DEVELOPMENT OF A ROBOT GUIDED OPTICAL MULTISENSORY INSPECTION SYSTEM FOR INLINE INSPECTION OF CYLINDER HEADS

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ABSTRACT:

The project RoboMAP is a cooperation of different partners from science and industry, including our institute. It aims at the development of an inspection system for quality assurance in the automotive industry. The objects to inspect are cylinder heads. In particular the valve seats and the valve stem guides are of special interest. The latter lie in the inner part of the cylinder head and are therefore difficult to access. The different kinds of geometry in combination with other goals, such as inline capability and flexibility regarding measurable object variants, impose the need for a new generation of optical measurement techniques. Tactile methods are not applicable, particularly because of their slow operating speed. A boost of flexibility is achieved by integrating a robot into the system in order to position the multi-sensor in an optimum configuration to the object for inspection. This additional capability is further exploited by integrating a single camera into the system which is used for detecting the cylinder head's pose. Thus there is virtually no need for a predefined object position. Next to a general description of the project, we focus on the calibration of the system. Due to the various kinds of involved sub-systems, the overall calibration will be performed in separate steps yielding a network of transformations. As the object recognition is also being used for the calibration tasks, we give an overview of the approach we take.

1. INTRODUCTION

Modern automotive industry faces increasingly high demands on the quality of its products. State of the art technology involves highly efficient motors, whose manufacturing can only be accomplished in facilities which themselves utilise state of the art tools and quality assurance systems. Particularly the importance of the latter has come to more attention in the past few years as good quality assurance helps to drastically reduce unnecessary production costs. Thus there is a huge development effort in this sector. In many cases it aims at shaking off the major weaknesses of old-fashioned systems.

The first weakness lies in the operating speed. Traditional tactile systems allow only very low sample rates. Therefore they are more and more replaced by much faster optical inspection systems, although in most cases optical systems do not reach a comparable level of accuracy. Still, most optical systems use triangulating measurement techniques which are well suited for the measurement of outer geometry (Frankowski et al., 2001), but cannot be applied satisfyingly to inner parts of work pieces. Hence recent developments try to combine different sensors in order to handle different geometry characteristics (Böhm et al., 2001).

Furthermore, most quality assurance systems are statically installed in the production line, which leads to a second problem. They usually can only be applied to similar parts or cause downtime when being reconfigured for the inspection of different objects. This conflicts with the fact that modern production lines need to produce various object variants in order to enable the manufacturer to produce according to more and more personalized consumer demands. New developments tend to employ industrial robots to handle the inspection sensory, thus being able to position the sensory in ideal configuration to the object.

Nevertheless, there is still a need for further sophisticated inspection systems which combine these trends and, beyond that, provide a level of accuracy comparable to tactile systems. It is obvious, that such complex systems demand for likewise advanced calibration methods (Roos, 2003).

2. SYSTEM DESIGN

Six partners from science and industry participate in the research project RoboMAP (**Robo**t guided inline **M**ulti-Parameter **A**bsolute and **P**recise measurement system), which aims at the development of an inspection system for cylinder heads. It encounters the afore-mentioned goals with a unique concept regarding system design and measurement strategy. To motivate the overall concept one should first take a look at the cylinder head's features of interest (Figure 1).

In order to guarantee an efficient performance of a motor it is of great importance that the calottes of the cylinder head are machined at highest precision. Especially the valves have to fit accurately into the valve seats to ensure no loss of pressure during combustion. Thus the valve seats as well as the valve stem guides are of main interest in the inspection task. The calotte itself, as well as parts of the valve seats, is easily accessible. Therefore it is well suited for optical inspection using a triangulation system, such as the fringe projection system we employ in the project. It consists of two cameras and a projector, which is a very small and light weighted prototype and yields an accuracy of better than 100µm.

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On the other hand the valve stem guides are of cylindrical shape and can only be accessed by reaching through the valve seats into the inner part of the cylinder head. For this task we utilize an interferometer with a needle-shaped probe, which operates with an accuracy better than 10µm (Knüttel and Rammrath, 2007). The probe emits a laser beam at its end, perpendicular to its main axis. It can be rotated around and / or transposed along the axis, so that linear, circular and helix-shaped measurements are possible.

