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Decision Support System for Dimensional Inspection of Extruded Rubber Profiles

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ABSTRACT Since small and medium enterprises (SME) generate the most of gross domestic product and employment opportunities in developed countries, further progress of the Industry 4.0 strongly relies on the development of dedicated solutions for SMEs-specific problems. Dimensional inspection of extruded rubber profiles represents one such an open issue in the automotive industry, which currently requires a manual measurement and comparison of profiles' cross section with the corresponding technical drawings. Starting from the requirements acquired from the industry practice, this study proposes a novel solution that automates all steps during the inspection process allowing an operator to make the final decision with respect to his observations. The proposed workflow includes the following steps: 1) image acquisition, 2) system calibration, 3) profile segmentation, 4) landmark registration and 5) augmentation of the referent technical drawing over the acquired image. The overall solution was developed by using a single camera and dedicated algorithms for profile detection and augmentation of the referent technical drawing. The extensive validation showed that the solution increased operators' productivity and reliability by a considerable margin (∼6%), while it remains affordable, user-friendly and generic.

INDEX TERMS Quality 4.0, dimensional inspection, image analysis, rubber profiles, computer vision.

I. INTRODUCTION

Although there is no strict definition of the term Industry 4.0 (I4.0), in its wider form, it refers to the process of adaptation and transformation of the global industry under the influence of ongoing technological advance [1], [2]. In the last five years, major driving forces (known as nine pillars) of I4.0 are: autonomous robots, simulation, horizontal and vertical system integration, internet of things, cybersecurity, cloud, additive manufacturing, augmented reality, big data and analytics [4], [5]. Despite the fact that the greatest progress has been made in the field of manufacturing automation [6], it is well known that shifting towards the paradigm of I4.0 will also change the way how companies are carrying out their other business activities [7]. With this in mind, as well as the complexity and speed of the technological development in the twenty-first century, it is more precise to discuss the branches of I4.0, such as: Quality 4.0 [8], Maintenance 4.0 [9], [10], Safety 4.0 [11], Cybersecurity 4.0 [11], Operator 4.0 [12], Logistics 4.0 [13], etc.

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Regarding the Quality 4.0 (Q4.0) pillar, which is the subject of this study, major challenges are related to the digitization and automation of the quality assurance (QA) process (which includes inspection, reporting, continuous staff education, to name a few composing tasks). Although the QA is very wide topic, the core of the Q4.0 may be defined as the adaptation of innovative technologies (mainly ICT) [8]. Computerized quality control is one of the most important challenges of the I4.0, which has gained a lot of progress with the recent advance in computer vision (CV) [14]. Briefly, CV uses various artificial intelligence (AI) algorithms for analysis and interpretation of images collected with digital cameras [15], [16].

Beside the fact that there are verified commercial solutions for general purposes (i.e. Atos, GOM, Germany; eviXscan 3D, Poland; Zeiss Comet, Germany etc.), which have been extensively used in industry, their cost and complexity are major barriers for wider usage among smaller companies. This study emphasizes needs of SMEs because of the fact that they generate the most of the GDP and employment opportunities in developed countries [17]. Thus, more efforts need to be invested into development of dedicated and affordable

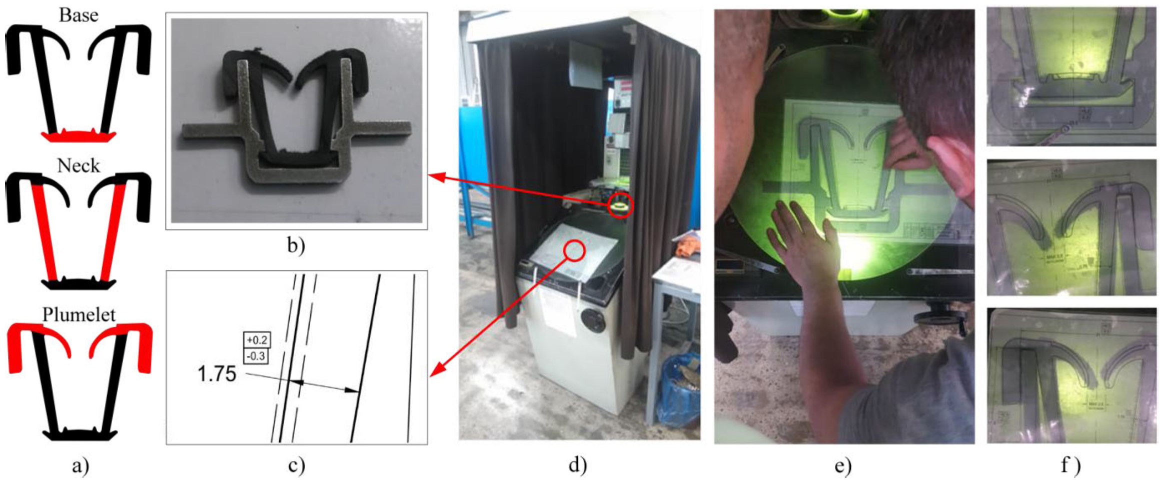

FIGURE 1. Dimensional inspection of extruded rubber profiles. (a) Composing parts of the considered profile. (b) Rubber profile mounted on the metal carrier. (c) Part of the technical drawing with focus on tolerances that need to be inspected. (d) Profile projector. (e) Manual inspection using the profile projector. (f) Inspection of specific parts by re-positioning the technical drawing over the projected silhouette of inspected profile.

solutions for specific problems in manufacturing industry that are not covered with commercial packages. Dimensional inspection of the extruded rubber profiles represents one such problem, which will be considered in more detail. Briefly, the extrusion is a continuous manufacturing process, which takes the plastic mass as the input material (most commonly in the form of granulate of various shapes) and the machine tool for forming the desired rubber shape [18]. At the moment, quality control of rubber parts is very demanding process for both humans and computerized systems. The main reason is the fact that the rubber is a very flexible material, so that one has to bring inspected part into an appropriate referent position in order to perform direct measurement or comparison with the geometry defined with technical drawings.

