Smart portable laser triangulation system for assessing gap and flush in car body assembly line

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***Abstract*— In this paper a smart portable laser triangulation system for assessing gap and flush in car parts coupling is presented. This system is designed to make it possible an accurate measurement by human operators along car-body assembly line. The device is integrated with additional sensors managing safety of operators and measurement uncertainty minimization. Moreover, it embeds Wi-Fi communication capabilities for autonomous data exchange with plant middleware infrastructure exploiting the OPC-UA framework.**

Keywords—gap&flush, dimensional measurement, non-contact sensors, smartphone

I. INTRODUCTION

In modern digital factories, performing in-line quality control on 100% of production is a key strategy to target a zero-defect manufacturing (ZDM). This is particularly relevant in multi-stage production, where the overall production system performance depends on each single process and on the interaction between stages. In fact, the real time and early identification of deviations and trends, performed at single process level, allows to prevent the generation of defects and their propagation to down-stream processes, enabling the entire manufacturing system to perform early detection of process deviations and self-adaptation to different conditions. However, a zero-defect strategy requires reliable information to support any decision. Reliable information requires accurate measured data from the process and the product, a close integration of process and quality control and capability to keep measurement uncertainty under control [1][2].

These concepts are the basis of a recent European project, the GO0D MAN project [3], which implements a distributed system architecture built on agent-based Cyber-Physical Systems (CPS) and smart in-line quality control systems designed to exhibit real-time adaptive behaviors, in order to keep measurement uncertainty under control even in case of variations of process/product parameters and in presence of disturbances.

The automotive industry is a relevant example of multi-stage manufacturing targeting the zero-defect objective. Within the automotive industry, car-body assembly represents a key sub-set of multi-stage process. In this process, for instance, checking gaps and flushes among adjacent surfaces is of uttermost importance for both aesthetic and functional purposes. Indeed, these quantities are measured through the whole car body assembly chain, from body in white to the assembled car.

Gap is the space between two opposite surfaces, measured along the tangent plane on the surfaces in exam. Flush is the mismatch between two surfaces, i.e. the distance between two adjacent surfaces measured in the orthogonal direction to the tangent plane on the surfaces in exam (Fig. 1).

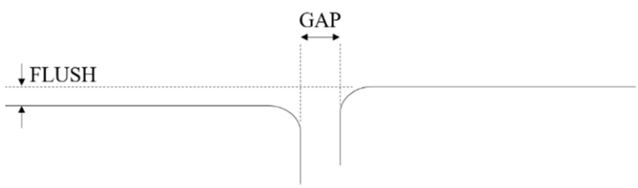


Fig. 1. Gap & Flush definition

Depending on the automation level of the assembly process, gap and flush can be measured automatically, in dedicated measurement areas, exploiting non-contact methods based on optical triangulation [4][5][6], or manually by operators, who exploit feeler gauges (Fig. 2a) and dial gauges (Fig. 2b). However, in the latter situation, no continuous data acquisition can be performed, so there is no recorded data at the end of the inspection.

(a) *(b)*

Fig. 2. Operators' devices for measuring gap and flush: manual feeler gauge (a) and dial gauge (b)

Contrarily, compliance to the Industry 4.0 paradigm requires continuous data availability and possibility to push information gathered from the line to the plant middleware. As a consequence, it becomes important substituting conventional manual devices with new instrumentations, representing the OT (operational technology) level of the process, continuously connected to the IT level of the plant. In this view, operators assume new responsibilities, becoming direct actors of the whole data acquisition chain. Indeed, when it comes to measurement performed by human operators, the uncertainty associated to the measurement system should be combined with the uncertainty due to operators 'behaviour. Since this latter contribution can be times higher than the uncertainty associated to the measurement system, it becomes clear the need of developing measurement devices and associated use strategies easing the operator in the measurement process, so as to reduce the overall uncertainty of the measurement.

This paper presents a novel hand-held device for in-line measurement of gap & flush based on optical laser line triangulation suited to be used by a human operator (Fig. 3). The device exploits a smartphone, equipped with a series of sensors, for managing: a) data acquisition and processing; b) minimization of measurement uncertainty; c) communication with plant IT level; d) operators' safety.

