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Mussel Classifier System Based on Morphological Characteristics

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ABSTRACT The recognition, counting, and sorting of mussels in marine cultures for seed production are currently performed by visual examination experts (i.e., entirely dependent on human resources). In this paper, we present the development of an automatic mussel classifier system based on the morphological characteristics for the simultaneous recognition and sorting of five mussel species. The proposed system provides rich statistical information needed for tracking the long-term evolution of culture parameters. In our experimental demonstration, we have achieved a recognition rate of 95% in most of the test probes for the five studied mussel species. A single sample of dozens of specimens can be classified within seconds with real-time capability when the vision interface is not used. Finally, the system has the potential to be extended for the automatic classification of mussels worldwide.

INDEX TERMS Digital imaging processing, machine learning, machine vision, mussel classification, real-time classification.

I. INTRODUCTION

Mussel farms in Chile are among the most productive in the world and have produced over 300,000 tons in 2016, Table 1. Most of this production corresponds to the Chilean blue mussel (*Mytilus chilensis*) whose taxonomic status has been debated due to its similarities with others blue mussel species (e.g., *M. edulis*, *M. galloprovincialis*) (see [1]–[4]). Since mussel production around the world requires mussel seeds to start the growing process in longline culture systems, seed availability is critical to mussel production. In Chile, *M. chilensis* seeds are provided only by natural larvae settlements on net collectors placed in coastal sites where the larvae are seasonally available.

Because of massive bio-fouling on the collectors, *M. chilensis* seeds are mixed with other settlers (e.g., micro- and macro-algae, barnacles, piura). Similarly, mytilidae species such as *Aulacomya ater* (cholga), *Choromytilus chorus* (giant mussel), and *Semimytilus algosus* (bicolor mussel), are also common at the collectors (Fig. 1). This mixing of species, the similarity in shape, and size of different mussel species, increases the difficulty of visual taxonomic identification.

In the trading process between seed collectors (Fig. 2(a)) and mussel farmers (Fig. 2(c)), the taxonomic identification of seeds is a controversial issue, because mussel farmers look for only Chilean mussel seeds and tend to depreciate the price if those seeds are mixed with other mussel species.

TABLE 1. Table of production for 2016 in tons obtained from SERNAPESCA-CHILE (2017)(www.sernapesca.cl).

Species	2016 Production
M. galloprovincialis	Not yet cultivated
S. algosus	Not yet cultivated
A. ater	8,491 tons.
M. chilensis	302,777 tons.
Ch. chorus	2,339 tons.

In the debates surrounding the correct taxonomic status of Chilean mussels, several identification techniques have been applied, starting with a morphological approach and graduating to more conventional genetic views. The current identification procedure requires a visual examination by an expert, which is not always available at production sites. Moreover, the latest molecular methods require sophisticated laboratory tests that take several days to achieve an acceptable result. Additionally, mussel seeds are traded in several geographic locations, that does not have a reference center to

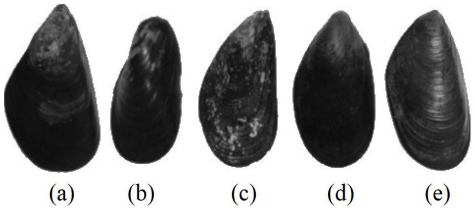

FIGURE 1. Species of mussels to be classified: (a) Mejillón Araucano (*Mytilus galloprovincialis*), (b) Mejillón Bicolor (*Semimytilus algosus*), (c) Cholga (*Aulacomya ater*), (d) Chorito or Mejillón Chileno (*Mytilus chilensis*), and (e) Choro Zapato (*Choromytilus Chorus*).