Both sensors share a common work space and need to operate as a combined system without disturbing each other. Thus a multi-sensor chassis has been designed, which integrates both sensors and a linear stage. The stage's large scope enables the interferometer to move out of the field of view of the fringe projection system.

An industrial robot is applied to position the multi-sensor. It provides complete control over the full 6DOF of the sensor. Thus it enables the system not only to measure different feature sets of one object but also of different object variants without a need for mechanical reconfiguration. The system's flexibility is further augmented by introducing an initial object recognition step to the inspection procedure. The goal is to free the system from the need for a precisely prepositioned cylinder head. For this purpose a single camera is mounted statically into the system's workspace and used for the detection of the cylinder head's pose in the robot's coordinate system.

The recognition's result is transferred to the robot control unit which is then able to position the multi-sensor appropriately over the calotte to check. Then the fringe projection system scans the calotte. First results, such as the volume of the calotte can be derived from this measurement. But it is also used to refine the information on the cylinder head's pose by fitting the measurements to the cylinder head's CAD model and reposition the multi-sensor accordingly. As the interferometer probe needs to be inserted into the valve stem guide, which has a diameter of only about 5mm, the repositioning needs to be performed very precisely.

Amongst other topics our institute is responsible for the object recognition step and the calibration of the overall system. Especially the latter is of major importance for a successful realization of the RoboMAP system.

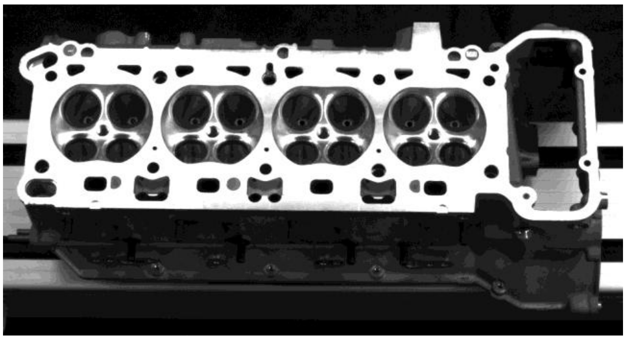

Figure 1. Image of our test cylinder head taken by the object recognition camera

3. CALIBRATION

3.1 General Description

As described before, the whole system consists of several components. Each component produces and / or processes geometrical data in its own coordinate system. If the data to process is obtained through another system it has to be transformed accordingly. Figure 2 depicts the linkage of all important coordinate systems. The calibration of the overall system can be understood as the determination of a network of transformation parameters which, if concatenated, enable us to transform any geometrical data into the coordinate system of one of the components.

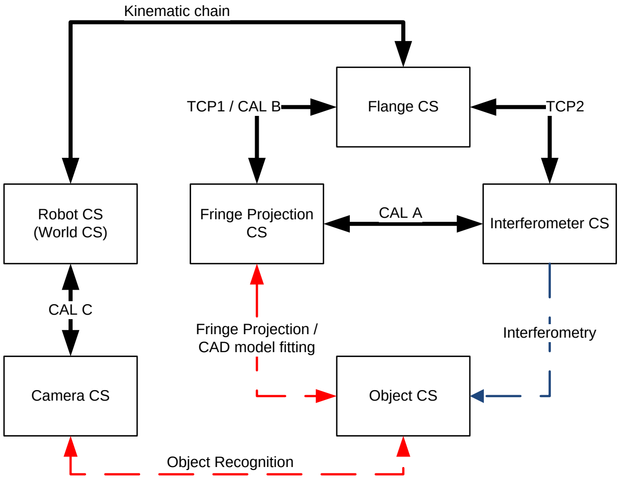

Figure 2. Diagram of the network of coordinate systems; double arrows depict transformations, dashed lines depict sensor measurements

The two sensor coordinate systems need to be determined with respect to the flange coordinate system (or robot hand coordinate system). These two sets of parameters are referred to as Tool Center Points (TCP) and are directly used by the robot control unit for sensor positioning. Furthermore, the object recognition yields the cylinder head's pose in the camera coordinate system. In order to derive the correct measuring position of the fringe projection system in the robot coordinate system from this result, it has to be transformed accordingly. The necessary calibrations can be classified into the multi-sensor calibration, which includes both TCPs and the transformation between the two sensors and the calibration determining the transformation from the coordinate system of the object recognition camera to the robot coordinate system. We refer to this calibration as external calibration as the camera is not part of the robot guided sensory.

