A. Montalto, S. Graziosi, M. Bordegoni, L. Di Landro

An Inspection System to Master Dimensional and Technological Variability of Fashion-Related Products: a Case Study in the Eyewear Industry

Computers in Industry, Vol. 83, 2016, p. 140-149
doi:10.1016/j.compind.2016.09.007

An inspection system to master dimensional and technological variability of fashion-related products: a case study in the eyewear industry

Abstract

Innovation of fashion-related products implies the continuous search for new and appealing shapes and materials in a short period of time due to the seasonality of the market. The design and manufacturing of such products have to deal with a dimensional variability as a consequence of the new shapes. An additional difficulty concerns properly forecasting the technological behaviour of the new materials in relation to the manufacturing process phases. The control of dimensional variations requires time and resource intensive activities. Human's manual and visual inspection solutions are more common than automatic ones for performing such control, where skilled operators are typically the only ones capable of immediately facing non standard situations. The full control of such variations is even more subtle and mandatory in the field of spectacles, which are fashion-related products and also medical devices. This paper describes an inspection system developed to monitor the dimensional variations of a spectacles frame during the manufacturing process. We discuss the methodological approach followed to develop the system, and the experimental campaign carried out to test its effectiveness. The system intends to be an alternative to current inspection practices used in the field, and also to provide a methodological approach to enable engineers to systematically studying the correlations existing among the frame main functional and dimensional parameters, the material behaviour and the technological variables of the manufacturing process. Hence, the system can be considered a method to systematically acquire and formalise new knowledge. The inspection system consists of a workbench equipped with four high-quality commercial webcams that are used to acquire orthogonal-view images of the front of the frame. A software module controls the system and allows the automatic processing of the images acquired, in order to extract the dimensional data of the frame which are relevant for the analysis. A case study is discussed to demonstrate the system performances.

Keywords: Inspection systems, image processing, eyewear industry, knowledge-based engineering, product variability

1. Introduction

In order to remain competitive in the market, companies need to continuously capture and fulfil customers' expectations and put on the market a wide range of new products and services that must be highly customisable. The fashion industry (e.g., textile and apparel manufacturers) has to deal with this challenge since the shift from one season to the other settles the short time to market of their collections [1]. Together with time constraints, one has to consider also the intrinsic variability of the geometries/shapes designed as well as of the materials used, due to the commitment of constantly innovating the product from both the aesthetic and technological point of view. Additionally, guaranteeing high quality standards is a must-have requirement, especially in case of high-end products.

The eyewear industry is affected by these challenges (e.g., see [2, 3, 4, 5]). In addition, the eyewear industry faces a further level of complexity. In fact, spectacles are wearable medical devices, which must be compliant to dedicated medical/safety standards, which vary according to the market where the product is sold (e.g., just for the frame we can mention ISO TS 24348, ISO 7998, ISO 8624, ISO 10685-1, ISO 10685-2, ISO 10685-3, ISO 12870, ISO 13666, and ISO 16034). Their shape must also fulfil specific morphological requirements in order to guarantee comfortable wearability. For example, the frame geometry and mechanical behaviour plays a key role in guaranteeing the proper position of the optical centre of the lenses and of the temples, while different variants of the same frame are necessary when a collection has to be sold in the Asiatic or in the European markets, because of the different morphological characteristics of the population (e.g. see [6]). As a consequence, the range of marketing, technical, medical, ergonomic and manufacturing requirements that engineers have to simultaneously take into account, when designing spectacles, is wide and articulated.

Innovation in the domain of materials opens up new possibilities concerning the aesthetics of spectacles. However, this represents a further challenge to tackle since getting a complete and quick characterisation of the technological properties of these materials is not always possible due to: the short lifetime of the product development process; the high number of variants of materials to manage in parallel (which are required by different brands/collections); the fact that the new materials may not have been used before for manufacturing spectacles.

In order to fulfil high quality standards, ad-hoc post processing and finishing activities have to be planned in advance and then performed on the product, in order to eliminate any dimensional/finishing variations. For example, despite of cellulose acetate has been used for years to manufacture frames, eyewear manufacturers are continuously looking for new variants in terms of e.g., colours and textures. Dedicated technological processes together with the change of the material chemical composition (e.g., adding specific colourants or plasticisers) have given in years the possibility to fully exploit the chromatic potentials of the material [7]. However, these changes can lead to acetates having major differences for what concerns their manufacturability. The variability related to the technological properties of the material could alter the shape of the frame. As already discussed, ad-hoc post-processing and finishing activities have to be planned on the product. Such activities even if effective, make longer and more complex the manufacturing process.

With the aim of mastering variability, we have developed an inspection system and a dedicated software tool that can rapidly acquire and evaluate the main geometric/dimensional variations of spectacle frames during pilot productions (which is the phase when design changes are not recommended but still feasible). The objective was to develop an approach and a dedicated system to support engineers in deepening the correlations existing among the frame main geometric parameters, the material behaviour and the technological variables of the manufacturing process. We wanted to develop a technique able to systematically collect and generate as much knowledge as possible to be used as design indications during the early phases of the design process in order to improve the overall process efficiency and the product quality (e.g., see [8]).

The paper describes the methodology used to develop the inspection system and to test its performances for what concern its level of usability/implementability, within a real production environment, and the kind of knowledge the system is able to generate. The case study, developed in collaboration with an eyewear company, is focused on monitoring acetate frames. Hence, the discussion of the methodological approach is focused on this type of material, although potential extension to different materials, objects and processes is apparent.

2. Variability issues of fashion products

2.1. A focus on the eyewear industry: spectacles frames

The quality of a frame is strongly related to the finishing characteristics of its surface, and to the fulfilment of the dimensional/geometric requirements stated for the main dimensional parameters. These parameters, as it will be detailed in Section 3.1, are the ones influencing the functionality, wearability and aesthetic of the spectacles. Their values can vary according to fashion-related aspects, which determine the changes to be applied both at the shape- and material- level. This fashion-related variability is a peculiarity and a plus of the product. However, it is also a challenge that concerns forecasting, already at the design phase, the technological properties of the new material in relation to its adaptability to the eyewear manufacturing process. Indeed an unexpected behaviour of the material could lead to a dimensional variability of the shape of the frame.

The difficulties in controlling this variability are several if we consider also the kind of dimensional parameters to be controlled. Indeed, most of them are angles, whose measurement is mainly performed manually on the physical object, by means of dedicated devices/supports. For example, in Figure 1 it is provided a simplified explanation of how one of these manual strategies works: the proper placement of the frame on a graduate map enables the extrapolation of the face-form angle of the spectacle frame (see Figure 2). Such angle, as it will be explained in Section 3.1, determines the curvature of the front of the frame. Considering the high variability of the shapes of the frames, good manual skills and expertise are required to guarantee the proper placement of the frame on the map as well as the reliability and repeatability of the measurement. For these reasons, such measurements are usually performed by skilled operators.