This study focuses on the inspection of extruded rubber profiles produced for the needs of automotive industry. Available literature on this topic is mainly related to profiles that have simpler shapes or otherwise require complex equipment. Liguori et al. proposed an on-line stereo system that performs 3D profile reconstruction on the basis of using 2D images acquired from multiple industrial cameras and a special illuminator [19]. Perlo et al. used a special magnetic resonance (MR) sensor, which was mounted on the production line for precise cross-sectional inspection of extruded profiles [20]. The MR-based methods have advantage in terms of providing insight into the interior of profile (density, detection of defects and cavities), but they are considerably more expensive and have smaller resolution compared to vision-based methods. Karunasena and Wickramarachchi proposed a system based on the use of cameras and lasers, which was dedicated for controlling rectangular rubber profiles [21]. Anchini et al. have also proposed a system based on the use of two cameras and light illuminator, which was suggested as reliable for inspecting profiles with regular shapes, while a special software package was presented for manual inspection of U-profiles [22]. According to the considered literature and needs of nowadays industry, it may be found that there are increasing demands for further improvements of computerized tools for the dimensional inspection of extruded rubber profiles. Thus, the aim of this study was to develop an affordable software solution based on using a single camera that digitalize the inspection process and eases generation of accompanying QA reports.

II. MATERIALS

A. USE CASE AND THE CURRENT PRACTICE

As a representative use case, we selected the complex rubber profile whose cross-section is shown in Fig. 1. This and other similar profiles are regularly manufactured in the Gomma Line company (Kragujevac, Serbia) for the purposes of the EU automotive industry (Fiat, Renault Nissan, SIGIT, UAZ, GAZ, HI-LEX, to name a few customers). The major composing parts of the profile are: base, necks and plumelets (Fig. 1a).

The current, widely accepted, practice assumes a manual dimensional inspection by using a device called ''profile projector'' (Fig. 1d), which projects a shadow of the rubber profile onto the technical drawing printed on a special paper. Briefly, an operator could perform dimensional inspection by overlapping the profile silhouette with its technical drawing (Fig. 3e, Fig. 1c previews one segment of the technical drawing). The task of QA personnel is to examine deviations of the rubber profiles' length and thickness from dimensions specified with the technical drawing, as shown in Fig. 1f. During the inspection process, operator has to mount the rubber profile onto its corresponding metal carrier (Fig. 1b), which brings the profile into its intended operating position.

As it may be seen from Fig. 1f, even with the metal carrier, it is difficult to inspect all composing parts of the profile at

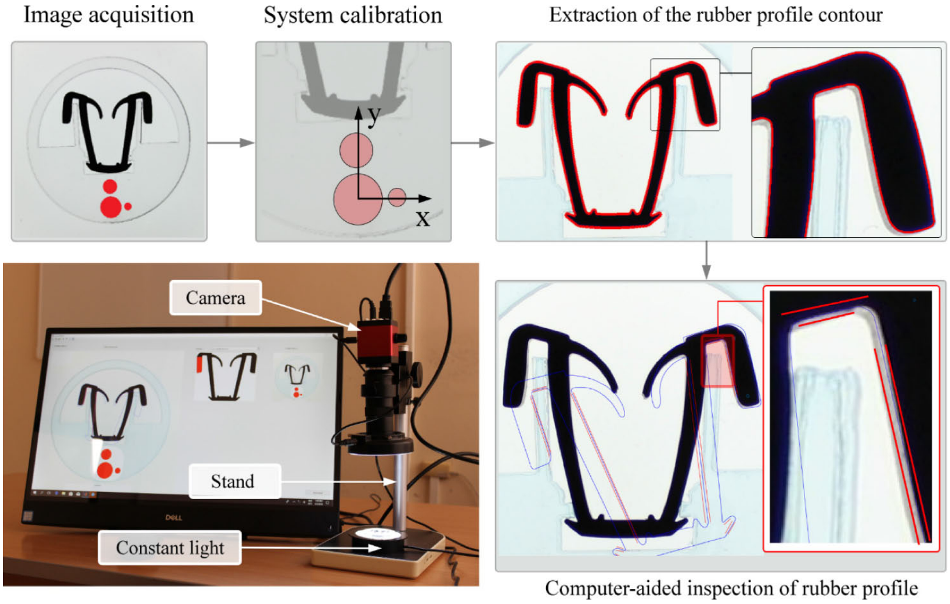

FIGURE 2. Equipment and workflow of the proposed procedure.

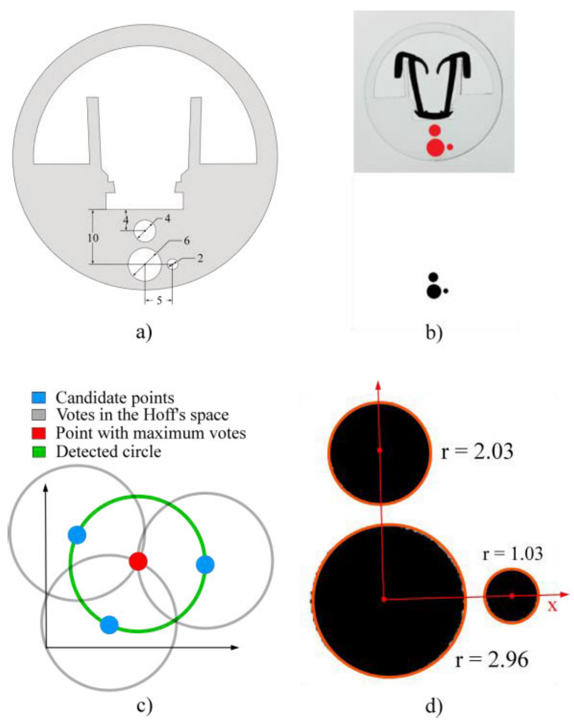

FIGURE 3. Profile carrier and system calibration. (a) Dimensions of the Plexiglas carrier. (b) Extraction of red calibration circles. (c) Detection of the calibration circles using the Hough's circular transformation. (d) Calibration results.

