

Visual Inspection and Error Detection in a Reconfigurable Robot Workcell: An Automotive Light Assembly Example

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Abstract: Small and medium size enterprises (SMEs) often have small batch production. It leads to decreasing product lifetimes and also to more frequent product launches. In order to assist such production, a highly reconfigurable robot workcell is being developed. In this work, a visual inspection system designed for the robot workcell is presented and discussed in the context of the automotive light assembly example. The proposed framework is implemented using ROS and OpenCV libraries. We describe the hardware and software components of the framework and explain the system's benefits when compared to other commercial packages.

1 INTRODUCTION

Nowadays robots have become essential in multiple industrial tasks. The robotic solutions are usually applied for complex repetitive tasks and high unit volume (Gaspar et al., 2017). However, in small or medium-sized enterprises (SMEs) a few-of-a-kind production scenarios (Krüger et al., 2014) are more typical. Since SMEs provide more than 40% of the value added by the manufacturing industry in the European Union (European commission, 2013), it is vital to allow them introduce efficient and easily reconfigurable robotic solutions to ease and speed up the product manufacturing.

To facilitate the production in SMEs, a reconfigurable workcell is being developed and introduced (Gaspar et al., 2017) as a modular system, where hardware and software components allow for fast and easy reconfiguration.

In this paper, we present a visual monitoring system, which is designed to detect errors during the assembly process within the reconfigurable work cell. We describe the hardware and software components of the system and evaluate its applicability on the example use case, namely, to the automotive light assembly.

The paper is organized as follows. In Section 2,

the relevant information about the work cell development as well as the available monitoring systems is given. Section 3 presents the motivation for our developments. In Section 4, the use case details are presented. In Section 5, the monitoring problem is described and the measurement points are identified. In Section 6, the proposed hardware and software solutions are presented. The results are described and analysed in Section 7. Section 8 concludes the paper.

2 RELATED WORK

Fulea et al. (Fulea et al., 2015) surveyed the literature on the topic of reconfigurability, focusing on industrial robotic workcells (as parts of reconfigurable manufacturing systems), aiming to identify the main approaches on reconfigurability and its relevant implementations in the robotics (and related fields). Setchi and Lagos (Setchi and Lagos, 2004) provided a review of reconfigurability and reconfigurable manufacturing systems. Bi et al. (Bi et al., 2008) presented a survey of Reconfigurable Manufacturing Systems (RMS). It included general requirements of next generation manufacturing systems and discussed the strategies to meet these requirements.

Duro et al. focused on the applicability of the

Multicomponent Robotic Systems and Hybrid Intelligent Systems for industrial tasks (Duro et al., 2010).

Gaspar et al. (Gaspar et al., 2017) presented a novel automatically reconfigurable robot workcell that addressed the issues of flexible manufacturing. The proposed workcell is reconfigurable in terms of hardware and software. The hardware elements of the workcell, both those selected off-the-shelf and those developed specifically for the system, allow for fast cell setup and reconfiguration, while the software aims to provide a modular, robot-independent, Robot Operating System (ROS) based programming environment (Quigley et al., 2009). One of the innovative hardware elements for this cell type is a flexible fixture based on a Gough-Stewart platform called the hexapod presented by Bem et al. (Bem et al., 2017).

An industrial monitoring problem is highly relevant and has been studied in several research projects. For instance, the SCOVIS project investigates the automatic work flow monitoring in a car assembly environment in order to improve safety and process quality (Kosmopoulos et al., 2012; Mörzinger et al., 2010; Voulodimos et al., 2011).

The monitoring of assembly processes is usually addressed by building customized solutions using commercial framework packages as Halcon (Eckstein and Steger, 1999) or Cognex (Scola et al., 2001) frameworks. These frameworks are powerful and contain multiple efficient algorithms for pattern recognition and image analysis. Another possible option is to use other commercial frameworks (Matlab (Hanselman and Littlefield, 2005)) or free libraries such as OpenCV (Bradski, 2000).

3 MOTIVATION

Since the general project architecture suggests to use the ROS framework (Gaspar et al., 2017), we look for a software package or library that can be integrated with ROS interface in a straightforward way.

To our knowledge, there is no straightforward way to connect the ROS (Quigley et al., 2009) interface with such frameworks as Halcon or Cognex software. Moreover, the use of a commercial software would increase the overall cost of the robot work cell. This leverages the use of the free and open source systems as ROS (Quigley et al., 2009) in combination with the OpenCV library (Bradski, 2000).