The paper is organized as follows: the device is presented in Section II; Section III describes the software strategies for ensuring a robust measurement; Section IV provides some results while Section V draws the main conclusions of the work.

Fig. 3. Application example of the portable gap & flush measurement device

II. SMARTPHONE-BASED GAP&FLUSH MEASUREMENT SYSTEM – HARDWARE CHARACTERISTICS

Laser line triangulation (Fig. 4) is a well-known technique: a laser line is projected onto a target surface while a camera detects light scattered by a target at an angle. An image of the laser line is therefore formed on the camera, from which the profile *Z(X)* can be computed through trigonometric relations. Gap and flush are then extracted by processing the *Z(X)* profile.

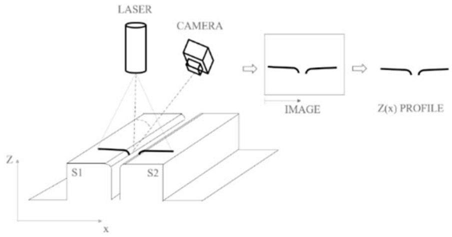


Fig. 4. Measurement principle of laser line triangulation

One key challenge of a portable laser scanner targeted to the automotive industry, specifically to the car body assembly process, is the possibility to work on very different surfaces of very different materials behaving differently from an optical point of view (e.g. translucent, transparent, reflective materials). This requires to properly chose the wavelength of the laser source. Two aspects should be considered:

- *Surface diffusivity*. To ensure diffusive behaviour for light scattered from a target surface it is fundamental to increase the ratio of the surface roughness (Ra) over the laser wavelength.
- *Light absorption*. Light absorption depends on surface colours, its coating layers and pigments. Moreover, when it comes to plastic components (e.g. used for rear lights), plastic colours as well as the characteristics of the functional facets become important. Dedicated tests to assess the reflectance of the material involved at different wavelength can be run, e.g. by exploiting spectrophotometers.

The device developed uses a laser of 405 nm, i.e. operating in the violet region, since it was demonstrated to provide the best results on all surfaces involved in the car body assembly. The camera was chosen to embed a sensor providing sufficiently high sensitivity in this spectral region. The choice fell on a Raspberry PiCam, having a low size sensor (sensor optical size: ¼''), assembled in a small board (size: 25 x 24 x 9 mm;), as well as a relatively high resolution (2592 x 1944 pixels), adjustable focus (focal length: 3,6 mm; numerical aperture F#: 2.9) together with a good spectral response in the violet region (QE of 65% at 405 nm). Indeed, this camera makes it possible to operate at short device-to-target distances (nominal stand off distance 30 mm).

A Time of Flight (ToF) laser module is embedded on the device. The aim of such sensor is to conditionally switch on/off the laser source when the device-to-target distance gets above functioning range (stand-off distance ranging from 30 mm to 40 mm). Indeed, this helps in providing a feedback to the operator with the intent of lowering the uncertainty associated to a manual measurement.

The time of flight sensor and the optical triangulation hardware, i.e. laser and camera, are managed by a Raspberry PI Zero model which is powered by a smartphone hard-connected to the board. The smartphone communicates with the Raspberry PI exploiting the Termux environment [7] (Android terminal emulator and Linux environment app) and is exploited also for performing calculation, interacting with the production line (e.g. reading of the barcode associated to the car under inspection) and exchanging data with the plant middleware.

Fig. 5 provides an overview of the hardware used inside the device.

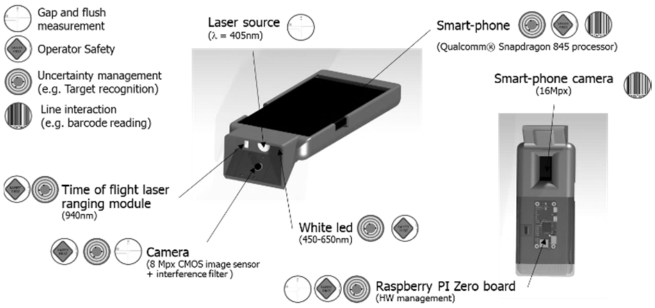


Fig. 5. Smartphone-Based Gap&Flush Measurement System

Fig. 6. Example of device measuring on a sample of car rear-lights

Fig. 6 presents the device in the hand of the operator, while measuring gap&flush on rear lights.

