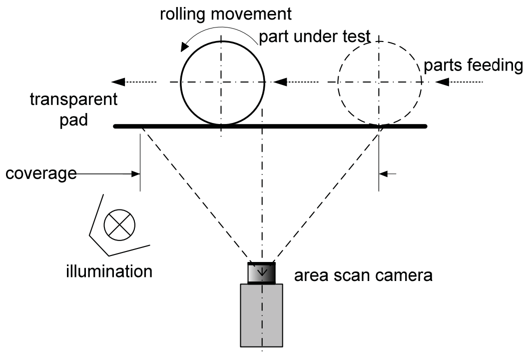

Fig. 1: Imaging system with an area scan camera according to [1]

The camera and the illumination are located below the glass plate and are aligned toward of the test object. To ensure the illustration of the entire surface, the circumference of the part under test gets visualized by rotating the part to inspect continuously.

Thereby the cylindrical test part accomplishes a rolling motion in the field of vision of the camera. With the aid of a suitable illumination on the underside of the glass it gets illuminated in that way, that on the instantaneous axis of rotation a strip-shaped light reflex is built in which the errors are contrasted. The exposure time of the image sensor is adapted to the speed of rolling in such a way, that one part revolution is scanned in one image.

3.1.2. Line scan cameras

The approach of the surface inspection of a cylindrical object with a line scan camera is based on the concept of successive surface scanning. For capturing the surface, a relative movement between the surface and the camera is required. The object under inspection rotates around its longitudinal axis. During the rotation of the inspected part, the camera takes consecutively line shaped areas of the surface. The width of the captured areas depends on the parameters of the imaging system. The sampling frequency results from the required resolution of the image. Surface inspection with a line scan camera and direct optical path are used relatively often in practice. The rotation of the part under test around its own axis is often ensured by a direct drive and by clamping the part. An automatic inspection system for security relevant valve bodies on the basis of a line scan camera is mentioned in [2]. An indirect drive of the parts under test with a rolling movement and without clamping the parts is proposed in [3] and SEEBACH 2010 #361}. A possible slip between the drive rollers and the test part is compensated by the selection of a longer image acquisition. In the captured image of the surface, the border areas overlap to a certain degree.

3.2. **Multi camera systems**

In order to meet a given test time, it is possible to capture the surface of the part under test simultaneously by several partial views from different angles using multiple cameras. One of the commonly used imaging systems is an arrangement with multiple area scan cameras radially arranged around the test part. The required number of partial views depends on the required quality of the surface assembly. By decreasing the demands, a cylindrical surface can be illustrated with three sub-views. But the achievable image quality is not always sufficient for the demands placed on a global surface inspection, due to the lateral resolution of a single image in the circumferential direction decreases significantly towards the edges of the object. The highest lateral resolution of a partial view is available in the central area of the object. The descending lateral resolution affects the size of the smallest feature of a detected surface negatively. To set high standards definitely six cameras can be necessary. Basically, the cameras are arranged in a circle at equal angular intervals around the part under test. The camera axes are aligned radially to the axis of the part to inspect (Fig. 2).

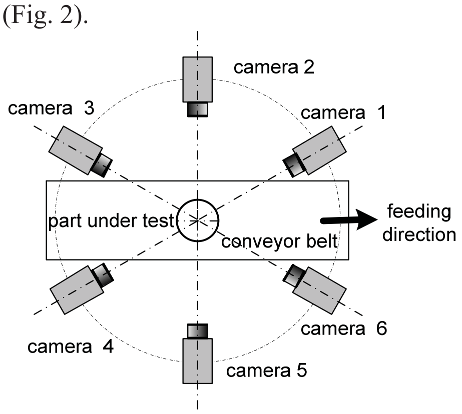

Fig. 2: Multi camera system with six radial arranged area scan cameras

The supply of parts to the camera system is carried out continuously by a conveyor belt. Such a system is described in [4]. The system is primarily designed for the testing of barrel-like beverage containers, and consists of four area scan cameras, which are radially arranged around the test object. A similar system is described in [5]. The number of cameras depends on the requirements of the inspection task. In general, systems with four cameras are used. An inspection system for all around inspection of cylindrical packaging with six area scan cameras is described in [6] and a similar system for the inspection of small volume parts, such as metal rings, is presented in [7].

Disruptive effects that occur in connection with complex illumination arrangement can potentially be compensated by an axial displacement of the cameras in relation to the axis of the part which was tested. A typical representative of such solutions is described in [8]. A variation of the test arrangement with radially arranged cameras is described in [9]. Here, the optical axes of the cameras are not perpendicular to the longitudinal axis of the tested part, but form an acute angle. The cameras are positioned underneath the part to inspect (Fig. 3).