3.2 Multi-Sensor Calibration

The multi-sensor calibration will directly influence the step of positioning refinement during the inspection. As mentioned this is the most critical step in the whole procedure. The ideal concept for this step would be to create a calibration device to which the multi-sensor can be mounted. It should provide a manifestation of the flange coordinate system and geometrical features for each sensor, whose positions need to be known very precisely in the same coordinate system. The features should be designed to derive the 6DOF information from their measurement.

3.2.1 Calibration Object: In order to meet these requirements we designed a special calibration object (Figure 3). This object consists of tempered steel and provides four spheres as features for the fringe projection system (as proposed in VDI/VDE, 2002). The spheres are located in the corners of the field of view of the sensor, arranged as a rectangle. Furthermore the object provides features for the interferometer. These features include, in the probe's operating direction, a bevel representing a valve seat and a gauge ring with an inner diameter of 25mm, followed by a gauge ring with an inner diameter of 5mm which represents a valve stem guide. The bottom base of the latter additionally provides a notch.

The measurement of one of the cylinders yields four DOFs: the direction of the probe's axis with respect to the cylinder main axis (two angular DOFs) and the decentration of the probe perpendicular to the cylinder main axis (two translational DOFs). While the missing rotational DOF (rotation around the axis) is obtained through measurement of the notch, the missing translational DOF (translation along the axis) can be determined through detection of jump edges, e. g. when crossing from the first to the second cylinder.

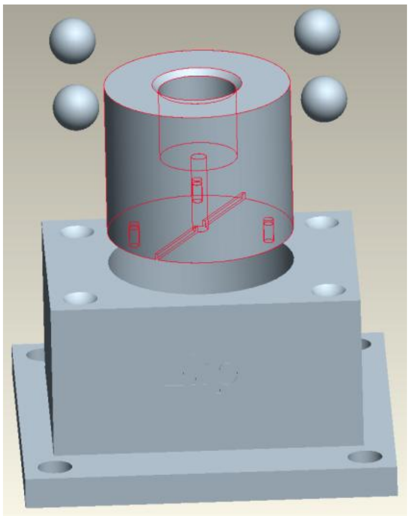

Figure 3. Exploded view of the CAD model of the calibration object

The calibration object was planned to be integrated to a calibration device in the afore-mentioned way. The major weakness of this approach lies in the necessarily high demands on the alignment of the 5mm cylinder and the interferometer probe due to its narrow depth of focus. This requirement is directly linked to the accuracy of the multi-sensor chassis. At its prototype state the chassis does neither provide such precision nor any possibility for a precise and stable realignment of the interferometer. This means if the alignment of the interferometer and the calibration object was incorrect, only the calibration object could be realigned. In such a case the position of the object's features in the flange coordinate system would change and the coordinate machine measurement would have to be repeated. For this reason we decided for a more intricate, but flexible two-step solution.

A first device is designed to provide the transformation parameters between the two sensors (step CAL A, see Figure 2) and a second is designed to obtain TCP1 (step CAL B). Both devices are similar in terms of their basic design, a closed framework structure with a mounting component for the multi-sensor chassis on the top part and a calibration object mounted beneath the sensors.

3.2.2 Calibration step A: The main structure is constructed using x-shaped aluminium profiles (Figure 4). To maintain as much flexibility as possible, the profiles are mounted using slides. Slides are also used to mount the multi-sensor chassis and a positioning device for the calibration object.