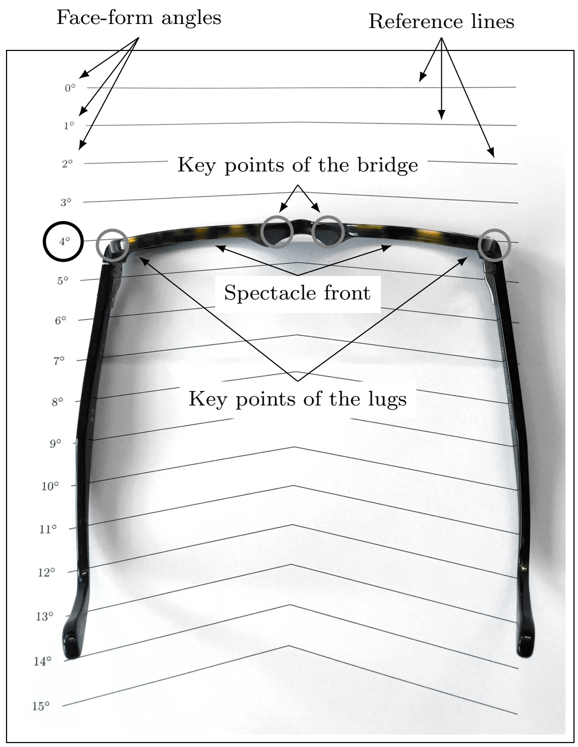

Figure 1: A simplified representation of the procedure used for measuring the face-form angle of a spectacle frame, by means of a graduated map (the image provides a simplified version of this map). The value of the angle is derived by manually superimposing the front of the frame on the reference lines. The correct value of this angle corresponds to the best fitting configuration between the frame curvature (using as reference some key points of the frame, such as the extremities of the bridge and of the lugs for each side) and the grade of the reference lines. In this case, the correct value is 4°.

In such a challenging context, experienced eyewear engineers/designers play a key role. Thanks to the knowledge and skills they have acquired along the years, they have the background knowledge necessary to forecast the technological behaviour of the raw material. Notwithstanding, as already underlined, ad hoc post-processing activities are usually necessary to eliminate any misalignment between the desired shape of the frame and the one obtained through the manufacturing process. Such activities, even if fundamental to guarantee the respect of high quality standards, negatively affect the efficiency of the process. The strong hand-craft essence of the eyewear manufacturing process, which is both a consequence of the high variability of the product characteristics and a guarantee of excellence in terms of product quality, makes human's manual and visual inspections the only strategy that is currently technically and economically feasible to master such inefficiencies.

However, the optimisation of the process is not only a matter of strengthening the quality control phase, which is already carefully-planned, but mainly of developing a methodology to reduce such variability. A possible strategy could be to monitor the frame shape evolution along the process and then, elaborate the data acquired to generate and store new knowledge about the product variability in relation to the technological properties of the raw material used. The final aim is the systematic extrapolation of a bunch of considerations, to be used as reference to drive the design of the next collections of frames so as to reduce, as much as possible, ad hoc post-processing activities while keeping the same high level of quality. However, a tool and the related methodology to perform such kind of evaluations is still lacking.

Two are the main reasons behind this lack. First, the manual and visual inspections currently performed have been used for years in this field and are thus, recognised approaches. The second reason is related to the limitations given by the frame itself and by some peculiarities related to the specific industrial field. Indeed, despite of devices for the automatic acquisition and measurement of the 3D shape of objects, are well-known in several industrial and research fields (e.g., see [9, 10, 11, 12]), their use for the eyewear one is still limited. The main issues are discussed in the next Section.

2.2. Alternatives to current inspection systems

Nowadays, automatic inspection systems play a key role in industry since, they not only are a guarantee of the quality of the product, but as underlined in [13], the automatic storage of the information collected can open up new scenarios: the data acquired during inspections can be used as input for planning further evaluations and/or for designing new strategies for improvement. That is because any inaccuracies encountered can be the result of the effects given by a number of multiple factors/variables of the process. For this reason it is important that such systems are used starting from the early phases of the manufacturing process, in order to have the time necessary to intervene [13]. To reach this target, such systems should be easily integrable into already existing industrial environments so as to also facilitate the internal sharing of these data [13].

However, as discussed in [14] for the clothing industry, the implementation of automatic solutions is not straightforward for a number of issues, among which: expert operators play a key role since they are still the only ones able to successfully cope with expected and, especially unexpected, variability; the ample spectrum of raw materials to be processed. Furthermore, the investments necessary to implement strongly customised and robust solutions, to face non standard situations, limit their implementation. Despite of all these complexities, interesting attempts are available in literature, such as the ones developed to automate or support the analysis of fabrics or of clothes surface characteristics also using computer vision algorithms (e.g., [15, 16, 17]). Besides these algorithms have been successfully implemented in the food industry [18] in order to control the intrinsic variability of food, such as vegetables and fruits, for what concern their shape, size, texture, and colour (e.g. see [19, 20]).

Among the automatic devices mostly used for performing dimensional measurements on physical objects, there are those based on the acquisition of their 3D shapes. Such systems can be clustered into two main categories: contact and contactless. Even if powerful and effective, their use in the eyewear industry is limited by the reasons hereby discussed. The use of contactless devices (e.g., 3D laser scanning or close-range photogrammetry, [21]) is prevented by a number of factors, such as: the thinness of the spectacle frame (from 2,5 mm to 5 mm); the transparency and the reflectance of the material (dark hues, transparent and mirroring surfaces cannot be acquired unless a modification of the frame surface finishing is performed using ad-hoc coatings). Contact devices (e.g., Coordinate Measuring Machines — CMM — with mechanical probes [22]) could be valid alternatives but, in this case, the limitation is given by the probe, which must be in contact with the surface of the frame and it could scratch it. Hence both these two types of techniques could be of great help, but mainly when performing evaluations on prototypes. Furthermore, even if the 3D model, provided as output by these devices, is nowadays extremely accurate, the acquisition phase takes time (in the order of tens of minutes) and requires the involvement of an expert operator.

Considering all these challenges, we have focused our research on developing an inspection system, based on computer vision. Specifically, we wanted to monitor the main macroscopic variations of the frame dimensions from which deriving additional considerations for what concern the thermal/mechanical behaviour of the raw material in relation to the various steps of the manufacturing process. To this aim we designed an inspection system able to provide an accurate measurement of the frame dimensional parameters and also to automatically elaborate and store the data acquired. The system is flexible, since it works for any geometry of the frame, and low cost (e.g., as done in [23]) because based on commercial technology. Additional requirements were that no specific manual skills or expertise were necessary to use it, that the system had to be used for quickly analysing small and high variable production volumes, and that it could be easily installed within real industrial setups. The final aim was to acquire and extrapolate all the information necessary to guide the design phase and boost the competences and knowledge of the engineers in mastering the dimensional and geometric variability of the product.