The processing using the well known software as Halcon or Cognex can only be organized using the procedure schematically shown in Figure 1. The image must be obtained from the camera using the ROS-based framework and saved on a hard drive.

Thereafter, the image can be read and processed by a software package. The ROS node keeps listening to the specified folder for the results. As soon as the image processing is finished and saved, the ROS node reads the results and sends a notification to the robot.

This solution is rather time-consuming and inefficient. Hence, we have developed our own system, which is completely integrated into the ROS framework. Our system is based on OpenCV library, i. e., the main algorithm implementations are tested and optimized. Several algorithms are combined into processing pipelines, suitable for the example use case. The main idea of our software package is to use fast and efficient algorithms that do not require any prior training due to the fact that for each task in each use case the collection of a big amount of data seems infeasible.

Therefore, we propose a novel system, based on OpenCV and ROS libraries, which is designed for monitoring tasks in a robot workcell.

4 AN EXAMPLE USE CASE: AUTOMOTIVE LIGHT ASSEMBLY

Automotive lights (headlamps) are made up of typical rigid structural elements such as housing, actuators, bulb holders, adjustable screws, heat shields, wires and other components (Gaspar et al., 2017).

In Figure 2, two housings of car lights assembled by ELVEZ company are shown.

There are several details that have been used for robotic assembly. The components are listed below and shown in Figures 2 and 3:

- Housing X07 or X82;
- LWR drive;
- Heat shields (left and right);
- Bulb holder;
- Adjusting screw.

Such components as harness connection (cf. Figure 4) have been excluded as not suitable for the robotic assembly.

5 QUALITY CONTROL TASKS

In general, visual inspection is to identify whether a particular attribute is present, properly located on a predetermined area, and not deviates from a given set of specifications (Liu et al., 2015).

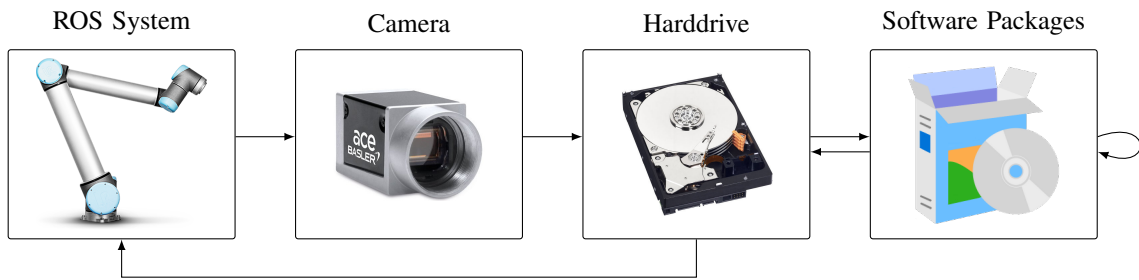


Figure 1: The image processing pipeline, when a software package is not straightforwardly combined with a ROS-based system.



Figure 2: Two models of left and right automotive light housings produced by Elvez. Left: Housing X07; Right: Housing X82.

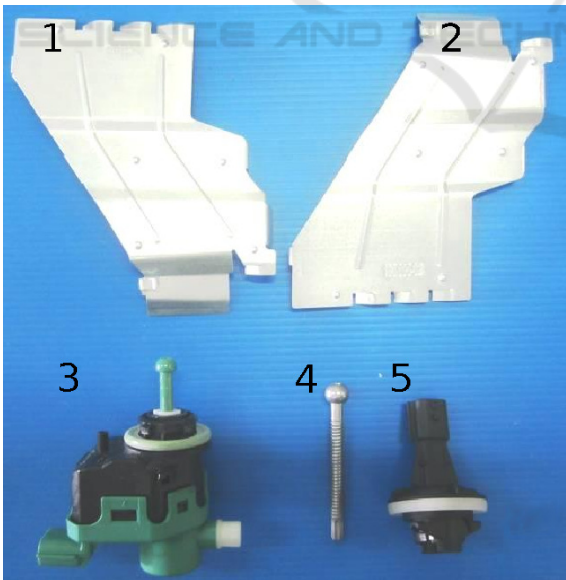


Figure 3: Components for the assembly process. 1 and 2 are the heat shields. 3 is the LWR Drive. 4 is the adjustment screw. 5 is the light bulb holder.