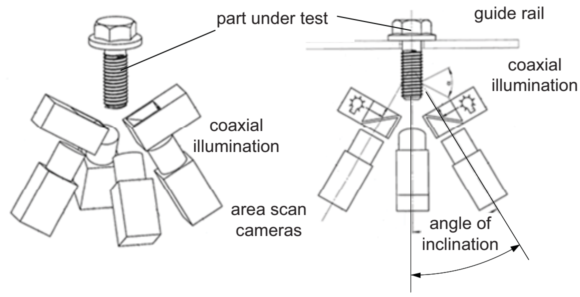

Fig. 3: Tilted multi camera system according to [9]

3.3. **Catadioptric imaging systems**

Imaging systems not only consisting of refractive but also of reflecting optical elements in the beam path are called catadioptric systems [10]. The image of the object is specified by refraction of light rays in lenses (dioptric) and by the reflection from mirrors (catoptric). In terms of following considerations lenses and other refractive optics are meant as dioptric elements. An approach proposed in [11] uses a line scan camera in combination with a pivotable mirror to deflect the optical path. The inspected cylindrical objects are transported on rollers (Fig. 4) and fed into the inspection system. The rotation and a translational motion of the test parts are carried out simultaneously. The imaging is performed by a line scan camera. The pivotal movement of the mirror is synchronized with the linear movement and the rotation of the tested part in that way, that during a panning of the mirror a complete snapshot of the lateral surface of the inspected part is generated. A typical application for this imaging system is sorting of dry cell batteries.

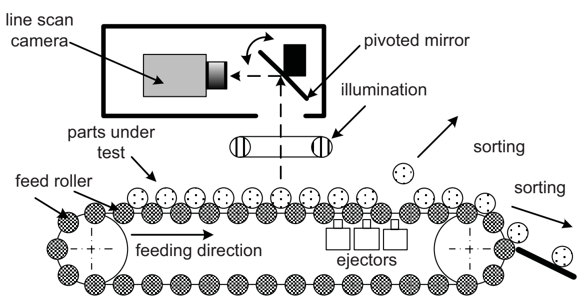

Fig. 4: Inspection system with a line scan camera and pivoted mirror according to [11]

An inspecting system using two area scan camera units with entocentric lens and a mirror system each is described in [12]. The cameras observe the surface to inspect by means of mirrors and acquire two partial views. The partial views each have shifted viewing perspectives and map the surface in an overlapping way. Primarily, this imaging arrangement is designed for the testing of cigarettes. Similar imaging systems are described in [13]. Here various configurations of free-form mirrors (Fig. 5 left), flat mirrors and prisms (Fig. 5 right) are used along the beam path. The arrangement creates a distorted continuous image of the surface of the object with free-form mirrors. Imaging systems with prisms and plan mirrors create two separate partial views in a camera image.

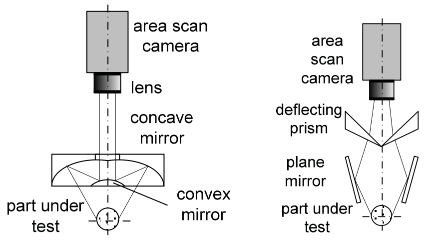

Fig. 5: Catadioptric imaging ystems,
free form mirror system – left, prisms and plain mirrors – right; according to [13]

A mapping solution based on a plan mirror and a corner mirror (Fig. 6) is described in [14]. During the test the inspected part is located in the middle of the arrangement and gets inspected simultaneously from four different perspectives by one camera. The transport of the inspected part is linear across the axis of the camera on a conveyor belt. A similar test system is presented in [15]. Typically, this arrangement is used to inspect cylindrical and cylinder-like objects such as rods, tubes and pills [16].

Systems with coaxially arranged axes of the camera and of the inspected part belong to another subset of possible imaging systems. They form the outer surface of a test object in multiple views within a camera image.

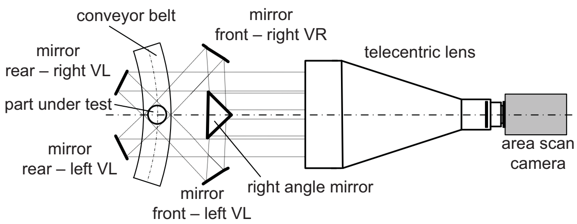

Fig. 6: Catadioptric imaging system with tilted mirrors and radial camera alignment

The mirrors are located above the test object, equally distributed on a circumference and inclined to the vertical position (Fig. 7 left). In the camera image the partial views of the faces of the inspection parts appear arranged in a ring around the top view of the inspection part (Fig. 7 right). The number of facet mirrors used in the imaging system depends on the application and ranges four or six to eight or even more.