3. Mastering variability through a dedicated inspection system

Before designing a vision system a number of aspects has to be clarified in advance, starting from the kind of information the system has to acquire and how this one can be extracted from the acquired images [24]. The working conditions of the system have to be also carefully take into account (e.g., see [25, 26]) since they influence the quality of the data provided. Hence, the first issue in our study was to exactly define what to measure and to properly set our design requirements.

Specifically, we analysed the following aspects: the kind of devices currently used (an example is shown in Figure 1); how the front is placed/oriented to perform the measurement; the key points of the frame involved in the measurement; any tip given by expert operators; the standards (i.e., ISO 8624) taken as reference to perform the measurement; when and where the measurement is usually carried out.

In the following, we first detail the design requirements we have set before starting the design activity (Section 3.1); then, we describe the architecture of the system (Section 3.2.1) and finally, we focus the discussion on the procedure developed for enabling the automatic processing of the images acquired (Section 3.2.2) in order to automatically extract the data of interests.

3.1. Setting design requirements: the key parameters of a frame

The fulfilment of all the marketing, technical, ergonomic and medical requirements mentioned in Section 1 implies a careful measurement of several specific geometric parameters of the frame. The shape of the frame (together with its colour, material and finishing) is the expression of the identity of a brand while, from the functional/medical one it has the role of keeping the two lenses in the right position (e.g., see [27]) and of imposing them two tilts: the face-form and the pantoscopic angle (see Figure 2 and 3). The ISO 12870:2012 and ISO 8624:2011 standards define the list of the parameters of a frame, which are related to this functionality. Since they are a sort of invariants for any frame,

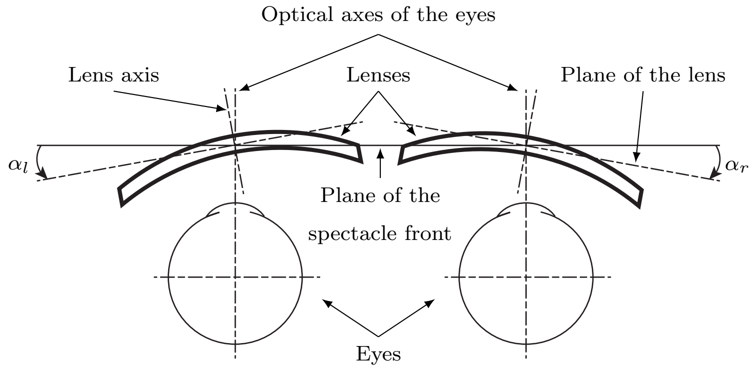

Figure 2: Graphical representation of the face-form angles of a spectacle front (base view). α_l and α_r are, respectively, the face-form angles for the left and the right lens of the spectacles. Adapted from ISO 13666, page 136 [28].

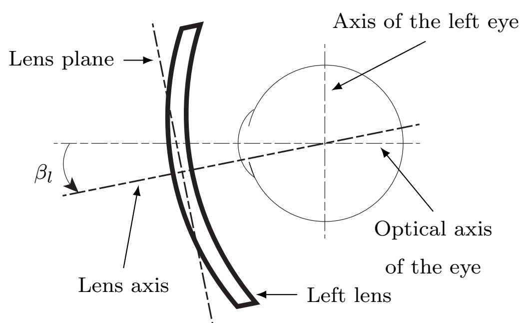

Figure 3: Graphical representation of the "as-worn" pantoscopic angle (β_l) of a spectacle front for the left lens (side view). Adapted from ISO 13666, p. 22 [28].

once an effective method to measure them is defined, it can be used for any kind of shape. Summarising, two main categories of parameters can be identified: *linear* (e.g., related to the bridge dimensions and lug sizes) and *angular* (the face-form and pantoscopic angles).

The first category (i.e., linear) is obtained, in case of acetate frames, through a CNC milling process. During this phase the complex thermo-mechanical behaviour of the acetate is just marginally involved. Consequently, these linear parameters can be easily monitored since the obtained geometric and dimensional tolerances are a consequence of the machine set-up. Angular parameters are obtained by means of thermo-mechanical processes (i.e., once heated up the front of the frame is shaped using a mould with a curved surface), during which the complex viscoelastic behaviour of acetate could lead to unexpected side-effects. For this reason, the quality control check is focused on keeping under control the values of these two tilts which are considered as a quality indicator of the manufacturing process. However, due to the variability issues discussed in Sections 1 and 2 such measurements are performed manually by expert operators.

This manual approach strongly depends on the operator's ability who has to take out the frame from the production line and quickly perform the measurement. An alternative to this approach could be the design of an ad-hoc automatic measurement system. However, such an approach, whether technically and economically feasible, is not easily implementable in a manufacturing process whose workflow and structure is, for its nature, strongly hand-crafted (see Section 2). Hence, the new inspection system should be: easy to use and install; accurate (to avoid any risk related to the misinterpretation of the information); economically sustainable; independent from the operator's manual skills. Finally, it should not damage the frame. The need for minimising its manipulation implies the use of non-contact measurement methods while the need for simplicity and rapidity implies the use of optical techniques based on visible light.

3.2. The design of the inspection system

3.2.1. The system architecture and main components

From the hardware point of view, we developed a workbench to acquire orthogonal-view images of the front of the frame by means of four high-quality commercial webcams (Logitech c920, resolution 2 MP) placed in fixed positions (see Figure 4). They are located in the following way: one frontally (to measure the face-form angles), two laterally (to measure the left and right pantoscopic angles) and one at the top side (to control the alignment of the front with respect to the structure). The selection of the correct placement for the camera was made according to the following aspects. Close distances are preferable because the front would appear larger in the image, facilitating the implementation of

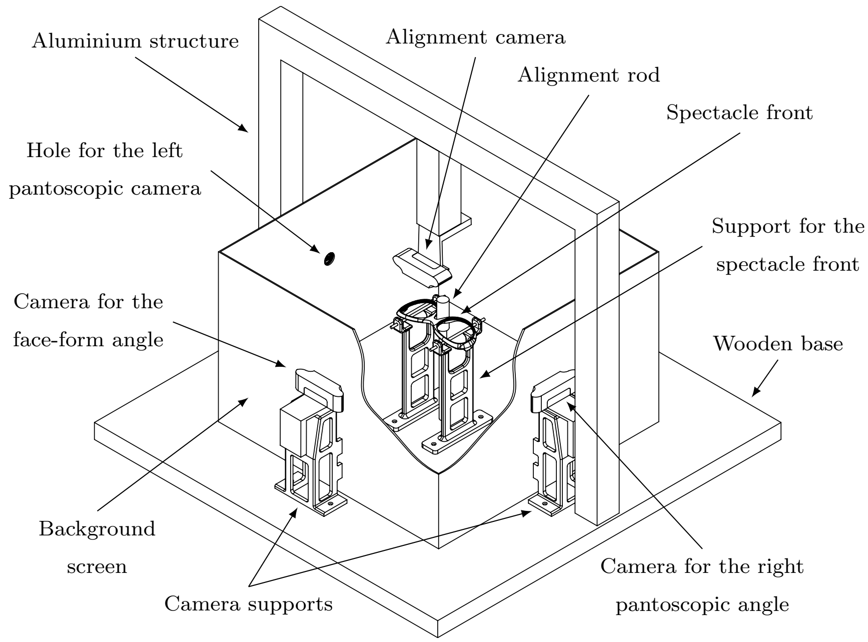

Figure 4: The bench developed for measuring the face-form and the pantoscopic angles of a frame. It consists of the following components: a wooden base; an aluminium structure; four cameras (only three cameras out of four are visible in the image); a background screen (the screen is represented as broken-out only for illustrative reasons); the supports used for the cameras; the spectacle front; an alignment rod.