There are two types of quality control tasks: a binary decision and a measurement. In the binary task,



Figure 4: An example of a harness connection. It was excluded from the automated assembly process.

the algorithm needs to make a decision, for instance, if a detail is damaged or incorrectly placed. The measurement task requires to measure a distance between two details, a height of a screw, an angle of rotation of the detail.

Whereas the first task can be implemented using a camera, which has been only intrinsically calibrated, the second task requires the extrinsic camera calibration (Hartley and Zisserman, 2003) to obtain the measurement results in physical units, for instance, in *mm*. In this work, we describe and demonstrate the solutions of the first type.

Here, we consider the following quality control

tasks:

1. Is a certain part of the housing damaged?
2. Is the screw properly assembled and no damages occurred?
3. Is the LWR drive properly assembled and no damages occurred?
4. Is the light bulb holder properly assembled and no damages occurred?

6 METHODS

For our framework, we have chosen hardware and software components that are described below.

6.1 Hardware and User Pre-Setup

The monitoring of the execution and detection of errors is performed in the workcell using a 2D color camera (Basler acA4600-7gc), which is mounted together with a light ring to the robot using a pneumatic tool changer system as seen in Figure 5. This system allows the robot to release a gripper and pick up the camera. This high resolution industrial camera produces 14MP images and has been selected to be able to catch even minor detail damages and assembly inaccuracies. The camera has a rolling shutter and a relatively low frame rate of 7 frames per second, which makes the camera suitable only for situations where the observed object is static relative to the camera.

As part of the reconfigurable workcell that our proposed system is part of, the user has several ways of planning the assembly sequence. It is possible to use kinesthetic guidance in order to teach robotic sequences or use a simulation environment to design a sequence. In both cases the user must define when and where the visual inspections will be performed.

In this paper, we are proposing a solution for binary decisions, in which case camera plane alignment is not so critical as in measurement inspections. That means a user can use kinesthetic guidance or simulation in order to select the camera pose for an arbitrary inspection. There are several constraints that must be obliged in order to come to a viable assembly and inspection solution, e. g., the camera field of view (lens), the robot configuration to reach the required camera pose (collision, workspace), and the cycle time.

6.2 Software Solution

We have developed a framework, based on OpenCV (Bradski, 2000) using ROS interface (Quig-



Figure 5: The industrial camera with a light ring mounted on the UR-10 robot with the pneumatic tool changer system. Left: a general view. Right: a close-up view.

ley et al., 2009), C++, and Qt (Summerfield, 2010). The framework consists of several ROS modules, where the central is the Monitoring one.

The image data stream is published through the ROS module for the Basler camera. As soon as the request for inspection arrives to the Monitoring ROS module, it acquires the data from the camera, executes the corresponding processing, and returns the status of the operation (a boolean value, indicating, if the detail is damaged or not). Additionally, a graphical user interface is developed to demonstrate the monitoring routine.

6.2.1 The Processing Pipeline

First, ideal or template images are acquired (cf. Figure 6) and the corresponding regions of interest (ROIs) are predefined by the user. After the templates are defined, the actual processing of new image data can be executed.

Second, the template ROI is detected in the newly acquired image. The search of the template starts within a neighborhood of the ROI location in the ideal image. The search is based on the assumption that the ideal template and the actual image data are always acquired under very similar conditions, namely, the same controlled lighting and the pose. The template image is overlaid with the corresponding patches of the original image and in each point in a certain neighborhood of the template location a normalized correlation coefficient is computed. The location of the global maximum is considered as the template location (cf. Figure 7). Finally, the detected ROI of the same size as the template image is extracted from the acquired image and passed for further processing.

Third, the subimage preprocessing is executed. Under preprocessing we understand illumination correction and denoising (Masters et al., 2009). It is crucial to apply these techniques not on a full acquired image, but on the extracted subimage to reduce the computational cost and the overall execution

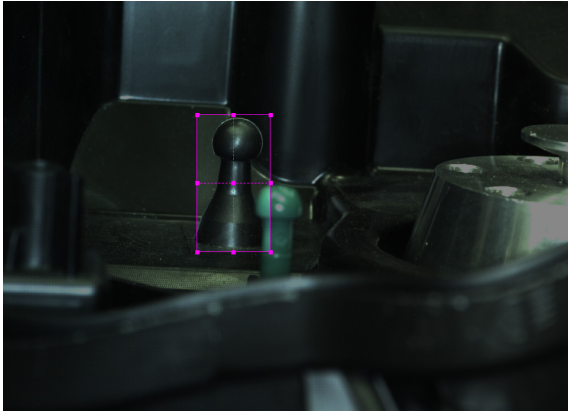


Figure 6: The process of template selection.