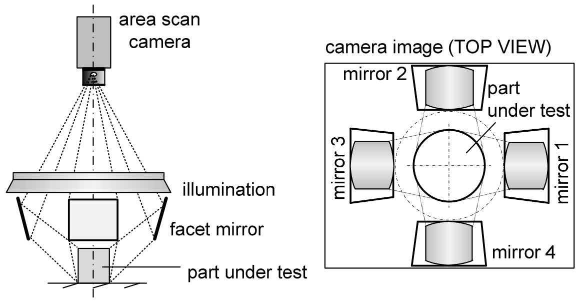

Fig. 7: Catadioptric imaging system with multiple inclined mirrors and axial camera alignment

A test system based on facets mirrors is described in [17]. It consists of mirror optics with six facets and is used for inspection of both the shell and the inner surfaces of straight prismatic bodies. A related system with faceted mirrors for the inspection of bottlenecks is used by [18]. A system with eight facets mirrors which is optimized for the inspection of external surfaces of rubber gaskets is described in [19]. It should be able to inspect parts with diameters in the range 38…50 millimeters at a detailed resolution of up to 33 µm. In the imaging system described in [20], the surface areas of test objects are represented by multiple facets mirrors. In addition in this system a further beam deflection in the beam path on a truncated pyramid-shaped body with eight mirror reflecting surfaces takes place (Fig. 8-left). In contrast to the imaging systems of KRZYWINSKI [18] and ASENTICS [19] in which the mirrors are positioned above the test object, it is also possible to realize imaging systems with facets mirrors which are positioned below the top edge of the part under test. In [21] a mirror system consisting of four mirrors to inspect small objects with a height of some 10 millimeters is described as well. Due to the design of the beam path the facets mirrors have to be positioned in the inspection part layer. Although the image quality is enhanced by the mirror arrangement, a higher handling cost for the placement of the test pieces is required. One possible approach to ease the handling is to position the facets mirror below the part under test whereas the test parts are supplied on a transparent pad to the testing system. A system according to this principle is used by HARTMANN [22] (Fig. 8 left). Test systems based on this principle are suitable for inspection of surface features with high contrast and relatively large spatial error characteristic, such as print image inspection or completeness checking of machined parts. Imaging systems with conus mirrors - also known as conical mirrors, interior cone mirror or concave mirror - are working on a similar principle as imaging systems with faceted mirrors. In contrast to this, the beam deflecting is not realized by plan faceted mirrors, but by a cone-shaped mirror with a circular mirror surface.

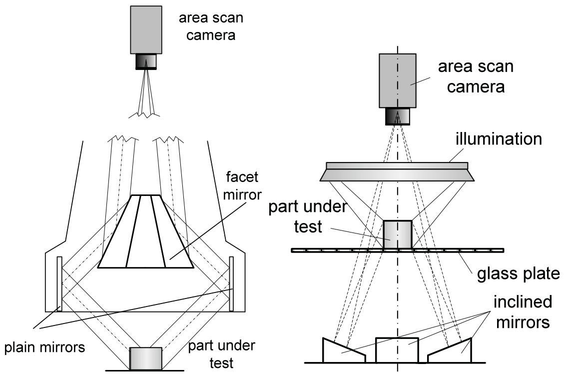

Fig. 8: multiple mirrored optical path according to [14] – left, multi mirror system underneath a glas plate according to [22] – right

The camera is positioned axially to the part under test. If the conical mirror is located above the test object (Fig. 9 left), an independent feeding of test parts is possible. The imaging is done when the test parts have reached a position coaxial to the camera axis. At the camera image the outer surface of the part under test is displayed as a ring-shaped, distorted image of the surface. In the central area of the picture the front side of the part under test is imaged (Fig. 9 right). Such a test system is described by SPITZLEY in [23] and [24]. It is used for quality assurance of the thread on a complete formation and continuous coating in the screw manufacturing.

An imaging system with a test part positioned within the body of the mirror is described in [25]. The body of the mirror having a conical reflective surface encloses the test object in this way that a multi-axis feed movement is necessary.