image recognition algorithms. However, close distances would entail perspective distortions, focalisation issues, and the possibility that details of larger frames do not appear in the picture (we wanted to define a unique placement for all the possible shapes of a frame). On the other hand, wide distances imply few usable pixels to perform the analyses. In any case, distortions are inevitable: the $x - y - z$ position of the lugs, with respect to the lateral webcams, changes continuously due to the variability given by the different models/collections. The same occurs for the frame with respect to the frontal camera. For these reasons, views are not perfectly orthogonal.

In order to place the front of the frame in the proper position we built two supports whose dimensions were set so as to be suitable for the all range of frame models/collections. The supports were built using a stereolithography 3D printer. Specifically, two H-shaped structures allow the horizontal positioning of the front (Figures 4, 5). The front is placed above two metal beams (one for each structure). The distance between these H-shaped structures has been set considering the maximum frame dimensions (calculated using the boxed lens size, e.g., see [27]). A coloured grid (not represented in Figure 4) has been integrated into the support to enable an easy alignment of the front. A standing rod is placed in the centre of the vision system to facilitate the centring of the frame with respect to the cameras, and to fix it in the right position through friction. Its diameter and the sponge on the upper part make it adaptable to all the different models of bridges. The supports were designed so as not to be invasive in the images or mask the points chosen as reference for the automatic processing of the images (see the next Section 3.2.2 for a detailed description). Surrounding panels were used to create a homogeneous background to facilitate image analyses and to hide the body of the webcams. The background has been built in two variants: clear and dark, to offer an adequate contrast in relation to the hue of the frame. The background has been designed so as not to alter the natural illumination of the scene. We were aware that an ad-hoc illumination system could have been developed to reduce reflections, shadows, noise, and inhomogeneities, and to facilitate image elaboration generating a high contrast between the object and its background [13, 18, 24, 29]. However we decided to test our vision system using environmental illumination. We found that different illumination conditions, e.g. within offices and production areas, did not significantly alter the image quality. Clearly, for the future engineering of the system, a proper illumination system could be implemented to keep the working conditions of the system under control. For what concerns the cameras, we decided to use commercial solutions since they have a good performance/cost ratio, they can be easily connected to computers, they are adaptable to different levels of illumination. Furthermore, as discussed in [24], this strategy helped us to get an immediate feedback of the effectiveness of the system architecture. These webcams are designed to work in different lighting conditions, and are able to automatically set themselves. The webcam used to check the alignment of the frame (see Figure 4) is hold by an aluminium structure through an orientable junction, so as to allow any setting. The wooden base has a thickness of 30 mm, which acts as a solid support for the bench without the need of fixing it. The overall encumbrance of the system is $1 \times 1 \times 1$ m. A further optimisation of these dimensions is still possible.

3.2.2. The procedure for the analysis of the images

We developed a dedicated software module (using the MATLAB® 2015a environment) to automatically extrapolate, from the images acquired by three of the four cameras, the values of the pantoscopic and face-form angles, taking as reference specific points/edges of the frame shape. The Logitech software, controlling the webcams, enables a quick set-up of each device (in terms of focus, resolution, and brilliance). For each frame, four pictures (an example of the front view is provided in Figure 5) are taken, named and stored into a database through a dedicated MATLAB routine able to control and turn on each webcam. The MATLAB application automatically imports these images and elaborates them according to the steps hereby described (they are inspired by the suggestions retrieved in literature e.g., [24]). A flowchart has been modelled to summarise the whole procedure (see Figure 6).

Step 1: Image Preprocessing. Images are cropped in order to eliminate irrelevant pixels. The dimensions of the rectangular shape used to automatically crop the images depend on the angle to measure and thus on the image. Cropping parameters are set in advance taking as reference the dimensions of the biggest frame currently in production. The images to crop are two for the pantoscopic angle (i.e., in order to measure left and right angle) and one for the face-form one (in this case, one image is sufficient to simultaneously measure left and right angles).

Step 2: Image processing and analysis. First, the image is converted into a greyscale. After that, a brightness-and-contrast adjustment is applied to enable

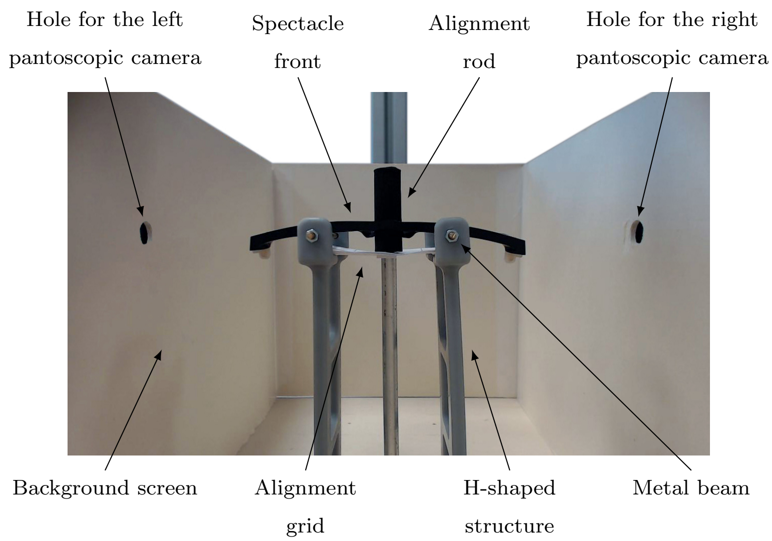

Figure 5: Image of the frame taken with the frontal camera of the bench. This is the image that will be used to calculate the face-form angle of the frame.

image segmentation in order to make the shape of the frame stand out and to simultaneously hide the supports and the background (Figure 7). The adjustments modify the histograms of the images in order to get a bi-modal distribution of the intensity with the target of completely erasing grey pixels. The values to set the histograms for the thresholding were experimentally identified. These parameters are suitable for spectacles frames with dark hues (we tested them on black and different types of tortoise). Despite the values of the parameters have been pre-defined, the operator can freely modify them in relation to the specific hue of the frame. Future developments of the application will include automated method to perform the entire thresholding process (e.g., Otsu or other methods [30]) in order to increase the robustness of the system but giving the possibility to the operator to always modify freely the contrast considering the high variability of the frame hues.