For the determination of the relative pose of the two sensors only the features of the calibration object need to be known in one coordinate system. Thus the object can be realigned as a whole without consequences to the calibration procedure. For this purpose we place the calibration object on a positioning device. It consists (from bottom to top) of two goniometers and two linear stages. The goniometers' rotational axes are orthogonal and meet in a common point. This is used to adjust the direction of the normal vector of the support face of the upper goniometer, which coincides with the direction of the cylinder main axis of the calibration object. The two linear stages are also mounted with orthogonal axes. As they are mounted on top of the upper goniometer their axes are always perpendicular to the direction of the afore-mentioned vector. This enables us to compensate for a decentration of the interferometer probe by translating the calibration object perpendicular to the cylinder axis after compensation of a directional misalignment.

Once the calibration object is aligned correctly with respect to the interferometer probe, we can, within certain restrictions, refine the fringe projection system's alignment in order to obtain a relative orientation of the sensors near to the planned values. After this alignment step the calibration of the sensor's orientation can be performed to obtain more precise information on their relative pose. The evaluation of this device is still ongoing. So far it only includes measurements of the interferometer. Results can be found in chapter 3.2.4.

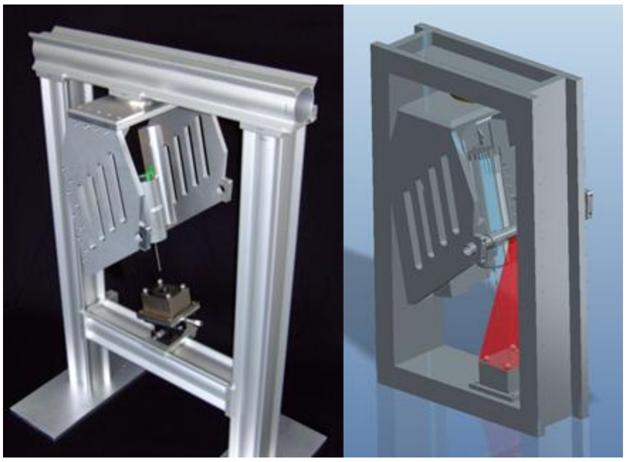

Figure 4. Left: Photograph of the device for calibration step A; Right: CAD drawing of the device for calibration step B

3.2.3 Calibration step B: The device planned for this step, the determination of TCP1, will consist of a framework of welded u-profiles (Figure 4). In contrast to the first device there will be no movable parts. The calibration object, as well as the flange for the multi-sensor chassis, will be mounted firmly to the frame. The flange and the spheres of the calibration object will be measured with a coordinate measuring machine. By measuring the spheres with the fringe projection system we gain information on the pose of the fringe projection system in coordinate system of the flange. As the transformations between the two sensors and the flange add up to a redundant part of the calibration network, we can obtain TCP2 by concatenating TCP1 with the result from calibration step A.

3.2.4 First Results: The interferometer measurements at the calibration object show that the features provided for 6DOF determination suffice. A coordinate machine reference measurement of the object was provided by our partners. For the determination of the 6DOF parameters three different measurements are taken at the 5mm cylinder; a helix-shaped measurement along the cylinder, which avoids the notch and the edge of the 5mm to 25mm crossing, circular measurements in height of the notch and linear measurements of the edge of the crossing. The latter are taken in eight different directions.

Figure 5 shows the cylindrical coordinates of the points of a helix shaped measurement of the 5mm cylinder. The difference Δd of the measured distances to the reference value for the cylinder radius r_{ref} is plotted against the probe's rotation angle ω and its translational position l. One would expect Δd to be of constant value. Instead a clear wave-like distribution in direction of ω can be seen. It is mainly caused by decentration of the probe. An angular misalignment of the probe and the cylinder axis does not significantly influence the wave shape, as the so-caused amplitudes are very small compared to the amplitudes caused by decentration. Instead an angular misalignment depicts itself as a change in amplitude and orientation of the wave which depends on l. It can be interpreted as a changing decentration caused by angular misalignment.