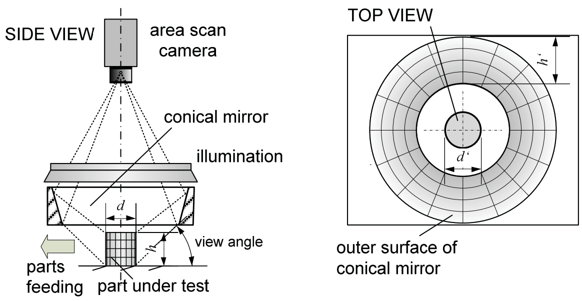

Fig. 9: Catadioptric imaging system with a conical mirror above the part to inspect

WU describes an imaging system based on a conical mirror with a lowering mechanism in [26]. A typical application for the use of such an inspection system is the inspection of screws. With the aid of conical mirrors cracks and other damages at area of the cylindrical screw head can be detected. Such an application is described in [27].

3.3.1. Lens systems with hypercentric view

Hypercentric imaging systems - also known as pericentric – are characterized by a perspective, which images more distant objects in the picture bigger than close ones. The following section describes imaging systems that achieve the effect of hypercentric imaging by the use of refractive optics. Unlike mirrors, lens systems use the physical effect of light refraction and not the effect of reflection. Here, the beam is deflected in this way that a hypercentric all-round view is created on the surface of a part under test. The outer surface is visible as a hyper-centered distorted representation in the camera image. Lens-based hypercentric systems are described in [28] and [29]. The test object arranged coaxially to the optical axis of the imaging system is shown here by a combination of two free form convex lenses (Fig. 10).

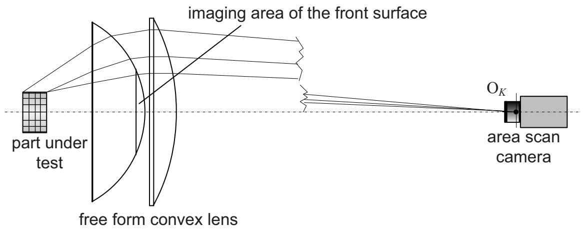

Fig. 10: Lens based hypercentric imaging system

A hypercentric imaging system is also described by SEDAZZARI [14] and [30]. A possibility of hyper-centric imaging of elongated objects with a combination of lenses is described in [13]. It is an optical system with cylindrical concave and convex lenses. Such systems are used for the testing of hydraulic and pneumatic cylinders, but also of brake, clutch- and ABS-cylinders as well as geometrically similar parts [31].

4. METHODOLOGY AND APPROACH FOR DESIGN OF INSPECTION SYSTEMS

4.1. **Procedural developing method**

The design of automatic optical inspection systems is usually carried out in several procedural steps (Fig. 12). First, the definition of the **inspection task.** It is given by a precize characterization of the **inspected parts**, the defects characteristics and the boundary conditions of the inspection process. These include parameters such as the geometry of the testing part, the size and appearance of the defect to detect, conveing speed or the cycle time of the inspection process respectivelly [32]. Other conditions, such as the cinematical properties of the testing parts and the available installation space, also play an important role in system design. Aspects like a specific mechanical or physical sensitivity of the testing part surface or of the structure of the testing part respecitvely can be crucial for a specific handling method and thus for the inspection method. Therefore, the parts handling constrains should also be comprised into the specification of the inspection task.

<table>
<tr><th>characteristic features</th><th colspan="13">implementation option</th></tr>
<tr><td>camera format</td><td colspan="9">area scan camera</td><td colspan="4">line scan camera</td></tr>
<tr><td>number of cameras</td><td>1</td><td>2</td><td colspan="2">3</td><td>4</td><td colspan="2">5</td><td>6</td><td colspan="4">...</td><td>n</td></tr>
<tr><td rowspan="2">light path between imaging sensor and object</td><td colspan="3" rowspan="2">dioptric</td><td colspan="10">catadioptric</td></tr>
<tr><td colspan="3">flat mirror</td><td colspan="3">conical mirror</td><td colspan="2">spherical mirror</td><td>2 facet mirrors</td><td>n facet mirrors</td></tr>
<tr><td>workig principle of the lens</td><td colspan="5">entocentric</td><td colspan="6">telecentric</td><td colspan="2">hypercentric</td></tr>
<tr><td>alignment of object axis vs. camera axis</td><td colspan="5">axial</td><td colspan="5">radial</td><td colspan="3">inclined</td></tr>
<tr><td rowspan="2">parts movement in regard to the camera</td><td colspan="6" rowspan="2">no movement</td><td colspan="7">relative movement</td></tr>
<tr><td colspan="5">linear</td><td colspan="2">rotational along own axis</td></tr>
</table>

Fig. 11: Morphological analysis of imaging systems for rotationally symmetric parts (based on [33])

These given conditions lead to a preselection of a **inspection method** carried out by a developing engineer. Usually, these decisions are performed based on experience and often supported by laboratory tests – especially concerning illumination techniques and parts handling. There are several approaches to find solutions for appropriate inspection systems. The expertise of experienced users is available in a non-systematic form. The selection and design process can be seen as an activity that requires creative skills and a broad expert knowledge. In many cases finding a solution either is characterized as intuitively or depends on already known or existing technology. The quality of the inspection **system´s design** depends finally on the expert knowledge level. This knowledge could also be provided in macros, catalogs or databases. All these utilities support the developper in finding an appropiate solution. This process can be described as a creative act and is often subjective.