In case of transparent frames, a modification of the background and of the rod is necessary (i.e., a dark background instead of the clear one and a white sponge rod instead of the black one). The MATLAB application is then able to

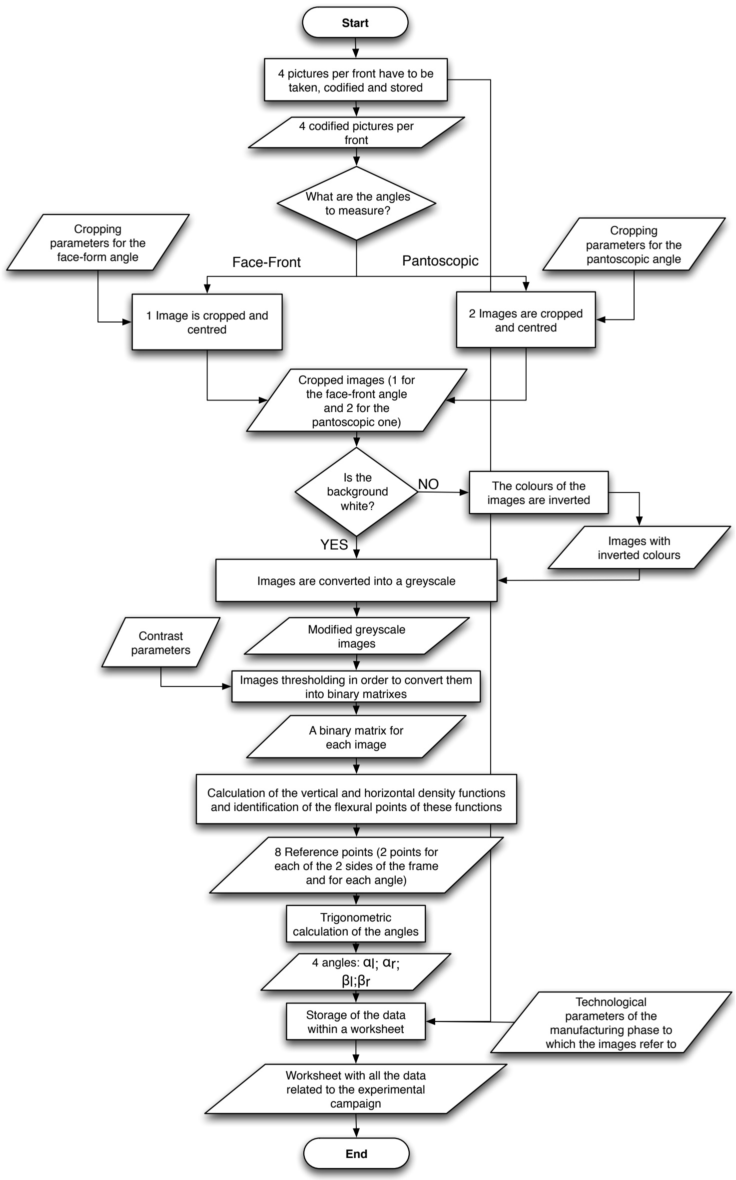

Figure 6: The flowchart of the procedure designed to enable the automatic processing and storage of the images acquired with the inspection system. The final output is a worksheet where the values of the four angles (left and right for both the face-form and the pantoscopic angles) together with all the relevant details related to the experimental campaign, are automatically stored.

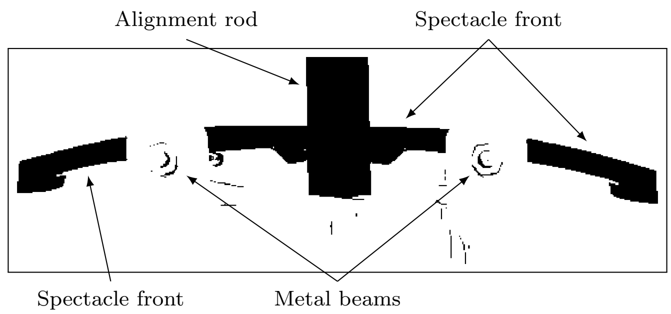

Figure 7: Same image of Figure 5 (spectacle frame viewed with the face-form angle camera) but cropped, adjusted (brightness and contrast) and converted into a binary image (black and white).

recognise the colour of the background and to automatically invert the colours of the picture (see Figure 8). Then this one can be processed using the same procedure previously described.

Thereafter, the image is converted into a binary matrix, where the “0” elements represents white pixels and the “1” elements are the black ones. This matrix will be used to automatically identify the reference points that are necessary to measure the angles. To this aim, we have developed a dedicated procedure which works as follow. Adding up the values of the cells for each column, we can get the density distribution of the black pixels along the x-coordinate of the image. We get what we have called the *horizontal density* of the black pixels. Repeating the same procedure for the rows of the matrix, we get the *vertical density*, which reflects the distribution of the black pixels along the y-coordinate of the image. The peculiarity to invert the values “1” and “0” respectively for white and black pixels — in opposition to the standard assignments by MATLAB — is specifically related to how the *density functions* was defined: each element in the matrix must be greater than “0” to be summed. In this way, *density functions* can have elements greater than zero. Focusing the search over specific areas of the images (i.e., where the profile of the front frame overlaps the alignment rod and where the lugs of the frame are positioned), the software calculates the position of the frame reference points, locating

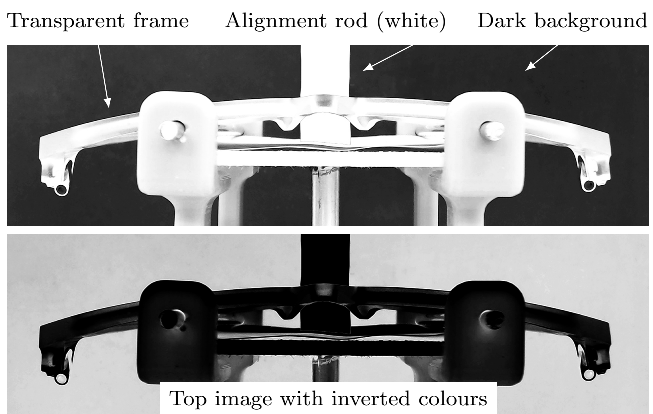

Figure 8: The strategy used to enable the measurement of the angles in case of transparent frames (viewed using the face-form angle camera). The conversion of the original picture in greyscale (top) into a new one with inverted colours (bottom) allows the software to calculate them using the same approach designed for dark hue frames.

them at the maximum variations of the two distributions. Respectively, the *horizontal density* is used for defining the x coordinate of the point, while the *vertical density* is used for the y coordinate (see Figure 9 which refers to the identification of the x-coordinate of the points of the right lug). Indeed, through a preliminary experimental campaign we found that these reference points are always in correspondence of the inflection points. This consideration has been fundamental for the automatic processing of the images considering that, during the manufacturing process, the edges of the frame are gradually chamfered according to the desired final shape. Hence, the position of these reference points may vary. For this reason, it was fundamental to identify a universal rule able to overcome this variability. In this way we have guaranteed that the system can be used to measure the evolution of the frame shape in all the stages of the manufacturing process. The identification of the reference points near the lugs has been implemented to follow the measurement procedure currently performed by the operators. This choice has been necessary in order not to introduce radical changes in the way frame measurements are currently performed.