III. Smartphone-Based Gap&Flush Measurement System – Software Characteristics

The software managing the whole device was specifically designed to operate on four levels:

A. Interaction with the operator;

B. Interaction with the production line

C. Processing of the image acquired and extraction of gap&flush data;

D. Communication with the plant middleware.

All the levels were coded exploiting Python, PhP and bash scripting.

A. Interaction with the operator

An interactive HMI was specifically designed to guarantee a user-friendly interface for the operator who has to manage the device. The HMI was developed as a web-service, to give the possibility of remotely connect to the device and access the user interface for supervision and debug purposes (e.g. during the training phase of operators).

Part of the core software is dedicated to guarantee safety of operators in using the laser-based device. Indeed, a convolutional neural network is exploited both for optimizing, in an automated way, the image exposure (which is highly material dependent) and guarantee that the laser source remains off if the device is not pointed towards a car.

B. Interaction with the production line

This level manages communication with the hardware embedded in the measurement system as well as with the car under inspection (e.g. barcode scanning, managing of ToF module, etc.). Images acquired by the Raspberry PI Zero board are transferred to the smartphone via a Virtual Ethernet adapter (Ethernet Gadget mode) through Type-C USB link and exploiting *ssh* protocol. Images acquired are then processed on the smartphone taking advantage of the Termux environment and using OpenCV libraries on specifically developed Python routines.

C. Processing of the image acquired and extraction of gap&flush data

When translating from 2-D camera coordinates to 3-D world coordinates, the accuracy of the estimated 3.D coordinates of a point in the space is limited by the image resolution. If a large spatial volume is projected onto the imaging surface each single pixel of the image surface records information from a range of positions. Therefore, algorithms which estimate features positions to subpixel accuracy by interpolating the sensor response function are useful [8].

Two line-detection strategies were implemented to extract laser line profile, namely Gaussian Kernel method [9] and the Steger's approach [10]. Steger's approach, being a ridge detection algorithm provides smoother line profiles with respect to the Gaussian Kernel method. However, the computational effort of Steger's approach is sometimes too important, and Gaussian Kernel is preferred. Left and Right profiles are extracted to be combined in the calculation step of Gap&Flush according to the following two strategies:

i. "Fitting" algorithm

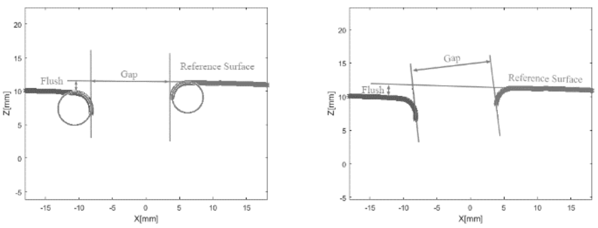
ii. "Feeler gauge/dial gauge" algorithm

No matter the algorithm used, the flush value calculation requires the definition of a reference surface (namely this surface should coincide with the body frame of the car). The fitting algorithm extract gap values by circle-fitting data points belonging to the facing curved edges of the line profiles. The gap is calculated as the distance between the two circles. Flush values are calculated by fitting the portion of line tangent to the circles and calculating their reciprocal distance. The second algorithm tries to mimic operator's approach to the measurement with feeler and dial gauges. It calculates gap values according to the following steps:

- Recognition of the point cloud extremes (left and right respectively for right and left edge);
- Parametric launch of two parallel lines tangent to left and right edge (slope is varied in 0.1 deg steps);
- Determination of the angle corresponding to the maximum distance between the two parallel lines.

The flush extraction algorithm is based on the following steps:

- Recognition of the point cloud extremes;
- Fitting the "reference" cloud with a straight line
- Determination of the angle corresponding to the maximum distance between the reference line and the other point cloud.