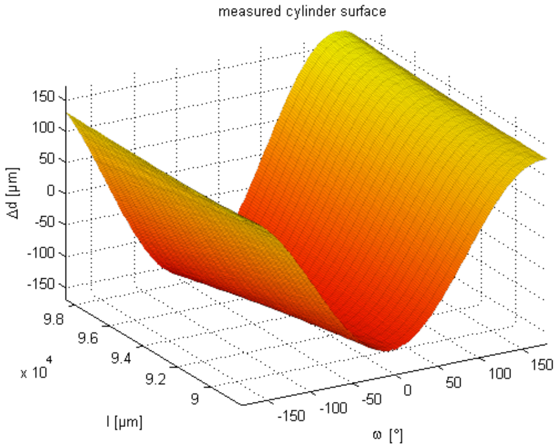

Figure 5. Plot of the cylindrical coordinates of a helix measurement at the 5mm cylinder of the calibration object; the measured distances have been reduced by the reference distance r_{ref}

We determine the misalignment and decentration of the probe axis and the cylinder axis by fitting the points of the helix-shaped measurement to a cylinder, using transformation equation (1). Equation (2) is used as model for the adjustment.

$$P_{Cyl} = R_y(\beta) R_x(\alpha) P_{Int} + \begin{pmatrix} t_x \\ t_y \\ 0 \end{pmatrix} \quad (1)$$

$$r_{ref}^2 = P_{Cyl}(x)^2 + P_{Cyl}(y)^2 \quad (2)$$

P_{Cyl} is defined as a point P_{Int} measured in the coordinate system of the interferometer after transformation into a cylindrical coordinate system *Cyl*. *Cyl* coincides with the calibration object's coordinate system in the Z-axis. After determination of the transformation parameters the measured points can be transformed accordingly to obtain P_{Cyl}. Figure 6 shows the cylindrical coordinates of P_{Cyl}. As can be expected for a cylinder, the surface has a constant distance to the cylinder axis.

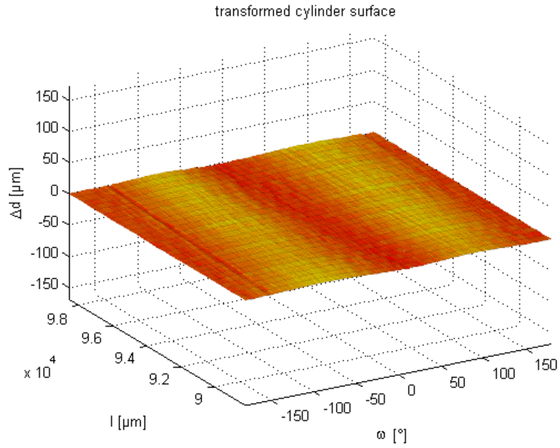

Figure 6. Plot of the cylindrical coordinates of a helix shaped measurement after transformation according to the cylinder fit

The crossing from the 5mm to the 25mm cylinder defines the zero-height of the calibration object coordinate system. Thus h_{ref} is defined as 0. The measurements at the edge have been carried out repeatedly with a translational step size of 1µm beginning in the inside of the cylinder and ending outside of it. This procedure was repeated in angular intervals of 45°. For each of the eight directions a histogram can be derived which pictures the number of existent measurements at each translational step, as shown in Figure 7. As expected, the histogram shows a slope at the edge. To determine an estimation of the true edge position we compute the slope's middle. The eight edge positions are then transformed into the cylinder coordinate system *Cyl*. The average of the transformed z values is used as edge height h. The missing translational parameter can then be computed as following equation (3).

To determine the missing rotational parameter γ from multiple bidirectional sets of circular measurements at the notch we again compute an existence histogram. The detected edge points are then again transformed into coordinate system *Cyl*. From the polar coordinates of the transformed points we can derive the angular notch position ω. As shown in equation (4), γ is again derived from a reference value, ω_{ref}. There is no correlation between the last two DOFs. Thus we can concatenate the determined transformations to the sought-after 6DOF transformation, see equation (5), which transforms the measured points into the calibration object's coordinate system *Cal*.

$$t_z = h_{ref} - h \tag{3}$$

$$\gamma = \omega_{ref} - \omega \tag{4}$$

$$P_{Cal} = R_z(\gamma) R_y(\beta) R_x(\alpha) P_{Int} + \begin{pmatrix} t_x \\ t_y \\ t_z \end{pmatrix} \tag{5}$$