once due to the rubber flexibility. Instead, operators have to manually re-position drawing over specific parts of the profile (base, neck and plumelet) in order to determine whether there are unadmitted deviations or not. The final decision about the profile QA is made by a trained operator by accounting the observed deviations from the anticipated tolerances. Results of the inspection are documented into an appropriate report and delivered to buyers along with the inspected profile cross-section.

B. CHALLENGES AND STARTING ASSUMPTIONS

From the SMEs QA management perspective, the shortcomings of the current practice are:

- Time required to inspect one cross-section is varying from half to one minute, depending on the operator's experience.
- Inter/intra observer reliability of the quality control should be improved. Even if the same operator mounts the profile twice on the carrier, it is common that the rubber profile occupies different position. This fact negatively affects reliability of the inspection results.
- Since the QA process is based on the subjective decision, QA management lacks information about the operators' utility. It would be useful to record each measurement in the form of an image, so that operators that perform the inspection incorrectly could be warned or additionally trained.
- The QA reporting currently assumes filling of various paper forms. Since the company has to perform one inspection after each 20-30 minutes of the profiles production, employees have to deal with the extensive paper documentation. Integration and digitalization of the described process could ease both quality control and management of the accompanying documentation.
- The restriction is that the company assumes no changes in its production line. It is important to note that the manufacturing and QA processes of the company have been defined with respect to the strict industry standards and contracts signed with buyers.

- Finally, considering the SMEs budgets, the solution should be developed by avoiding the use of expensive equipment (expensive cameras and/or accompanying software).

III. METHODS

The proposed workflow, shown in Fig. 2., is based on a series of successive steps that include: 1) image acquisition (Section A), 2) system calibration (Section B), 3) profile segmentation (Section C) and 4) Computer-aided inspection of rubber profiles (Section D). In the rest of the Methods section, each of these steps will be described in detail.

A. IMAGE ACQUISITION

Equipment used for the development and assessment of the proposed procedure is shown in Fig. 2. It included the DELL Inspirion 3477 touchscreen all-in-one PC (Intel i5-7200U, 8GM DDR4 RAM) and the Eakins 1280 × 720px 60 f/s camera that was fixed on the stand. The camera was connected to the PC via the HDMI-USB interface, which delivers the image focused on the rubber profile. The rubber profile was mounted on the carrier and placed above the constant source of light. Operator used the touchscreen to inspect the rubber profile in real-time through the interaction with the simple application, which GUI is shown in Fig. 2.

B. SYSTEM CALIBRATION

Purpose of the calibration is to determine the size of image pixels in millimeters and position of the local coordinate system that determine orientation of the inspected profile. The pixel size was estimated using the Microscope micrometer calibration ruler. In order to ease assessment of the local coordinate system, we replaced the metal carrier with a transparent profile carrier made of the Plexiglas, which has three red circles of different radius (Fig. 3a). It was assumed that the largest circle denotes the center of the local coordinate system, while the smallest and middle circles indicate directions of X and Y axes, respectively.

1) DETECTION OF CALIBRATION CIRCLES

The fact that calibration circles are red eases their detection. Since images are stored as RGB matrices in the computer memory [23], red circles were separated from the rest of the image by selecting the R-channel and applying simple tresholding (Fig. 3b bottom). Afterwards, positions and sizes of the circles were estimated by using the Hough's circular transformation (HCT) (Fig. 3c) [24]. The HCT is a robust technique able to detect centroids and radii of circular objects under the presence of noise or overlapping with other objects. Its robustness comes from the fact that it extracts centroid candidates through the voting in so-called Hoff's parametric space, and selecting these with maximum votes. Particularly, the voting assumes using the equation $(x - a)^2 + (y - b)^2 = r^2$ to search for centroids, where parameters (a, b) are coordinates of the centroid and r is the radius of the candidate circle. If the point (x, y) is on the circumference of a circle, then it satisfies the previously mentioned relation.

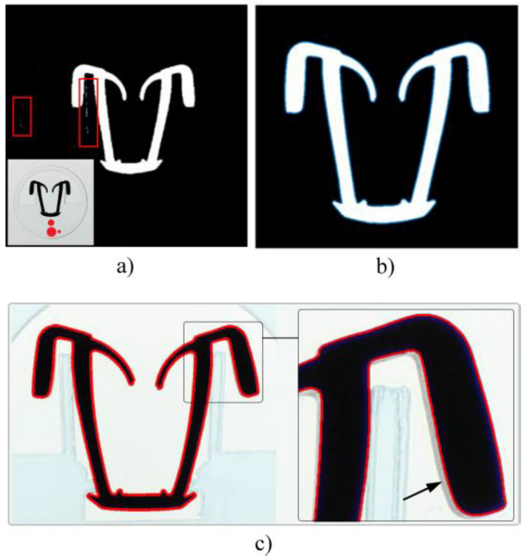

FIGURE 4. Segmentation and extraction of the profile contour. (a) Removal of background (red rectangles indicate residual noises). (b) Segmented profile. (c) Focus on the profile side edge.