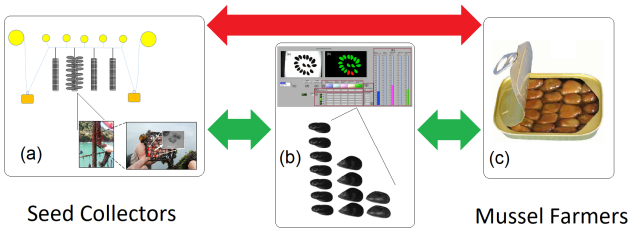

FIGURE 2. (a) Sample extraction at the seed collectors, in which a marine hang where mussels are fixed is lifted. Counting, recognition, and sorting have always been performed by eye which is excessively time consuming and statistically inaccurate. In this context, an automatic system (b) is developed to overpass the uncertainty conflict between both, the seed collectors and mussel farmers (c). Arrows represent the solutions flow.

clarify dispute over the mussel species presented in the seed sample, and the amount or percentage of each species in the volume being traded.

For these reasons, an applied research study was performed to develop an optical-digital system (Fig. 2(b)) to identify the mussel species among the seed settlers on the net collectors commonly used in Chilean mussel farming. An automatic vision system that allows for the classification, sorting and counting by mussel size has been developed using machine learning methodologies. The selected morphological characteristics are used to achieve feature recognition comparable to characteristic observations by a trained human operator. In this sense, it is expected that the system overpass the controversy between identifications. Previously developed vision systems for the remote recognition of parasites in clams reinforce the possibility to succeed with the proposed solution (see [5], [6]).

II. MATERIALS AND METHODS

In this section, we discuss the main issues concerning sample preparation. Additionally, the optoelectronic components of the machine vision system and its control software are described. Then, mussel classes from the database compilation are introduced. In the next subsections, a flow chart and the main algorithm's stages are briefly explained along with segmentation and mask generation processes, the mussel self-generated spatial reference system, the feature extraction process, and the automatic detection of anatomical reference points in mussels. Finally, feature extraction and dimensionality reduction of the feature vector are explained and a table of results (percent of sensitivity) is provided that summarizes the system performance.

A. MUSSEL SAMPLE SET PREPARATION

Sample preparation starts with extraction in the field by lifting a marine hang (line) where mussels seeds are fixed (Fig. 2(a)). Depending on both the stage of growth and the geographical location, several size ranks and species of mussels can be found. Moreover, depending on the quality of the culture, ambient conditions and human expertise the hangs can contain mussels from a single species or a mixture of additional species, such as sponges and crustaceans. Although this process appears simple, mussels must be individually recognized and classified by species by eye, which makes the entire process highly time consuming. Thus, for laboratory-tests and experimentation with machine vision, we used hundreds of mussels taken from several sites along the long line. Additionally, human classification by size is needed and, extraction occurs in several periods, which makes the entire research season dependent.

Once extracted and recognized, the mussels were washed to remove impurities to minimize the appearance of contour artifacts and separated into two sets. One set obeyed the tendency of mussels to stay edgewise when distributed over the photographic tray in their natural shape, which became a severe constraint for the training stage of the software. Thus, this set was created by separating the two valves and discarding the meat. This procedure ensures that the mussels will be distributed in front of the camera by taking advantage of the natural symmetry of both valves. This solution has been well established for laboratory training purposes. To avoid cutting the specimens for in-field applications, a specially adapted tray was designed. Thus, bivalve samples have been used in certain field tests for Chilean seafood companies with excellent results. A secondary set of mussels was stored in a freezer at $-4°$C for future use.

B. ILLUMINATION, CAMERA, AND DATA BASE

The main hardware components of the laboratory prototype (see Fig. 3) are specified as follows.

(a) A home-made illumination box fabricated with an aluminum holder with three square commercials LED panels, with one panel on the bottom and two on the opposite sides was used. The panels were 24 W and 300 mm $\times$ 300 mm $\times$ 38 mm and had an illumination angle greater than 110°. Lateral panels were slightly nonvertical (by approximately 5°) to obtain an angle of illumination that ensures the minimum appearance of shadows at the borders of the specimens to be sampled.