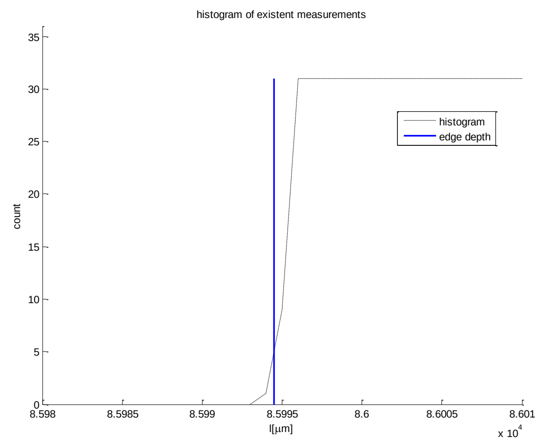

Figure 7. Histogram of existent measurements at the cylinder crossing edge with detected edge depth

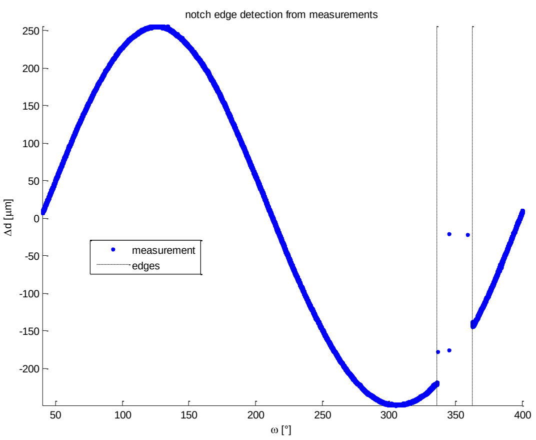

Figure 8. Measurements at notch height reduced by r_{ref} and the derived notch edges

∝	=	0.508	°
β	=	0.037	°
γ	=	194.721	°
t_x	=	69.414	µm
t_y	=	769.914	µm
t_z	=	-85966.080	µm
h	=	85966.080	µm
h_{ref}	=	0	µm
ω	=	345.586	°
ω_{ref}	=	180.307	°

Table 1. Summary of the results of calibration step A

3.3 External Calibration

This calibration step (CAL C) closes the network of transformations. In order to provide the cylinder head's pose in the robot coordinate system the transformation from the camera coordinate system to the robot coordinate system has to be determined. We choose a simple approach which does not imply any need for additional calibration objects and exploits functionalities of the sensors which are already part of the inspection procedure.

As analogue of the calibration object for the multi-sensor calibration we use a reference cylinder head. This cylinder head will be positioned in the workspace of the robot and an object recognition will be performed. The result of the recognition is the cylinder head's pose in the camera coordinate system, which is nothing else but the transformation from the object coordinate system to the camera coordinate system. In a second step the robot is positioned manually in order to measure a calotte with the fringe projection system. The measurements are then fitted to the CAD model of the cylinder head, which yields the transformation from the object coordinate system to the coordinate system of the fringe projection system. Concatenating the transformations, camera to object, object to fringe projection system, fringe projection system to flange and flange to robot we obtain the sought transformation parameters.

The long chain of dependencies makes clear that the parameters will not be very precise. Main error sources are the object recognition with an absolute accuracy of 1-2mm and the robot positioning which has an absolute accuracy of about 1mm. Compared to these dimensions we assume other influences to be negligible. The circumstance of a possible imprecise robot positioning for the first measurement of the fringe projection system was considered in the design of the sensor. It is compensated by a sufficiently large field of view, which enables us to handle a translational misalignment of up to 5mm. However we do not expect the accuracy of the obtained transformation to be worse than 3-4mm. Results of the object recognition can be found in the next chapter.

3.3.1 Object Recognition: We chose a commercially available software solution to solve this task (Wiedemann et al., 2008). It is a view based object recognition approach which uses the object's known geometry provided via a CAD model. Roughly described, the model is used to generate artificial views of the object which are then compared to the real image. Thus it is an extension of a 2D shape matching to a number of reference images, which as a whole set yield the three-dimensionality.