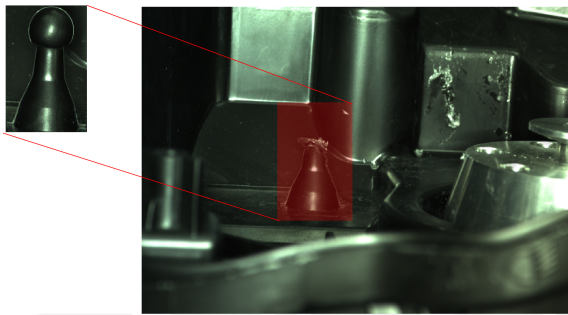


Figure 7: The process of template detection is schematically shown. The template image (left) is sought in the acquired image (right), and the region that is the most similar to the template image is marked red.

time. The subimage is converted to the L^*a^*b color space (Reinhard et al., 2001), which is designed to approximate human vision. The luminance channel (L) is extracted and the adaptive histogram equalization (Reza, 2004) is applied to it. Thereafter, the image is smoothed with median filter to preserve the edges.

Fourth, the use case-specific checks are executed. Usually, they include a segmentation step to extract the contours of the detail of interest, for example, using color global or local, automatic or manual thresholding. For the automatic thresholding, the Otsu thresholding (Zhang and Hu, 2008) is applied. Thereafter, connected components (Masters et al., 2009) are checked, and the component of interest is found and analyzed.

6.2.2 Framework Modes

The framework has three following modes:

- Template selection (online or offline);
- Offline processing pipeline testing;
- Online monitoring.

After the template selection, the user can test the developed detection pipelines and check different parameter settings on an image, acquired from the camera directly or saved on a hard drive.

In the current version of our framework, the processing pipelines are pre-programmed. The next version the user will be able to generate and save the processing pipelines.

6.2.3 Use Case-specific Algorithms

Here, we describe the algorithms that have been developed for the automotive light assembly use-case.

Damage on the Housing Part. An example is shown in Figure 7. In this task, the shape of the detail as well as its intensity are analysed.

The shape of the detail top is assessed using the Hough transform algorithm for circle detection (Masters et al., 2009).

The top circles are detected both in the template and the ROI images. If the distance d between the circle centers c_1 and c_2 and differences between the radii are greater than a user defined threshold T , the detail is considered to be damaged:

$$\begin{cases} d(c_1, c_2) \geq T & \text{Damaged} \\ d(c_1, c_2) < T & \text{OK} \end{cases} \quad (1)$$

For the intensity analysis, the template and the ROI images (I_t and I_{ROI} , respectively) are converted to the HSV color space (Masters et al., 2009), and the absolute differences between the intensity values are computed: $|HSV(I_t) - HSV(I_{ROI})|$. The total number of pixels, where the difference value is greater than a user defined threshold, is evaluated.

In Figure 8, an example of the ROI extracted in Figure 7 is shown. Since the detail is damaged, the Hough transform fails to detect the circle in the ROI, and the expected circle location is marked red. The parts, where the differences with the template image are significant are marked white. As it can be observed, most of the differences are located in the damaged region.

Detection of the Screw Height. Basically, it is required here to detect if the screw height lies in a user-defined range. In this case, a screw base is selected as a suitable template (cf. Figure 4).

When the template is detected, the coordinates of its top left corner $[x_1, y_1]$ and the bottom right corner $[x_1 + w, y_1 + h]$ are given, where w, h denote the width and height, respectively. To extract a region, which contains the screw, the following coordinates are taken: $[x_1, 0], [x_1 + w, y_1]$. Thereafter, the preprocessing

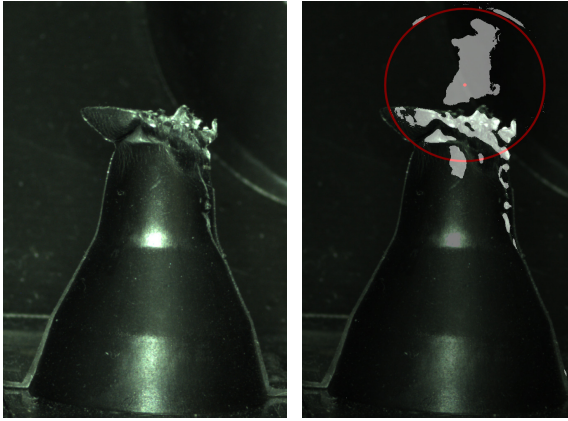


Figure 8: Left: the acquired image of the damaged detail. Right: The processing results are overlaid with the acquired image.