2) DETERMINATION OF A LOCAL COORDINATE SYSTEM AND THE SIZE OF PIXELS

After the detection of calibration circles, identification of the profile coordinate system is done by the simple sorting. Centroid of the circle with the largest radii corresponds to the center of coordinate system, while centroid of the smallest circle corresponds to the X direction and the centroid of medium circle corresponds to the Y directions. Since the pixel size is known, we used it to assess the average accuracy of the proposed procedure. Obtained results showed that the proposed procedure results in an error of ∼0.05 mm (the difference between measured and ground truth radius of the calibration circles), which is acceptable since the tolerances were within the range of +0.3 and −0.2 mm.

C. EXTRACTION OF THE PROFILE CONTOUR

Profile segmentation assumes separation of its silhouette from the rest of the image, with the end goal to extract its contour points. Removal of the calibration circles was done by neglecting the R-channel of the image (Fig. 4a), while the Plexiglas carrier was removed by thresholding. As shown in Fig. 4a with a red color, some portion of residual noises (caused by the light reflection through the edges of the Plexiglas carrier) may still remain on the image after these two steps. This problem was solved by eliminating all white regions that contain less than 500 pixels. Finally, the contour shown in Fig. 4c was extracted by computing edges of the remaining white region, which are further used for defining a closed contour [25]. The algorithm starts from the first edge found on the image, and afterwards it keeps connecting

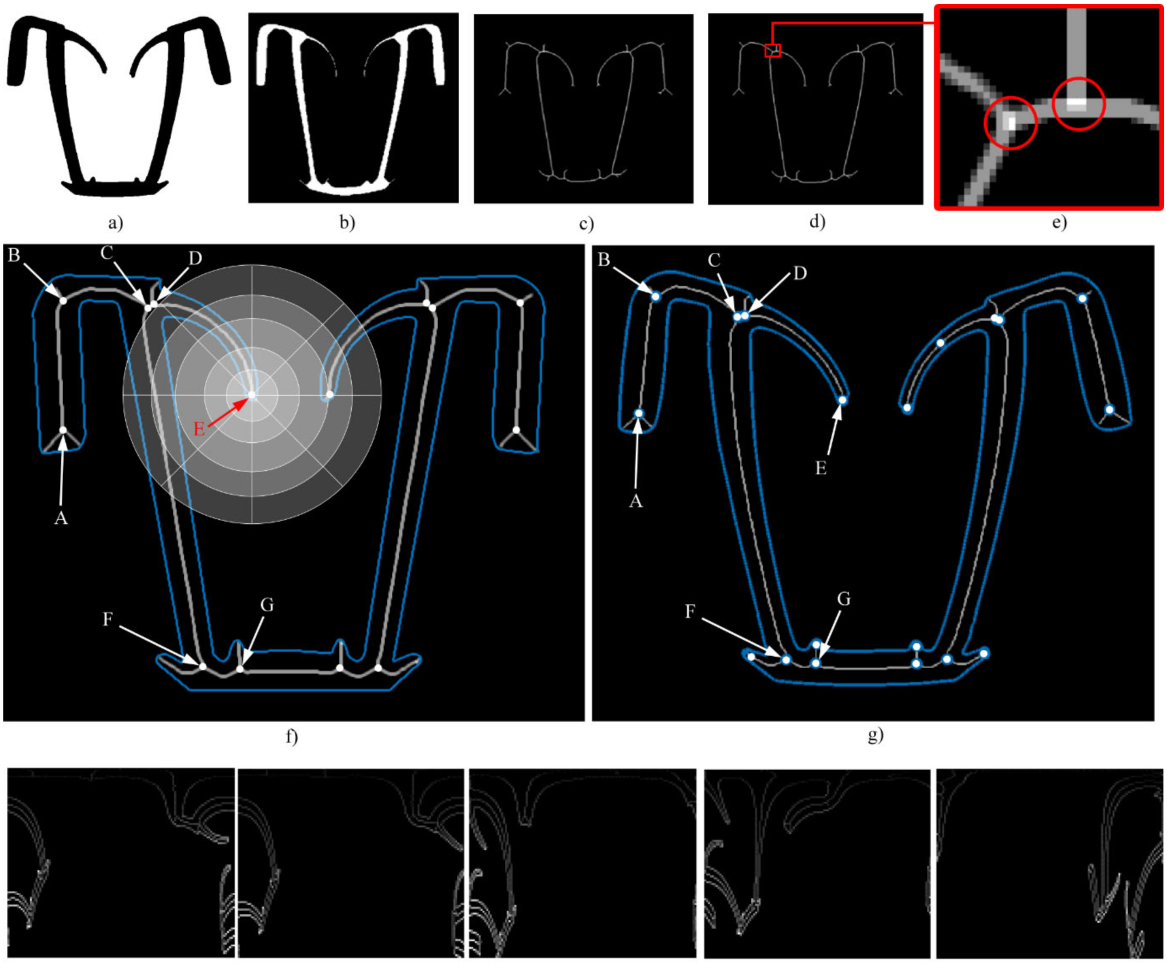

FIGURE 5. Co-registration of landmark points. (a) Segmented profile. (b) Eroded image of the segmented profile (after 20 iterations). (c) Eroded image – the final skeletonized image. (d) Skeletonized image convolved with the 3 × 3 unit operator. (e) Bifurcation points after the convolution. (f) Landmark points on the referent technical drawing with the sketch of Shape context on the point E. (g) Landmark points on the inspected profile. (h-l) Shape contexts computed for various landmark points: (h) point A from the referent drawing (i) point A from the inspected profile; (j) point B from the inspected profile; point (k) C from the inspected profile; point (l) E from the inspected profile.

its neighboring edges [26] until a closed contour is formed. As it may be noted, the obtained contours are fairly accurate (almost at the pixel-level). Additionally, the procedure has the ability to distinguish the profile top surface from the side surface (grey color in Fig. 4c right).