Once the inspection method has beeen focused, detailed system parameters such as the light path, camera type (line or area scan camera), camera resolution, number of cameras and the optical parameters have to be determined. A suitable optimization of the cycle time or the transport speed respectively, with the exposure time of the imaging sensor and the illumination arrangement play a major role in these calculations.

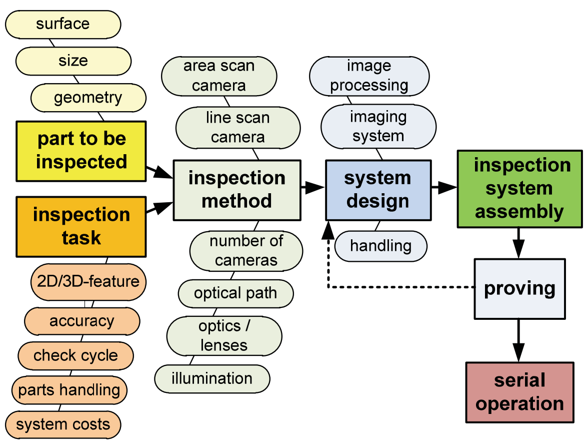

Fig. 12: Features and procedural steps to develop an automated optical inspection system

The construction of an inspection system depends on the selected inspection approach and consists of serial components, special parts or is built up according to a special design. The selected components are embedded into the overall system by taking into account that the functionality has to be guaranteed under conditions of use. The overall system must be **assembled** after these functions´ tests. Afterwards, the testing phase begins, in which the observations and test results with the requirements of the inspection task can be compared. But before the testing system delivers the desired performance and turns into the final state of continuous use, an iterative adjustment of the system design or the design parameters in terms of the fulfillment of requirements is necessary. In many cases this process is time consuming and consequently expensive.

The minimization of the number of iterations between the **system design** and the **proving** directly disaffects the overall development time and therefore the development costs. At this point, the concept of the present study takes action. The design and layout process between the definition of the inspection task and the construction of the inspection system is to be improved by a software-based tool. This software tool supports the design engineer, both during the decision process and during the design phase of the system. This is done to simplify and improve the design process.

4.2. **Approach to knowledge based design method**

The primary objective in the optimization of inspection systems´ development is to achieve sufficiently good result of inspection system in the possibly short time. In the developing process of automated optical inspection systems, it is necessary to work out specialized solutions which are tailored to a specific task.

solution identifier		AsR1	AsR2	AsR3	AsR4	AsR5	AsI1	AsA1	AsA2	AsA3	AsA4	LsR1	LsR2
part geometry													
ratio part diameter / part length	>>1	++	-	+	+	-	++	+	+	o	--	++	+
	ca. 1	++	+	+	+	++	++	++	++	++	o	++	+
	<< 1	-	++	o	o	++	-	--	--	--	++	++	+
rolling possible		.	X	.	.	.	.	.	.	.	.	(X)	
upright stand/clamping		X	.	X	X	.	X	X	X	X	.	(X)	
defect geometry													
ratio defect width / part diameter	<0.1	++	++	++	++	++	+	++	+	++	++	++	+
	< 0.05	+	+	+	-	+	o	+	o	+	++	++	+
	<<0.01	+	-	o	--	o	-	o	-	o	+	++	+
shape inspection													
diameter or shape inspection		++	--	++	o	o	o	o	o	o	-	--	-
length inspection		++	--	++	o	o	-	--	--	--	o	+	+
robustnes in													

features: X : significant; .:insignificant; (X): conditional | application: ++: very good; +: good; o: limited; -: poor; --: inapplicable

Fig. 13: Qualitative representation of features for selected inspection systems

In order to trackle the coordination of a given task and a set of possible solutions the authors are going to develop a system configurator for various inspection tasks. It is a database in which the knowledge about inspection systems is stored, or which could be described as a knowledge-based system for selection and design of optical inspection systems for rotationally symmetric parts.

As an approach to the solution in the first step, the characteristics and features of the existing inspection systems have been analyzed in a survey. The evaluation was performed by the method of morphological analysis described in [34] and based on [35] and [36]. The ordering characteristics of different approaches and design options are shown in a morphological box in Fig. 11. Through a combination of design possibilities, the variety of approaches becomes evident. Not all combinations of the solution elements are expedient options. Therefore it is necessary to define decision-support rules.