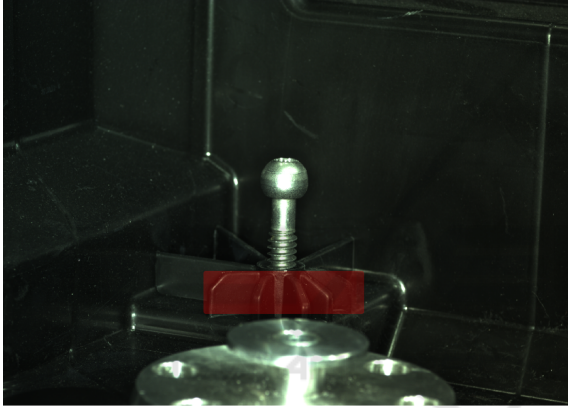


Figure 9: The base of the screw is a template, since this part does not change from image to image.

procedure described above is utilized. Finally, Otsu thresholding (Zhang and Hu, 2008) is applied to the image.

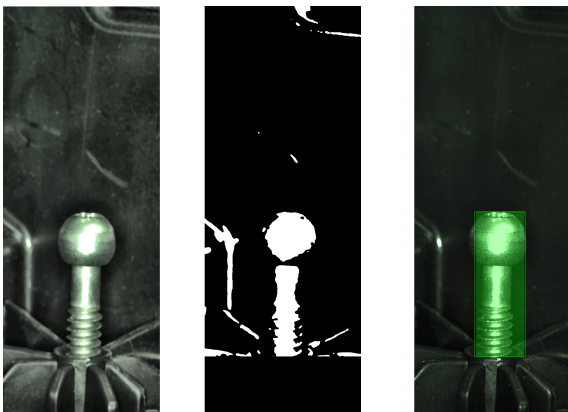


Figure 10: The screw is detected using connected component analysis.

From the thresholding result the two biggest connected components are extracted and their total height is measured (cf. Figure 10). If the height H of the screw does not lie in a predefined range, the case is rejected:

$$\begin{cases} T_{hmin} \leq H \leq T_{hmax} & \text{OK} \\ \text{Otherwise} & \text{Reject} \end{cases} \quad (2)$$

Detection of the Detail Position. Here, both problems of the LWR drive and the bulb holder positioning are solved with a similar processing pipeline. Basically, the template is detected and then the extracted region of interest (ROI) is compared to the template image. If the differences between the images are higher than a certain threshold the case is rejected. In Figures 11 and 12, screenshots from our framework, acquired in the Testing mode are shown. The LWR drive is properly placed, whereas the image with the bulb holder is rejected.

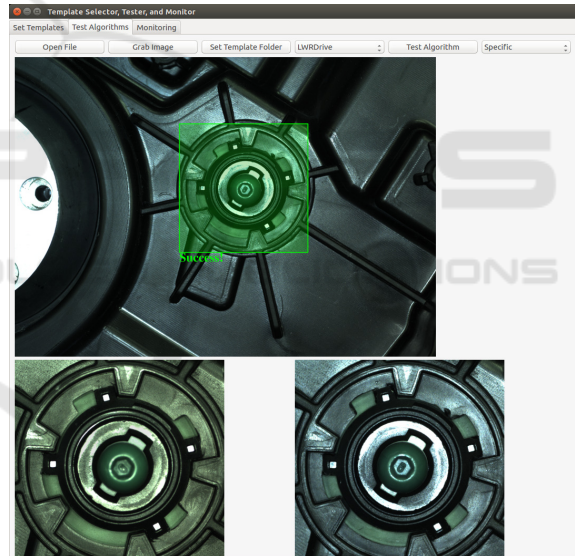


Figure 11: The detection result is positive.

7 EVALUATION AND DISCUSSION

We analyze the presented hardware and software components as well as discuss the advantages and limitations of the system.