D. COMPUTER-AIDED INSPECTION

The augmentation of the technical drawing over the currently inspected profile was done by using the previously defined local coordinate system and segmented contour. Fig. 1f illustrates the challenge emphasized in the introduction section – the rubber is very flexible material and it is difficult to bring the profile into its referent position, even after mounting on the carrier. As a consequence, it is necessary to sequentially inspect composing parts of the rubber profile (base, neck and plumelet) by fine-tuning (rotating and translating) of the augmented contour over the specific regions of interest. As a solution, we propose a procedure that automatically recognizes specific parts of the profile and then augment the technical drawing on them locally (Fig. 5 and Fig. 6).

1) DETECTION OF THE PROFILE LANDMARK POINTS

In order to automate the inspection of various parts-regions of the rubber profile, we defined a series of landmarks (called ''bifurcation points'') that uniquely identify and differentiate specific parts from the whole shape. The bifurcations were chosen as reliable because their presence could be expected regardless of the flexibility of rubber and profile composing parts (base, neck and plumelet). Bifurcations split the profile into a series of sub-parts – which is suitable for decomposing concave shapes and makes our procedure generic.

In order to detect bifurcation points automatically, we first created a binary mask form the previously detected profile contour (Fig. 5a). Next, we found skeleton points of the binary mask through its iterative eroding (until the remaining regions are thick one pixel, see Fig. 5(b-c)) [27]. Afterwards, we convolved the skeletonized image with the unit 3 × 3 operator, ending-up with the image shown in Fig. 5d. As a result, the value of pixels at the bifurcation points will be greater than 3 (Fig. 5e, white color), while values of all other pixels will be in the range from 0 to 3 (Fig. 5e, grey and black colors). Depending on the profile shape complexity, number of obtained candidate landmarks may vary up to several tens, which reduces the computational cost of the next step.

2) CO-REGISTRATION OF THE REFERENT LANDMARK POINTS

Referent landmark points A-G were sampled from the technical drawing, as shown in Fig. 5f. In order to augment the technical drawing over specific regions defined with these points, we need to identify their corresponding pairs from candidates extracted in the previous step (see Fig. 5g). For these purposes, we propose an adapted version of the Shape context algorithm (which was initially proposed for measuring similarity between geometric shapes) [28]. Considering an arbitrary contour (composed of n points), our procedure calculates shape descriptors that numerically express relation of the observed point with respect to the rest of n-1 contour points. In order to deal with contours composed of a large number of points more efficiently, the shape context was calculated as a histogram in the log-polar coordinates (Fig. 5f, point E). Briefly, histograms count number of points found in regions defined by varying bins-radii and angles. The sketch in Fig. 5f has 8 angular and 5 radial divisions, and the Shape context algorithm counts number of centerline and border points within the defined 8 × 5 regions. Since we assumed that the polar coordinate system is positioned at the currently observed point (point E in Fig. 5f), it is ensured that the calculated shape context is invariant to translation, while at the same time it is variant to the scaling. Since rubber profiles are symmetric, we used 15% closest points for computing shape contexts in order to reduce their scope to the local area and enable distinguishing of landmarks from the left and right sides. Examples of histograms computed for various landmark points are shown in Fig. 5(h-l).

Shape contexts of landmark points sampled from the referent drawing were computed only once and loaded on demand (Fig. 5h). For the currently inspected profile (Fig. 5(i-l), shape contexts were computed for all candidate landmark points extracted with the procedure described in Section 3.4.1. Since the shape context is a fairly robust descriptor, finding the correspondence between referent and candidate landmarks was reduced to a simple search and selection of a candidate with the minimal difference. An example of co-registered landmark point A is given in Fig. 5h (referent technical drawing) and Fig. 5i (image of inspected profile).

3) AUGMENTATION OF THE TECHNICAL DRAWING OVER CO-REGISTERED LANDMARK POINTS

As a reminder, we highlight the user requirement that the proposed solution should ease but should not change the current QA practice, which means that a human operator has to make the final decision while the rest of the process could be digitalized. Accordingly, we used the previously computed landmarks correspondence to augment the technical drawing over predefined regions shown in Fig. 6e. The alignment was performed by using the Iterative closest point algorithm (ICP), which aligns two groups of point cloud (orange color in Fig. 6b and Fig. 6c) by bypassing the optimal pairs and minimizing the distance between them [29]. Considering shape and size of the inspected rubber profile, point clouds were defined by using 100 points around landmarks (see Fig. 6b and Fig. 6c).

Regions from Fig.6e were defined by the company as mandatory to inspect, thus, our goal with the automation was to ensure that an operator will not omit any of them. To ease operator's work additionally, we enabled switching between 9 predefined views by using the drop down menu or by pressing 1-9 keyboard buttons. Fig. 6d shows the augmentation of the technical drawing over the left plumelet (defined with the landmark points A and B). Fig. 6f shows the augmentation of the technical drawing over the region defined with the landmark points B and C. Fig.6h shows the augmentation of the technical drawing over the left neck (defined with the landmark points C and F). Additionally, we developed a feature that allows a user to click on an arbitrary region and performs the local alignment of the technical drawing over this particular region (see Fig. 6(h-j) for illustration).

4) SUPPORTED FEATURES AND GUI

After the alignment, the operator is allowed to fine-tune the referent drawing over the inspected profile (with minimal zooming, translation and rotation). On this way one could precisely inspect specific regions. Beside mentioned, the presented solution has various supporting features like background removal, tools for measuring and annotating – which are useful for the preparation of QA reports. After the inspection is done, screenshots of the performed inspections are saved for the purpose of generating the QA documentation. The developed GUI with annotated basic functionalities is given in Fig. 7.