The rules for decision making are noted in form of a decision algorithm. Decisions in the design process can be realized through a variety of approaches such as decision tables, knowledge maps, semantic networks and decision trees [37]. The decision trees represent the knowledge in form of nodes and connections. Targets are represented as nodes and are connected by decisions [38]. The decision tree method has been selected for this task due to compatibility between the knowledge structure and aimed purpose.

Fig. 14 illustrates a schematic representation of the decision structure for the selection of an inspection system for rotationally symmetric parts. This decision system is originally realized as decision tree. Due to this method, it is possible to conceive a blueprint of an inspection system.

The input into this decision structure is crucial. Therefore, the developer must make clear decisions. Critical decision parameters are defined by special properties of the individual inspection principles. The entries are grouped into eight fields in Fig. 14. The range of solutions is specified by this input. Investigations and practical examinations are the basis of the shown decision tree.

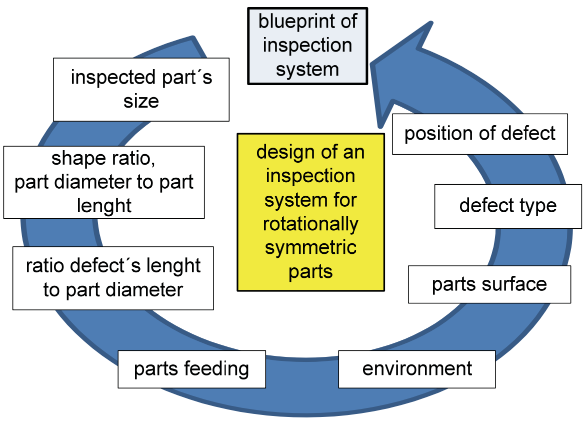

Fig. 14: Schematic representation of the decision structure

The user captures the known characteristics in a form, which gradually leads him through a decision tree-like structure. The specifications and parameters of each system are recorded in a database in the form of a decision tree. The critical features are common to all areas of the task definition. These can be both geometrical features and characteristics of parts defects. Thus, the number of iterations for the optimization of the inspection system can be reduced, which results in saving time and costs. The result of the decision process is usually not only one solution. Different possible systems can be proposed. The variety of solutions depends on the information of the inspection task.

5. APPLICATION

The function of the developed system to support the decision process shall be demonstrated by practical examples. Three different inspection applications are selected from various sectors of industry. These parts to be inspected have different geometries as well as differing conditions of inspection. Following practical applications are selected and will be described in following sections:

- proportioning pump cylinder
- fitting for hydraulic connection
- screw head

5.1. **Proportioning pump cylinder**

As an example for a pin-shaped object with fine surface defects and shape ratio of $d/l = 0.1$an inspection application for proportioning pump cylinders is selected. These parts are used as components of metering pumps, which make an oscillating movement along the longitudinal axis. These components convey the liquid medium accordingly to the displacement principle. The lateral surface is a functional surface with sealing function. It reduces leaks, which actually results from scratches on the sealing surfaces and manufacturing allowances within the system. Damaged surfaces result in reduced performance of the pump and lead finally to a preterm wearout of the system.

The geometry of the object to inspect can be characterized as following: cylindrical base body with a diameter of 5 mm, length of 44 mm, surface roughness $R_a = 0.4$ µm. The defects can be described as fine scratches on the surface and result from damages during production and handling operations. They have an average width of 80 µm, an average depth of 50 µm and length of several millimeters. The parts are delivered from the previous manufacturing process step in an ordered way. The inspection station should be integrated within the manufacturing line.

The entries in the decision support system lead to a suggestion for a line scan camera system with roller drive. This solution can be associated in Fig. 13 with the identifier LsR1.

Describing the decision process we can determine following substantial reasons. To visualize a defect the imaging of surface defects requires a relatively high lateral resolution. Assuming that a defect with a width of 80 µm is imaged with three image pixels, a lateral resolution in the image space of 33 µm / pixel is required. Because the part under test is highly curved due to the small radius, it cannot be illuminated uniformly in a larger area. By illuminating only a thin strip of the surface, just the surface defects are represented with high contrast. For their geometric properties the pin-shaped parts under test cannot be tested and fed in a free-standing way. To ensure an appropriate handling, positioning and smooth movement a roller-assisted handling is appropriate.

In a realization of the concept a system with a line scan camera and drive rolls has been realized (Fig. 15). The image acquisition, is performed while the the parts to inspect are placed on a drive system. This ensures a stable position as well as a constant drive speed. The drive rollers are made of rubber. The torque is transmitted by friction. To capture the whole surface and because a certain degree of slip cannot be excluded the part under test has be rotated by more than 360°. The illumination is realized as a coaxial lighting system with LEDs and a semipermeable mirror.