Further considerations were made for what concerns the identification of

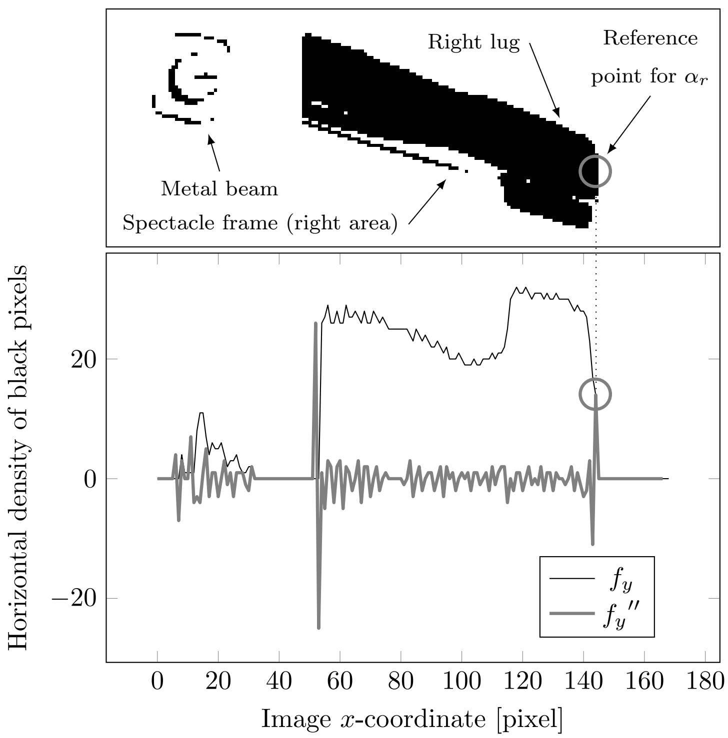

Figure 9: Zoomed image (top) of the right side of the frame (same binary image of Figure 7) and of its corresponding *horizontal density* function, f_y (bottom). The distribution is the sum of the “1” values (black pixels) for each column of the binary matrix. The x-coordinate of the reference points for the lugs is identified calculating the flexural points of the density function (using f_y''). The point of interest will be the one close to the spectacle frame extremity.

the reference points related to the pantoscopic angle. Following the standard procedure, the measurement of this angle requires the assembling of the entire frame (front and temples) and a dedicated device: it is a structure, which holds the spectacle frame and has a lateral graduate scale (i.e., a goniometer) where the orientation of the temples is used to extract the value of the pantoscopic angle. Actually, deepening the analysis of the frame shape, we realised that the pantoscopic angle corresponds to the tilt of the lateral edge of the lug with respect to the horizontal one. Hence, we decided to adapt the procedure previously described in order to detect the lugs in the pictures (taken with the lateral cameras). They are generally positioned in the bottom area of the pictures; hence, the software is forced to calculate the density functions (horizontally and vertically) of the binary images and searches for their inflection points in that area.

Step 3: Data extraction. Angles are determined through trigonometric calculations based on the relative positions, on the picture, of the reference points. Figure 10 and 11 respectively show the reference points selected to measure the face-form angles and the pantoscopic one as well as how the calculation is carried out. The calculation of the pantoscopic angle is more challenging because the length of the frame edge, to be used as reference for the computation (see in Figure 11 the "D" segment), is small and inaccuracies in the identification of the reference points (especially with chamfered edges) could cause consistent variations in the evaluations (up to $\pm 1°$). However, being aware of this issue (which occurs also using the standard approach), the values obtained for the pantoscopic angle, in case of small "D" values (less than 5 mm), have to be carefully checked.

Data are automatically exported into an external file to be stored and analysed. The software application is capable of running simultaneously three analyses using three picture for each frame: the frontal one taken with the face-form angle camera (to evaluate the α_l and α_r) and the two pictures taken with the left pantoscopic camera (to evaluate the left pantoscopic angle β_l) and the right

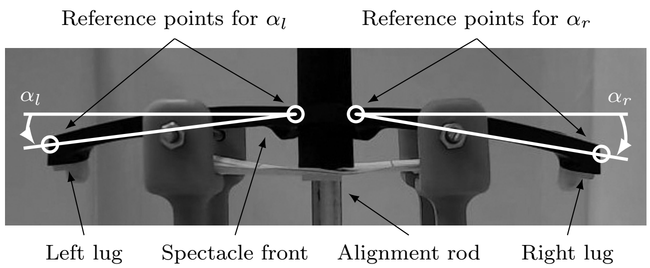

Figure 10: Graphical representation of the face-form angles, respectively on the right (α_r) and left (α_l) side, of the same frame of Figures 5 and 7. The circles indicate the position where the software locates automatically the reference points. The white segments have been sketched to graphically represent the input data used by the software to perform the trigonometric computation.

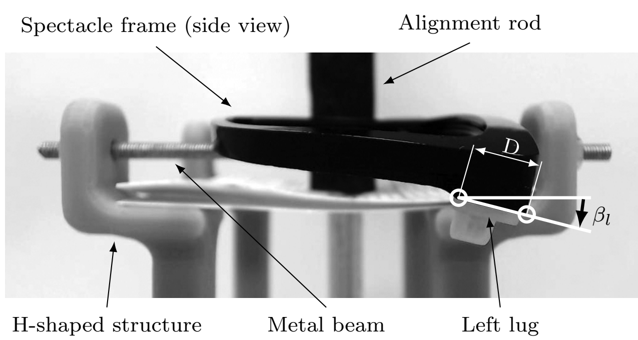

Figure 11: Graphical representation of how the measurement of the pantoscopic angle β_l (viewed by left pantoscopic webcam) is performed by the software. The circles indicate where the software locates automatically the referring points. The white segments have been sketched to graphically represent the input data used by the software to perform the trigonometric computation.

one (to evaluate β_r). The fourth picture, taken with the top camera, is stored so as to enable engineers to automatically recognise the specific model of the frame. To further simplify this recognition, all the images are automatically renamed using the identification code assigned to the frame. The time necessary to complete the data processing for each frame is 143 ms using a notebook with the Intel® Core^{TM} i7-4900MQ processor, RAM 16,0 GB DDR3, SSD 256 GiB, NVIDIA® Quadro® K2100M.

4. Experimental validation

4.1. Test of system effectiveness

The bench was tested using a reference object (a 100 mm length certificated gauge block, ISO 3650), in order to evaluate the effectiveness of the system (Figure 12). Since it is a parallelepiped, the output value of the software should be 0,0° for both the angles: the longer edges of its frontal view correspond to the face-form angles, while the lateral ones correspond to the pantoscopic angles.