E. ADAPTATION OF THE PROPOSED PROCEDURE

For the purpose of clarity and consistency, the proposed procedure was explained considering one representative profile shape (Fig. 1a). Since companies commonly have a series of various profile shapes in their assortment, this section explains how to adapt the proposed procedure for inspecting profiles of arbitrary shapes (use cases are shown in Fig. 8). Namely, two steps are: 1) production of a corresponding transparent Plexiglas profile carrier (profiles with internal bulbs do not need it) and 2) extraction of referent contour from a technical CAD drawing of the profile. Regarding the second step, it assumes extraction of contours, tolerances and landmark points from the CAD drawing. For these purposes, we used a simple GUI that allows us to manually extract-redraw contours and tolerances, while landmark points were extracted following the procedure described

FIGURE 6. Augmentation of the technical drawing over co-registered landmark points. (a) Default augmentation after the system calibration. (b-d) Alignment using the Iterative closest point algorithm (orange color indicates the point cloud selected for the fitting). (e) Sketch of the pre-defined inspection regions. (f-h) Augmentation of the technical drawing over the predefined regions (note how the neck is bended, which consequently requires an additional user interaction). (i-k) Inspection of the left neck by using the local alignment feature.

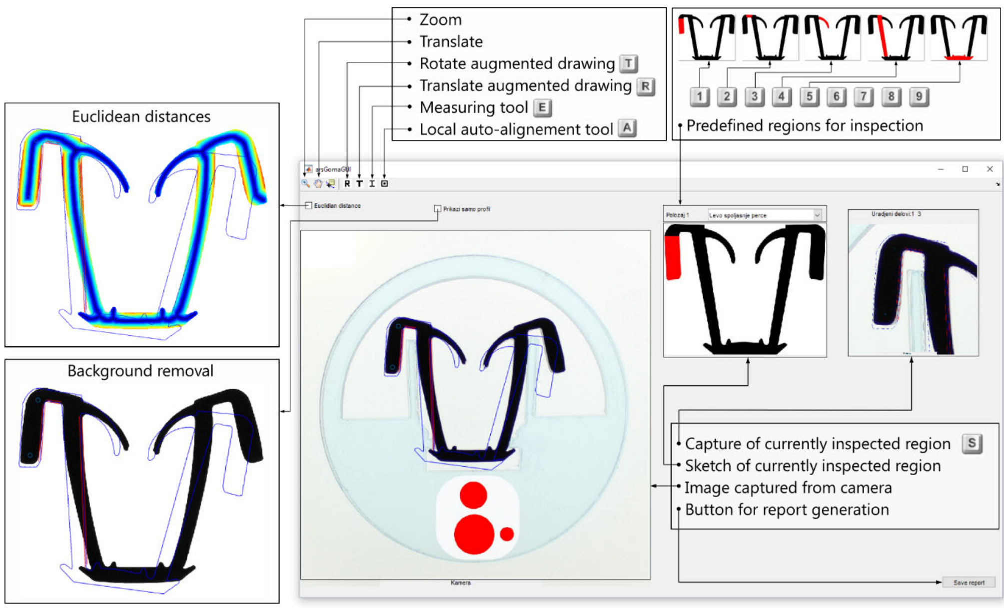

FIGURE 7. Demo GUI with annotated functionalities.

in Section II D 1. Finally, in order to predefine specific regions for the automated augmentation of technical drawing (Section IV D 3) a user has only to define pairs of previously extracted landmark points. Fig. 8e-f demonstrates augmentation of regions defined with landmark points A and B (Fig. 8b).

IV. RESULTS

All the results presented in this study were obtained by using the setup shown in Fig. 2. The implementation was done using the Matlab 2017b (Mathworks, Natick, MA); whose demo source-code is publically available on the GitHub repository: https://github.com/ArsoVukicevic/Rubber-profile-inspection.

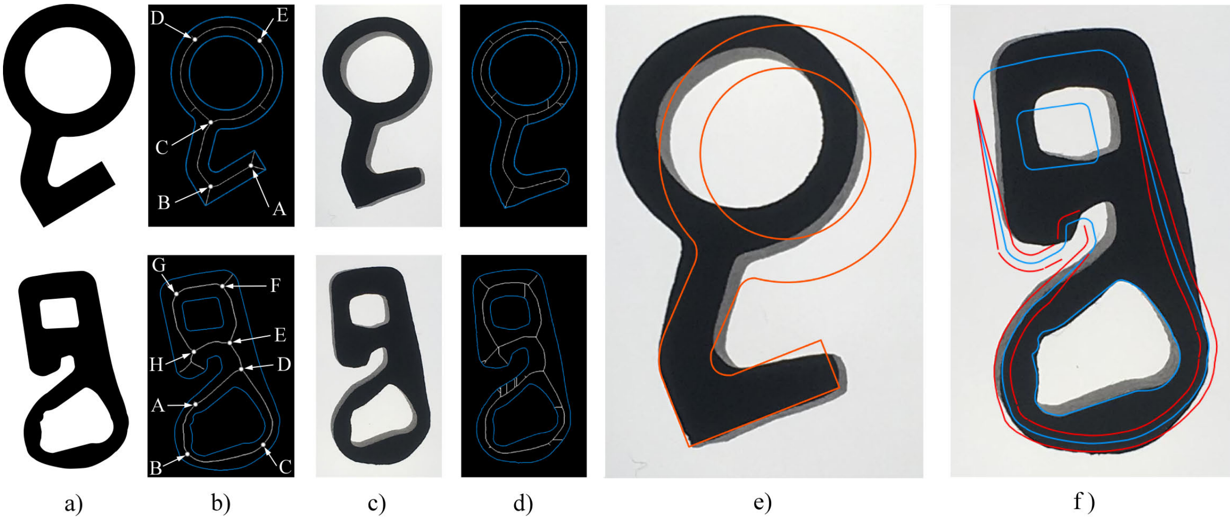

FIGURE 8. Adaptation of the proposed procedure for inspecting various profiles. (a) Referent shapes defined with technical drawings. (b) Contours and landmark points extracted from the technical drawings. (c) Acquired images of inspected profiles. (d) Contours and candidate landmark points extracted from the acquired mages. (e-f) Augmentation of the referent drawings over regions defined with landmark points A and B from Fig. 8b.