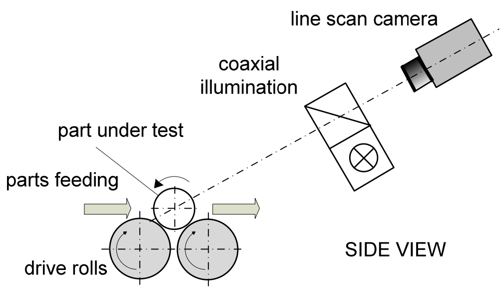

Fig. 15: Line scan camera setup for inspection of proportioning pump cylinder

Parts handling is provided here by a mechanical feeder which places the parts to inspect between the drive rolls. A resulting surface image acquired by the line scan camera is depicted in Fig. 16. The surface defects are here visible as dark line-like areas. Tests with image processing with image analysis software show a high defect recognition performance.

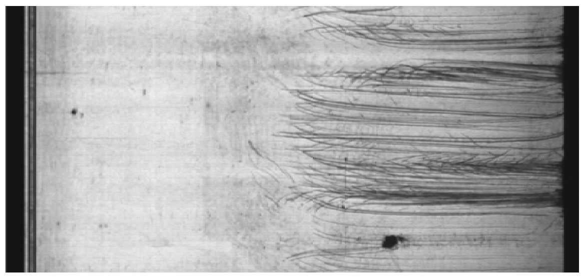

Fig. 16: Image of the proportioning pump surface acquired with the line scan camera

5.2. **Fitting for hydraulic connection**

As an example for an industrial part with a shape factor of $d/l = 0.8$ a fitting for hydraulic connection is selected. Such fittings are used to connect hydraulic hoses with corresponding sockets. The item has multiple shouldered diameters with an outer diameter of 20 mm, an overall length of 25 mm and a through-hole of 14.5 mm in diameter. The item is made of steel and has a surface roughness of $R_a = 1.2$ µm. Caused by mechanical impacts during the manufacturing process in combination with possibly material defects there are fine cracks on the lateral surface. The mean size of these defects is 80 µm in width and several millimeters in length. These cracks can lead to hydraulic fluid leakages and thus to environmental contamination. Additionally to the surface inspection a shape inspection has to be carried out. The length and shape of the specimens have to be verified with an accuracy of 200 µm. The inspection system should be realized as a stand-alone machine. Parts to inspect are delivered disordered in bins. Thus, a dedicated feeding and separating system has to be realized.

Due to the task specification the decision support system suggests a system solution based on an area scan camera and multiple views of the object. In the usual case of detection of defects on the lateral surface only, a line scan camera system would be the best choice. Because of the additional inspection task in shape inspection a high resolution area scan camera with a telecentric lens is selected instead. This solution can be associated with the identifier AsR1 in the table in Fig. 13.

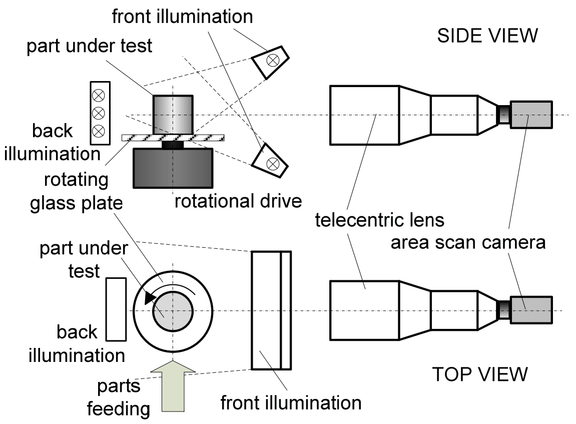

Fig. 17: Area scan camera setup for inspection of hydraulic connection fittings

The schematic view of realized inspection system is depicted in Fig. 17. To achieve a view of the complete lateral surface of the specimen, they are positioned on a glass plate in the inspection system by a picker arm. The glass plate rotates driven by an electrical motor with a speed of 60 r.p.m. The design of the rotary table in transparent glass was chosen to illuminate the test object both from above and from below. This allows a homogeneous illumination of the inspection area. The resulting image with marked surface defect is depicted in Fig. 18. Defect detection on the acquired images is quite challenging but can be performed with satisfactorily efficiency and stability.