(b) The camera system was a CCD sensor-type color camera with high-resolution (1936 $\times$ 1216) and USB 3.0 from Thorlabs (part number DCC3260M). The camera was selected due to its ability to communicate with Labview programming interfaces. Most of the camera operation parameters, such as ON/OFF switching, RGB filtering, and adjusting the pixel clock, exposition, and

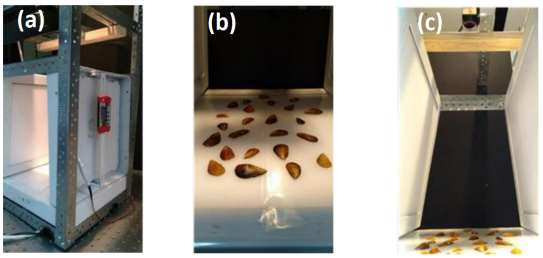

FIGURE 3. (a) Home-made illumination box fabricated with an aluminium holder with three commercial LED panels controlled via Labview. (b) One-valve samples treated to ensure that they lay flat over the LED for maximum visibility with the camera. Then, an acrylic tray was designed to avoid cutting the specimens; subsequently, bivalve samples were used. (c) Precise selection of camera height ensures optical field maximization without border aberration of the image. Height and camera resolution determine the minimum resolution for the region of interest (ROI) per specimen (100 × 100 pixels).

saturation, are freely accessible. In contrast, generic cameras are closed-casing systems with no ability to remotely control internal parameters if that advantage is desired.

(c) A commercial high-performance portable computer is required for easy transport and accurate real-time processing performance with a robust video card and processor.

(d) Finally, a database of more than 500 images was generated for training and validation.

C. MUSSEL CLASS LABELS FOR CHILEAN REGIONS

To test and train the developed mussel seed identification software to achieve the highest accuracy, a database of Chilean mussel valve shapes was established and organized by classes as shown in Table 2.

TABLE 2. Classes of mussel species present in the two selected geographical regions.

Species	Class label
Bio-Bio Group	
M. galloprovincialis	1
S. algosus	2
A. atra	4
Ch. chorus	5
Los Lagos Group	
M. chilensis	3
A. ater	4
Ch. chorus	5

The mussel species considered in the database were those under commercial trade in Chile and split into two geographic groups because these species obey different geographical distributions along the Chilean coasts due to natural growth factors. The Bio-Bio Group (Fig. 4(a)) includes *Ch. chorus, M. galloprovincialis, S. algosus, A. ater, and Ch. chorus*; the Los Lagos group (Fig. 4(b)) is composed of *M. chilensis, A. ater, and Ch. chorus*. *M. chilensis* has been erroneously cited as present in the Bio-Bio region and further north; however, these citations are mistaken due to the great similarity in the valve shapes of *M. chilensis* and *M. galloprovincialis* [4].

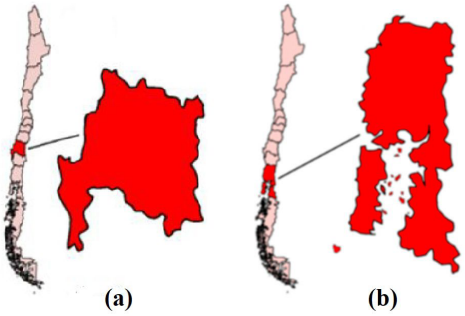

FIGURE 4. Coloured in red: (a) Bio-Bio region (36.00° to 38.30° S) and (b) Los Lagos region (40.15° to 44.14° S).

Moreover, splitting software training by geographic zones allows the system to be robust against the morphological variations of the mussel as previously reported [7], [10].

D. IMAGE PROCESSING ALGORITHM

Fig. 5 shows a complete flowchart of the image processing algorithm from image acquisition to the last increment counter stage for class and size. The chosen programming interface was Labview Version 2016-2017 from National Instruments.