However, we got 0,0° for the face-form angle and 0,3° for the pantoscopic one, which means that the accuracy of the system is higher for the face-form angle than for the pantoscopic one. Such error may be due to the following factors: the wrong positioning of the block above the support (the top camera does not guarantee a perfect manual alignment of the object), the misalignment of the cameras (i.e., perspective errors), and lens distortions (i.e., radial and tangential). The misalignment between the frame and the cameras is challenging to control due to the variability of the spectacles models. To deal with these factors, taking also into account the design constraints discussed in section 3.2.1, we adopted the following strategy: we distanced the frame 120 mm from the front-camera and 40 mm from the lateral-cameras. In this way, the frame is located in the central area of the cameras field of view, where lens distortions are minimal. In addition, these distances minimise also the errors due to misalignments because of the perspective. This strategy was effective since the values obtained for the gauge block have been considered as satisfactory for our aims. However, for what

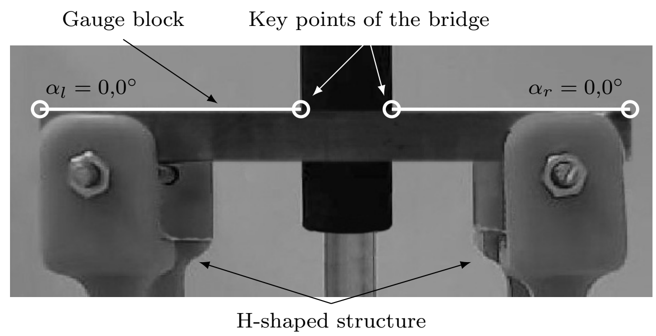

Figure 12: Graphical representation of the measurement performed on a gauge block (viewed by the face-form webcam) to test the effectiveness of the system. The circles indicate where the software automatically locates the reference points. The white segments have been sketched to graphically represent the input data used by the software to perform the trigonometric computation. In this case, the vale of the face-form angle is $\alpha_l = \alpha_r = 0{,}0°$.

concern lens distortions in the future version of the software a calibration phase will be implemented, manipulating the images using the *Camera Calibration Toolbox* of MATLAB [31], after a previous camera-calibration procedure.

4.2. Test of the system performances

We tested the performances of the system using a real case study developed in collaboration with the eyewear company's engineers and operators. In this Section we provide the quantitative data collected to demonstrate the performances of the system (they are summarised in Table 1).

We analysed the dimensional variability of 11 different spectacle models in relation to 5 different stages of the manufacturing process. The objective was to study the variability of the face-form and of the pantoscopic angles in relation to the following aspects: the stages of the process; the kind of acetate material used; the dimensional characteristics of the frame (e.g., the frame thickness). Indeed, the 11 models had different geometries in terms of shape, dimensions, face-form and pantoscopic angles. The typologies of models were selected so as to enable a reliable statistical analysis of the factors affecting such variability.

We decided to acquire 10 samples for each model. In total, the frames to measure were 550 (i.e., 11 models, 10 samples for 5 stages of the process). However, since each analysis consists in the identification of 4 angles (2 face-form angles α_l and α_r, and 2 pantoscopic angle β_l and β_r, see Figures 2, 3) we had to perform a total of 2200 measurements.

Using standard devices, the measurement of both angles (i.e., face-form and pantoscopic) requires about 1 min if performed by an expert operator. However, the measurement of the pantoscopic angle is not feasible until the lugs are assembled to the frame. Hence, it is possible only after a certain phase of the manufacturing process. Additionally, the only data collected are the values of the angles while there are nor physical, neither digital "signs" of the samples analysed. The estimated time to perform these 2200 measurements with these devices is about 12 hours (not continuous).

We performed the measurement (2200 angles on 550 specimens) using our system. The experimental campaign was completed in about 3 hours (not continuous). The most difficult task was the positioning of the spectacle frame, on the two supports, taking as reference the image given by the alignment camera (Figures 4). Despite of this difficulty, the positive aspects identified, together with the time reduction, were the following: the accuracy of the measurements (as a comparison, for a limited number of samples, we also acquired the values of the angles using standard devices); the possibility to store both the right and left values of the angles so as to automatically identify asymmetries; the digital "sign" of the sample analysed; the immediate availability of a worksheet with all the data acquired together with the information related to the dimensional characteristics of the frames analysed, the input data related to the material characteristics, the main technological parameters of each phase analysed. Furthermore, as underlined, each image is automatically stored and renamed so that it can be directly linked to the data.

Engineers and operators have started using the system after a short training period. The easiness to use, the efficiency and the effectiveness of the system were widely appreciated. The main limit is related to the use of the software due to the absence of a dedicated Graphical User Interface (GUI). However, this

Table 1: Comparison between the performance of the standard devices used to measure the face-form and the pantoscopic angles of the frames and the designed inspection system.

	Standard	Designed system
Operating principle	Human's visual measurement through graduated maps and dedicated portable devices.	Webcam-based image analysis.
Output: Face-form angle	1 value.	2 values (α_l and α_r). Asymmetries can be easily identified.
Output: Pantoscopic angle	2 values (β_l and β_r) but only once the frame is assembled.	2 values (β_l and β_r). The measurement is always feasible.
Additional Outputs		Worksheet with all the acquired and reference data; 4 images/frame.
Time to measure 550 frames	12 h (not continuous).	3 h (not continuous).
Uncertainty	$\pm 1°$.	Face-form: $\pm 0{,}1°$ – Pantoscopic: $\pm 1°$.
Usability	Easy to use for expert operators.	Easy to use for both experts and novice operators. A GUI is necessary for the SW module.
Encumbrance	$0{,}2 \times 0{,}2 \times 0{,}2$ m for the pantoscopic angle. A $0{,}21 \times 0{,}297$ m graduated map for the face-form one.	$1 \times 1 \times 1$ m.

limit can be easily overcome.

5. Conclusions

The design and manufacturing processes of fashion-related products, such as spectacles, have to deal with a number of challenges given by the rapid evolutions of the product shapes and of the materials used to manufacture them (e.g., see [32]). These rapid changes, of both the shape and the raw material used, could lead to an unexpected dimensional variability of the product during the manufacturing process. The careful control of this variability is a must for the eyewear industry, not only for the fulfilment of the company high quality standards but also because spectacles are medical devices. The strong hand-crafted essence of this industrial field is thus a key aspect; it is a guarantee of the fulfilment of the high quality standards and also the most effective strategy to deal with non-standard situations due to the high variable dimensional characteristics of the products, and of the technological properties of materials.

In this paper, we describe a methodology and the related implementing system to master this dimensional variability. The objective was not to support the frame inspection activity, rather to propose and develop a procedure to systematically get the proper input data necessary to derive the design and manufacturing indications necessary to control such variability. To this aim we have designed a visual inspection system able to easily and effectively monitor the evolution of the product shape.