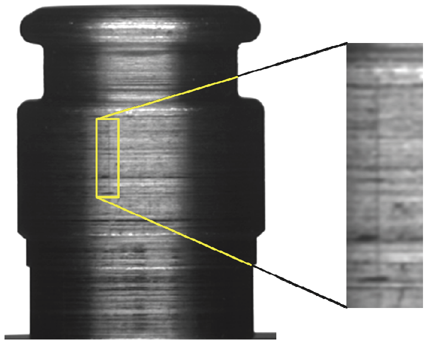

Fig. 18: Image of the surface of hydraulic fitting acquired with an area scan camera. The zoom frame shows the enlarged surface defect

5.3. **Screw head**

Third application example is performed with an industrial fastening screw. The screws are made of steel in a cold forging process and are galvanized afterwards. Typically such screws are applied in household electronic to fasten mechatronical components. The overall length of the screw is 15 mm. The inspection area is reduced to the screw head with an outer diameter of 8 mm, a height of 3 mm and a surface roughness of $R_a = 0.1$ µm. The shape ratio of the volume to inspect is here $d/l = 2.7$. The inspection task is to detect cracks in the screw head which occur during the manufacturing process. The form of appearance of head cracks is irregular, but it can be characterized by a wedge-shaped 3-D groove. The width and depth of the smallest cracks to detect are in the range of 150 µm. The crack does not represent a serious risk to the screw function but is undesirable due to esthetic reasons. The parts should be automatically inspected with a rate of 2 pieces per second in order to comply with the manufacturing speed.

According to the task specification the decision tree system suggests an approach based on a pericentric lens [39] and an area scan camera. This solution corresponds with the solution identifier AsA3 in Fig. 13. The special characteristic of this system is the positioning of the test specimen underneath the optics which allows a continuous parts feeding and therefore short inspection cycles. A schematic view of the realized system is depicted in Fig. 19. The optic is a commercially available lens.

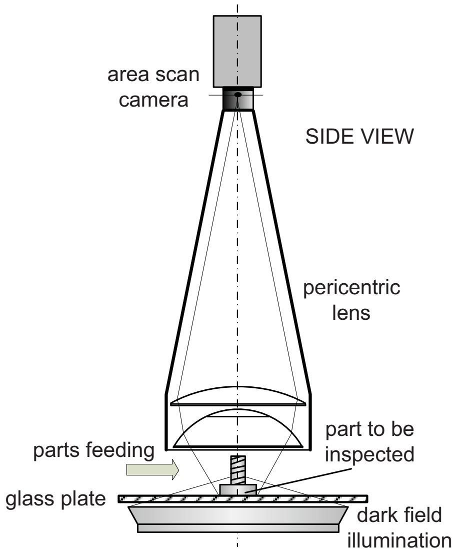

Fig. 19: Pericentric lens based inspection system for a screw head

The acquired image with a surface defect on a specimen is depicted in Fig. 20.

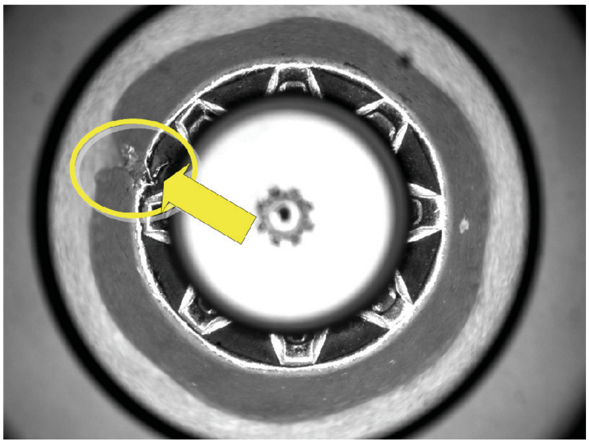

Fig. 20: Image of a screw head with a defect on the lateral surface acquired with a pericentric imaging system

6. CONCLUSION AND OUTLOOK

In this paper the authors present an approach for the selection and conception of automated inspection systems for rotationally symmetric parts. The aim of the approach is to support the selection of an appropriate configuration of an inspection system for a given inspection task. The resulting solution concept can be improved by detailing the inputs.

The knowledge for this selection procedure is implemented in a decision structure. An important prerequisite for this integration of knowledge in the decision-process is the analysis of existing inspection configuration and their features. This knowledge has been evaluated by surveys on available inspection systems as well as in practical experiments and in theoretical considerations. The observations were described in a formalized form and represented in a decision tree. This approach is presently going to be validated by experimental investigation and by industrial applications.

In further work, the decision system is planned to be linked to a software components library, thus a CAD sketch of the system concept can be provided automatically in addition to the textual specification. In addition to the resulting output, the input may also be designed more comfortable. As a future vision the inspection task could be derived directly from a CAD drawing of the test object.

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