In detail, a sector of a spherical shell is defined in relation to the model. The shell represents a space for possible camera positions. A certain number of virtual camera viewpoints is arranged in this area and the model is projected into each of the virtual image planes. In order to achieve a precise projection the calibration parameters of the real camera are applied. The generated artificial views are sorted in a hierarchical tree whose levels represent a densification of the viewpoints. Additionally, image pyramids are applied. This means on the highest level of the tree there is the lowest density of viewpoints and the lowest image resolution. This tree of views has to be computed only once and can then be used for the recognition. Here the search starts on the highest level. Candidates for a possible positive match between real image and artificial view are tracked down to the lowest level, following the tree structure. In case of our application, where there is definitely only one object to detect, only the best matching-result is used as approximate solution for a resection which concludes the process.

We do not use the whole CAD model of the cylinder head to perform the recognition steps described above. In fact we solely use one single face of the model, the combustion chamber sealing face. Several reasons led to this decision. First of all, the complete model contains plenty of information on the inner structure of the cylinder head. Obviously, this is of no interest to the object recognition task and can be omitted. But also on the outside the model contains a lot of edges which can be dropped. These edges are present in the model to approximate free form faces but are not existent at the real object. Thus, if kept, they would lead to confusions in the recognition procedure.

Furthermore, first experiments made clear that the acquisition of high quality images of the cylinder head is not easy. The complex geometrical structure of its surface in combination with its reflection properties demands a special lighting situation. The combustion chamber sealing face is the biggest planar face and is therefore, in spite of its' strong reflectivity, the easiest face to handle in terms of lighting. Furthermore it provides an unambiguous shape with very distinct edges. We developed an indirect lighting solution, positively exploiting the otherwise disadvantageous reflectivity of the sealing face. For this we installed a set of red high power LED-bars pointing towards the ceiling above the cylinder head, where we placed a diffuse reflector. This creates a very homogenous diffuse lighting of the sealing face. Using a matching lens filter and adjusting aperture and exposure time of the camera appropriately, we obtain images in which the sealing face depicts itself brightly in an otherwise dark image (Figure 1). Hence we can perform the object recognition on images with nearly ideal edge contrast. Our evaluation under laboratory conditions yielded a total error span of 1.02mm. Details can be found in earlier publications (Cefalu and Böhm, 2009).

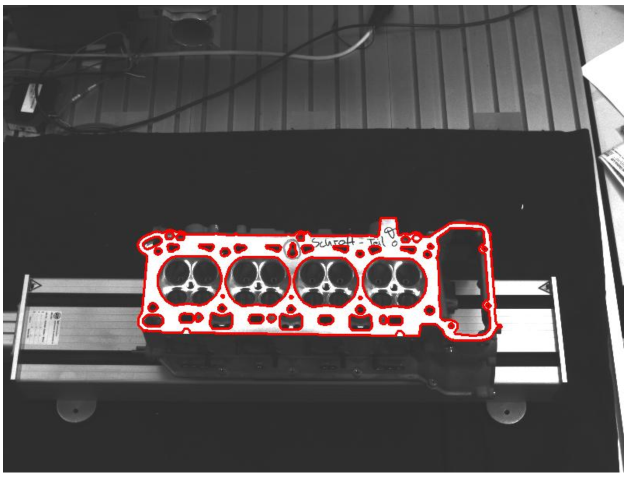

Figure 9. Image taken by the object recognition camera for evaluation purposes. The determined object pose is used to project the CAD model into the image (red).

4. SUMMARY

We presented the concepts of the RobMAP inspection system, an inline inspection system for cylinder head production in the automotive industry. It integrates the advantages of robot guidance and multiple optical sensor technology, following a special coarse-to-fine inspection strategy, which is initialised by an object recognition. One of the main challenges of the project is the calibration of the various single components in order to create a coherent system. For this task we developed an over-all calibration concept, including a two-step multi-sensor calibration and a separate external calibration.

Main topic of the multi-sensor calibration is the special calibration object whose geometrical features enable us to derive the sensors' position from measurements. First results show that the basic concept works well. For the external calibration we do not need special calibration objects. Instead exploit system functionalities which are part of the inspection. More precisely we use a cylinder head as calibration object and apply the object recognition as in an inspection task.

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