In this study, the task of dimensional inspection was considered as the binary classification problem. In order to verify and quantify performances of the developed procedure, results of the semi-automatic inspection were compared with the results of the manual inspection performed on the profile projector shown in Fig. 1. For these purposes, 25 defective rubber profiles were selected from the company database (which amount corresponds to 20-40 working days). In order to keep the set balanced, we included 25 correctly produced profiles as well. Two operators with various level of experience (1 and 12 months) were involved in the assessment. Each operator was asked to inspect 50 profiles manually and semi-automatically. The assessments were repeated twice in order to determine operators' intra and inter-observer variability (influence of human factor on the variability of performances). The ground truth values were defined through the expert consensus.

Adapted metrics that indicate operators performances included: accuracy Acc = (TP+TN)/(T+P) – ratio of correctly classified and total number of samples, positive predictive value PPV = TP/(TP+FP) – probability that correct samples are classified as defect-free, and false negative rate NPV = TN/(TN+FP) – probability that defective samples are classified correctly; where TP and TN represent the number of defect-free and defective samples that are correctly recognized; FP and FN are the number of profiles that are mistakenly classified as defective and defect-free samples; and P and N are the total number of defect-free and defective rubber profiles. These metrics were further used for the calculation of sensitivity, specificity and area under the receiver operating characteristic curve (AUC).

Regarding the assessment of the procedure sensitivity to human factors (experience and repeatability), intra-observer and inter-observer agreement were assessed by computing the kappa-κ statistics [30]–[32]. Particularly, the intra-observer agreement was measured using the Cohen's weighted kappa, while the overall inter-observer agreement was measured using the Scott/Fleiss' kappa.

V. DISCUSSION

In order to more objectively discuss the presented findings, this section was split into three separate sub-sections focused on elaboration of our findings, contribution and recommended directions for further applications and improvements.

A. FINDINGS

Because the rubber is very flexible material, dimensional inspection of extruded rubber profiles still represents challenging problem in the automotive industry. Although the complexity of the inspection is reduced to the comparison of the inspected part with its corresponding referent technical drawing, reliability of observers' subjective decisions remains major drawback of the current industry practice. Results from Table 1 indicate that experience of operators strongly affects performances of the manual inspection. All metrics showed that the experienced operator (a person with 12 months of experience in performing this task may be considered as senior) over performed the novice operator by the significant margin. In general, ensuring the highest possible reliability of the QA is considered among the most important in reducing flaws and spoilage in automotive industry. Particularly, because components are commonly made in large series–rejection of an order (due to a flaw in QA) cause serious losses for companies.

Considering the above mentioned facts, results from Table 1 indicate two-fold contribution of the proposed semi-automatic method. First, compared to the manual

TABLE 1. Performances of the manual and semi-automatic inspection of extruded rubber profiles.

Observer experience [months]	Manual inspection									Proposed semi-automatic method								
	Accuracy [%]	PPV	NPV	AUC	Sensitivity	Specificity	κ	κ-Intra-observer agreement	κ-Inter-observer agreement	Accuracy [%]	PPV	NPV	AUC	Sensitivity	Specificity	κ	κ-Intra-observer agreement	κ-Inter-observer agreement
1	0.79	0.80	0.83	0.79	0.82	0.76	0.58	0.63	/	0.85	0.87	0.85	0.85	0.86	0.84	0.72	0.75	/
12	0.84	0.82	0.85	0.84	0.86	0.82	0.68	0.76	/	0.9	0.91	0.88	0.9	0.88	0.92	0.8	0.79	/
Overall mean ± std (min – max)	0.81 ± 0.03 (0.78–0.84)	0.80 ± 0.03 (0.76–0.84)	0.83 ± 0.03 (0.79–0.86)	0.81 ± 0.03 (0.78–0.84)	0.84 ± 0.03 (0.8–0.88)	0.79 ± 0.03 (0.76–0.84)	0.63± 0.06 (0.58–0.68)	0.69± 0.09 (0.63–0.76)	0.67	0.875±0.03 (0.84–0.9)	0.87± 0.04 (0.84–0.91)	0.87± 0.02 (0.84–0.88)	0.875 ± 0.03 (0.84–0.9)	0.87 ± 0.02 (0.84–0.88)	0.88 ± 0.04 (0.84–0.92)	0.76 ± 0.06 (0.72–0.8)	0.77 ± 0.02 (0.75–0.79)	0.73

PPV – positive predictive value, NPV – negative predictive value, AUC – area under characteristic curve, κ - kappa value.

dimensional inspection, it increases performances of both novice and experienced operators by significant margins (accuracy, PPV, NPV, AUC, sensitivity and specificity values in Table 1). Secondly, which is more important, it increases intra/inter observer reliability of the dimensional inspection (kappa values in Table 1). Assessment showed that the proposed procedure enables novice operators (accuracy = 0.85) to reach performances of experienced operators that performed the dimensional inspection manually (accuracy = 0.84). This improvement is important since it increases companies' robustness to QA personnel fluctuation, which is considered as major concern in nowadays competing industry. Moreover, the obtained values of the kappa-statistics showed that the proposed procedure is advantageous in terms of the QA repeatability. Particularly, the intra-observer agreement ($\kappa = 0.77 \pm 0.02$) was on the edge with the operators' agreement with the ground truth values ($\kappa = 0.76 \pm 0.06$), while the inter-observer agreement between experienced and novice operator showed substantial agreement ($\kappa = 0.73$). Considering the presented findings, we report that the overall improvement of operators' performances was ∼6%.