(a) *(b)*

Fig. 7. Fitting algorithm (a) vs Feeler/Dial Gauge algorithm (b)

D. Communication with the plant middleware

The middleware of the GO0D MAN project is given by a Multi-Agent System (MAS), namely a distributed, agent-based control system [11]. Communication between the device and its associated agent takes place exploiting OPC-UA protocol and exchanging a *json*-formatted string containing line information (e.g. product/part number) and results from the test inspection performed. Communication is bidirectional, i.e. data are continuously sent from the device to its associated Resource Agent (RA), e.g. inspection results, data from the line, etc., and received from the agent (e.g. number of measurement points to inspect over the car body). This communication makes it possible an optimization of the whole inspection depending on managerial rules, e.g. reduction of takt-time. Within this communication scheme, the measurement device acts as OPC-UA server, while the agent associated to the device acts as OPC-UA client. Inspection results are transmitted to the agent by the device in a subscription-based communication. Moreover, the device stores data on a local database exploiting SQLite engine. The whole communication strategy is shown in Fig. 8.

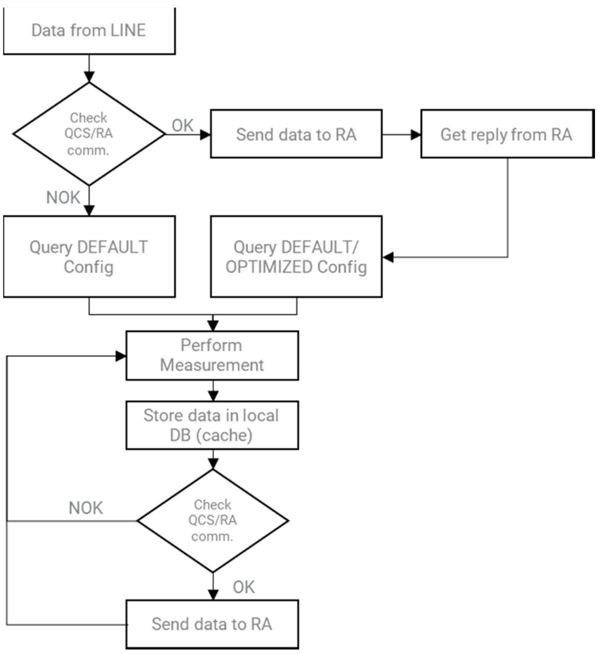


Fig. 8. Quality Contorl Station (QCS) / Resource Agent (RA) interaction for optimizing the measurement procedure

IV. Results

To estimate the uncertainty of the device, a type-A analysis according to the GUM [14] has been performed in laboratory conditions, on reference gaps and flushes provided by a cubing car frame, a highly accurate benchmark for optimizing and qualifying assembly parts, realized by milling a full size auto-body from solid aluminium, not painted.

The cubing car frame has been used as a target for gap and flush measurement and cubing nominal values as nominal references. Nominal values have been verified by measuring the same points with calibrated pins, at 0.01 mm uncertainty. Gap and flush values have been measured with the device in 6 different points, for a total of 42 acquisition, and the results in term of expanded uncertainty have been U_G=0.38 mm for gap and U_F=0.33 mm for flush values (95% confidence level).

Tests are currently under execution in Volkswagen Autoeuropa production line on daily basis. Once a statistically sufficient number of data are collected, it will be possible to compare the laboratory estimated uncertainty to the one obtained from field-measurements.

V. Concluding Remarks

A smartphone-based measurement device exploiting laser triangulation to assess gap and flush in the production line of car assembly has been presented. The device embeds a series of sensors to guarantee reliability of the measurement. The optimized laser wavelength makes it possible to perform measurements on multi-material behaving differently from an optical point of view (reflective, translucent, transparent parts). Safety for the operator is ensured by the conditional switch on/off the laser source in accordance to a series of events (e.g. stand-off distance compliant to requirements). Compliance to Industry 4.0 requirements is guaranteed by the use of OPC-UA communication protocol. Such a measurement system represents by right an Industrial IoT (Internet of Things) device ready to be integrated in an industrial context.

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