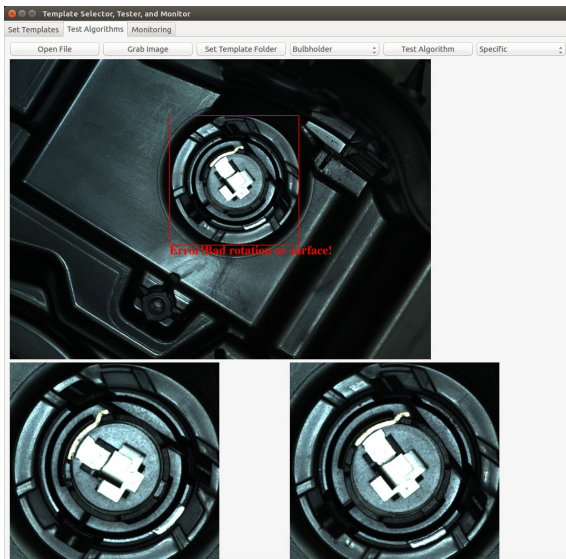


Figure 12: The assembly was not successful.

7.1 Hardware Components

Today the market of industrial imaging offers multiple 2D and 3D cameras. For instance, such companies as "The Imaging Source"¹ or Basler² present industrial cameras, which can be successfully applied for the monitoring task. Apart from that, these manufacturers support a multi-platform application programming interface (API).

Moreover, there is a specialized ROS module for Basler cameras, which is naturally built in the general software architecture of the reconfigurable work cell (Gaspar et al., 2017).

We have selected a color high resolution (14 MP) Basler camera, which allows for up to 7 frames per second. The resolution is $4608px \times 3288px$. This camera can only be used for acquisition of still images, i. e. the robot moves to a certain position, stops, and the image is taken. For such tasks as video tracking, this camera is not suitable.

For the selection of the appropriate lens, several parameters have to be taken into account. The main ones are the object size and the working distance. The sensor size and the lens mount are defined by the camera. Since the size of the imaged objects can be rather small, e. g. $10 \times 20 \text{ mm}^2$, and considering the sensor size, we have selected a $f25$ mm lens with a working distance 200 mm.

¹<https://www.theimagingsource.de>

²<https://www.baslerweb.com>

7.2 Software Components and Algorithms

We observed that measurement problems are very different even for the same use case. Hence, only limited generalization with respect to processing algorithms is possible. Namely, one is not able with the same algorithm to measure the height of a metal screw and detect, if some other plastic detail is intact. The general evaluation pipeline consists of the following steps:

1. Template detection
2. ROI selection
3. ROI pre-processing (denoising and illumination correction)
4. Segmentation and object extraction
5. Object evaluation (distance or angle measurement, binary decision)

The first three steps are rather general, and we use them for all measurement problems. Of course, prior to measurements, the user has to set up the templates for each problem.

For the first step, the template matching algorithm provided by OpenCV is applied. We observed that only normed metrics (for instance, `CV_TM_CCORR_NORMED`) work reliably for our problems. This straightforward template matching is applicable, when the assumption about the controlled lighting conditions holds. In a more general set up, this algorithm can be replaced with a more sophisticated object detection using descriptors, for example, SURF (Zhang and Hu, 2008).

The latter two steps are task-dependent. For segmentation and object extraction we usually apply some prior knowledge about the object appearance, e. g., color, shape, and location on the image. Here, such algorithms as color clustering or thresholding, and shape analysis (Hough transformation, Harris corner detection, Connected component analysis) are applicable.

For each measurement problem, we collected test images, acquired in a test environment as well as the real images, obtained during the assembly procedure. The parameters were pre-selected and optimized for the implemented use case.

A new use case, i. e. with new measurement tasks, the algorithmic pipelines and their correspondent parameters would have to be again selected and optimized. However, we assume that a set of image processing tools provided by the OpenCV library, such as pattern matching, denoising, segmentation, and feature extraction algorithms would be fully sufficient for a monitoring task.

Although the presented framework for visual inspection is efficient and completely integrated with the whole robotic work cell, it has certain limitations. First, the hardware choice is suitable for inspection of static images, but it is not suitable for video tracking. Second, the whole software system is tied to a specific ROS version, which is not downwards compatible. Third, the generation new processing pipelines would require from the user some knowledge on image analysis and robotics. Fourth, new templates will have to be generated and the parameters will have to be re-optimized, if the robot poses or lighting conditions change, which can be a rather time-consuming task.

8 CONCLUSIONS AND FUTURE WORK

The computer vision framework, which is used as a monitoring module in a highly reconfigurable robot workcell has been presented here. The hardware as well as software components were described and discussed. The automotive assembly use case example was used as an application example.

As future work, we will extend the software components to allow the user to generate processing pipelines as well as test the framework on further use cases.

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