The system consists of two modules: a workbench equipped with four high-quality webcams and a MATLAB software application in order to automatically process the images acquired and extrapolate the main dimensional parameters of the frame. These parameters are the pantoscopic and face-form angles which are the ones influencing the functionality, wearability and aesthetic of the frame. We aimed at providing an effective, easy to use, low cost and reliable system to acquire and automatically process these data. However, the design phase of the inspection system has been driven also by a further objective. Indeed, we were also looking for a methodology to enable a systematic acquisition of the information necessary to find any correlation existing between the dimensional evolution of the shape of the frame and the material technological behaviour. The intent behind the development of this methodology was to allow the company's engineers to generate new knowledge about the product, going beyond the acquisition of numerical data.

The case study developed in collaboration with an eyewear company has demonstrated the capabilities of the system. Compared to the approaches and devices currently used, the designed inspection system has demonstrated to be: more time effective; capable of performing new kinds of measurements; able to keep a digital *sign* of the samples analysed; easy to use; adaptable to different kinds of frame shapes and colours. Hence, once fully engineered, the system could represent not only an effective device to perform quality control checks during the manufacturing process, but it could be also used as a tool to extrapolate and store relevant design specifications, transforming engineers and operators' tacit knowledge into explicit one.

References

[1] A. Şen, The us fashion industry: a supply chain review, International Journal of Production Economics 114 (2) (2008) 571–593.

[2] A. De Toni, G. Nassimbeni, Small and medium district enterprises and the new product development challenge: evidence from italian eyewear district, International Journal of Operations & Production Management 23 (6) (2003) 678–697.

[3] G. Nassimbeni, Local manufacturing systems and global economy: are they compatible?: The case of the italian eyewear district, Journal of Operations Management 21 (2) (2003) 151–171.

[4] D. Campagnolo, A. Camuffo, Globalization and low-technology industries:

The case of italian eyewear, Knowledge transfer and technology diffusion (2011) 138–161.

[5] M. DeLong, C. Daly, Eyewear, fashion, design, and health, Fashion Practice 5 (1) (2013) 117–127.

[6] R. Ball, C. Shu, P. Xi, M. Rioux, Y. Luximon, J. Molenbroek, A comparison between chinese and caucasian head shapes, Applied Ergonomics 41 (6) (2010) 832–839.

[7] P. Carollo, B. Grospietro, 5.5 plastic materials, in: Macromolecular Symposia, Vol. 208, Wiley Online Library, 2004, pp. 335–352.

[8] J. D. Booker, Industrial practice in designing for quality, International Journal of Quality & Reliability Management 20 (3) (2003) 288–303.

[9] F. Blais, Review of 20 years of range sensor development, Journal of Electronic Imaging 13 (1) (2004) 231–243.

[10] M.-C. Amann, T. Bosch, M. Lescure, R. Myllyla, M. Rioux, Laser ranging: a critical review of usual techniques for distance measurement, Optical engineering 40 (1) (2001) 10–19.

[11] M. Pieraccini, G. Guidi, C. Atzeni, 3d digitizing of cultural heritage, Journal of Cultural Heritage 2 (1) (2001) 63–70.

[12] S. Martínez, E. Cuesta, J. Barreiro, B. Álvarez, Analysis of laser scanning and strategies for dimensional and geometrical control, The International Journal of Advanced Manufacturing Technology 46 (5-8) (2010) 621–629.

[13] J. B. Zhang, Computer-aided visual inspection for integrated quality control, Computers in industry 30 (3) (1996) 185–192.

[14] G. M. Acaccia, M. Conte, D. Maina, R. C. Michelini, Computer simulation aids for the intelligent manufacture of quality clothing, Computers in Industry 50 (1) (2003) 71–84.

[15] C. Anagnostopoulos, D. Vergados, E. Kayafas, V. Loumos, G. Stassinopoulos, A computer vision approach for textile quality control, The Journal of Visualization and Computer Animation 12 (1) (2001) 31–44.

[16] T. Lau, P. C. Hui, F. S. Ng, K. C. Chan, A new fuzzy approach to improve fashion product development, Computers in Industry 57 (1) (2006) 82–92.

[17] M. Carfagni, R. Furferi, L. Governi, A real-time machine-vision system for monitoring the textile raising process, Computers in Industry 56 (8) (2005) 831–842.

[18] T. Brosnan, D.-W. Sun, Improving quality inspection of food products by computer vision—-a review, Journal of Food Engineering 61 (1) (2004) 3–16.

[19] R. Posada-Gómez, D. Villanueva, I. González, Á. García, A. A. Aguilar-Lasserre, A. Martínez-Sibaja, Toward an automatic parameterization system for the classification of persian lemons using image-processing techniques, Journal of Food Process Engineering 38 (4) (2015) 345–356.

[20] C. Portalés, E. Ribes-Gómez, An image-based system to preliminary assess the quality of grape harvest batches on arrival at the winery, Computers in Industry 68 (2015) 105–115.

[21] E. P. Baltsavias, A comparison between photogrammetry and laser scanning, ISPRS Journal of photogrammetry and Remote Sensing 54 (2) (1999) 83–94.

[22] J. Bosch, Coordinate Measuring Machines and Systems, Manufacturing Engineering and Materials Processing, Taylor & Francis, 1995.

[23] F. Adamo, F. Attivissimo, A. Di Nisio, M. Savino, A low-cost inspection system for online defects assessment in satin glass, Measurement 42 (9) (2009) 1304–1311.

[24] E. N. Malamas, E. G. Petrakis, M. Zervakis, L. Petit, J.-D. Legat, A survey on industrial vision systems, applications and tools, Image and vision computing 21 (2) (2003) 171–188.

[25] Z. Bi, L. Wang, Advances in 3d data acquisition and processing for industrial applications, Robotics and Computer-Integrated Manufacturing 26 (5) (2010) 403–413.

[26] H. Golnabi, A. Asadpour, Design and application of industrial machine vision systems, Robotics and Computer-Integrated Manufacturing 23 (6) (2007) 630–637.

[27] C. W. Brooks, I. Borish, System for ophthalmic dispensing, Elsevier Health Sciences, 2006.

[28] Ophthalmic optics – spectacle lenses – vocabulary, Standard, International Organization for Standardization, Geneva, Switzerland (2012).

[29] C.-J. Du, D.-W. Sun, Recent developments in the applications of image processing techniques for food quality evaluation, Trends in food science & technology 15 (5) (2004) 230–249.

[30] M. Sezgin, et al., Survey over image thresholding techniques and quantitative performance evaluation, Journal of Electronic imaging 13 (1) (2004) 146–168.

[31] J.-Y. Bouguet, Camera calibration toolbox for matlab (2015).
URL `http://www.vision.caltech.edu/bouguetj/calib_doc/`

[32] S. Black, Exhibition review: Framed!: Contemporary eyewear in fashion, Fashion Practice 5 (1) (2013) 129–135.