B. CONTRIBUTION TO RELATED LITERATURE

During the last decade, a lot of efforts have been invested into advancement of quality control and dimensional inspection through the adaptation of machine vision techniques [33]–[36]. Although a series of commercial solutions has been established as industry standard for general purposes, the practice has shown that there is still a large number of specific industry problems that require dedicated solutions. Dimensional inspection of extruded rubber profiles represents such a problem, whose challenges have been elaborated and addressed within the present study (section II). Compared to previous studies, our approach has a series of differences that we would like to emphasize as contributions.

The first one is the fact that our study starts from the precisely defined SMEs' requirements, which resulted with the increased usability of the proposed solution. For example, none of the previous studies used carrier and consequently did not enable the inspection of profiles into their intended operating position. Instead, the previous studies assumed that the inspection should be performed assuming free position of the inspected rubber profile [18], [21]. According to our experience, this represents violation from the practice defined by the industry regulations and contracts between manufacturers and buyers. Following the requirements list, we proposed the solution that automates all the inspection tasks excluding the definite classification of the inspected profile – which should be performed by an operation.

Secondly, compared to the previous studies, our study avoided usage of multiple cameras [21] and complex techniques for three-dimensional inspection [18]. Instead, the present study was designed to support the current practice, which assumes inspection of profile's cross-section in 2D. This largely simplified the problem and increased reliability of the solution (error rate was ~0.05 mm), since methods for 3D-reconstruction from multiple views require very expensive equipment to reach accuracy bellow tolerances defined with technical drawings (+0.3 and −0.2 mm).

The third advantage of the present study is its adaptability, which was explained in Section III E. The proposed procedure is based on the contour detection and its shape analysis, as well as on the co-registration and alignment of the landmark points. By combining these techniques, the proposed procedure could be adapted for inspecting rubber profiles of various shapes (which is important since companies produce a wide spectrum of profile shapes).

Finally, one of the most important requirement from the industry practice was affordability of the solution. Together with the adaptability, costs are one of the most important barriers for general purpose solutions. These costs could be related to: expensive cameras, time needed to collect sufficient amount of annotated data for the purpose of learning of AI algorithms, GPUs needed to run AI algorithms efficiently, expertise needed to afterwards adapt initial solution for newly ordered rubber profile, to name a few. Considering this, the proposed solution avoids these obstacles and it represents an example of so-called ''low-cost automation'' [37], [38].

C. TOWARDS THE FULLY AUTOMATIC INSPECTION

Inspection based on using artificial intelligence algorithms represents an attractive topic in research community [39], [40] . In general, one could develop an AI-based system upon the proposed procedure by using the automatically extracted features for the purpose of learning and subsequent exploitation of trained AI algorithms. Here, features of interest are lengths and thickness of the composing parts. Distances and lengths of the base, the neck and feather could be assessed automatically by using previously described landmark points. Regarding the thicknesses, users were provided with the feature that automatically calculates thicknesses by using the previously skeletonized binary mask and the profile contour. Starting from the skeleton pixels, the procedure propagates towards the profile contour while accounting the number of steps-pixels propagated and writing them into the thickness matrix. Finally, the thickness colour-map shown in Fig.7 (Euclidean distances) was obtained by multiplying the thickness matrix with the pixel size determined during the calibration step (Section B).

Reasons why we omitted to further develop an AI-based system within this study are two-fold. First, although fully replacement of human operators appears attractive in literature, the practice in the field of quality control of extruded rubber profiles has shown that application of such solutions in real-world conditions remains negligible. Secondly, we would like to emphasize that one of the adapted requirements was to propose solution that ease but does not change the current company practice (which means letting human operator to make the final decision). To sum-up, at the current stage of the Quality 4.0 paradigm shift, companies are more interested for tools that could increase reliability and performances of human operators – instead of replacing them with computers. Accordingly, we decided to keep our study compact and relevant for both industry and research audience interested for the further automation of the proposed procedure.

D. APPLICATIONS AND FURTHER WORK

It is well known that repetitive jobs cause fatigue and decrease in workers' concentration and cognition, which need to be avoided for achieving the desired results in quality control. The proposed procedure reduces dependency on the human experts and effort needed to perform the dimensional inspection of rubber profiles. With the digitalization of accompanying reports, it is easier to reveal and prevent flaws in quality control. The captured images of dimensional inspections could provide management with insight into operators' experience, which further enables company to perform additional training for lower performing employees. Continuous training and improvement of employees is an important aspect of the nowadays changing industry. Accordingly, such digitalized QA systems could support both training and ensuring that operators reached desired excellence in the QA of extruded rubber profiles. To sum up, the obtained feedback from the considered SME was that, at the moment, digitalization brings bigger practical value compared to replacing human operators with computers. However, we except that further research on this topic could be directed to the further automation of the dimensional inspection of extruded rubber profiles.

VI. CONCLUSION

The considered problem of dimensional inspection of extruded rubber profiles in automotive industry is challenging because the rubber is very flexible material, which makes the manual inspection difficult and time consuming. Although some studies aimed to automate this task, their wider application in industry practice remains limited due to the rubber flexibility and variability of shapes that companies have to produce. Starting from the list of requirements acquired from the industry practice, this study proposed the novel semi-automatic solution based on the usage of affordable equipment and dedicated algorithms. The obtained results indicated multiple benefits that brings the proposed digitalized solution. First, it is experimentally shown that it increases operators' reliability by a significant margin, while reducing the time need to perform the inspection. Additionally, a series of side-benefits were emphasized, concluding that the proposed solution eases management of QA reports, tracking and revealing hidden patterns in QA flaws occurrence. These features could be further used for providing employees with continuous training and perfecting of their skills, which are important for ensuring SME's competitiveness on the global market.

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