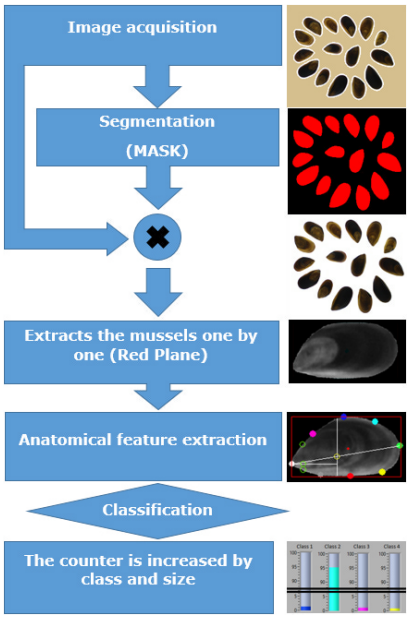

FIGURE 5. Flowchart of the classification solutions.

The flow chart in Fig. 5 starts with the selection of the input image that enters the digital image processing system. Additionally, the number of images in the folder is detected for continuous processing. The image processing algorithm is followed by the generation of a mask capable of isolating each mussel from the other objects in the scene.

1) SEGMENTATION AND MASK GENERATION

The goal at this stage is to generate a mask capable of isolating the mussels in the background. The stage was

implemented using sub-algorithms that obey the following sequence: (a) first, the binary mask of the input image is generated (mussels in red in Fig. 5); (b) then, the number of mussels in the scene is counted; and (c) finally, the image of a single mussel to be processed is extracted (mussel isolated in Fig. 5). Other sub-algorithms perform necessary image manipulation at this stage, such as contour generation and image rotation.

2) AUTOMATIC DETECTION OF ANATOMICAL REFERENCE POINTS IN MUSSELS

The automatic detection of anatomical points using the mussel contour was implemented with another group of sub-algorithms. These algorithms use geometrical information of the mussel's shell (upper valve) contour. Border detection can be used to obtain an unordered arrange of contour points $C_n = ((x_1, y_1), (x_2, y_2), \ldots (x_n, y_n))$ without knowing the relationship with the anatomy of the mussel itself *a priori*. Fig. 6 shows the points of interest to be automatically detected. The point "Umbo" (P1) is the most representative of the shell anatomy. This point is the origin (0,0) of the reference system.

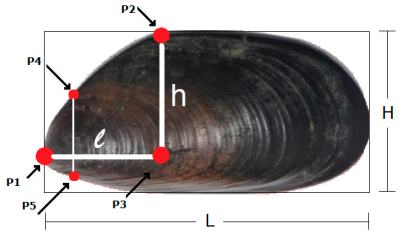

FIGURE 6. Anatomical points in the mussel.

To automatically detect all points of interest, the following steps were performed in the digital mussel mask. In step 1, the centroid of the digital mussel mask is calculated. In step 2, the distance between the centroid of the mussel and all contour points is calculated. In step 3, using distance information, function $D(\theta)$ which is a discrete curve of distances that possess one maximum that correspond to the most abrupt slope change, is defined; this point is "Umbo" (P1). In step 4, the mussel contour is reordered starting with "Umbo" in a counter clockwise direction. In step 5, point P2, which is the last of the ordered contour points in contact with the border of the circumscribed rectangle, is defined. In step 6, point P3 is defined, and it corresponds to the intersection of two straight lines arising from P1 and P2, in parallel to the borders of the circumscribed rectangle. In step 7, points P4 and P5 are determined, and they correspond to the intersections between a perpendicular straight line 1/4 from points P1 and P3.

E. FEATURE EXTRACTION

The proposed criteria to extract mussel characteristics were chosen based on their morphology. These geometrical features include the following: 1) the ratio between mussel area a and the rectangle area A (a/A); 2) the ratio between distance $\overline{P1P3}$ (l), and the length of the long side of the rectangle, L (l/L); 3) the ratio between distance $\overline{P2P3}$ (h) and the height of the rectangle H (h/H); 4) the normalized angle α_1, which is defined by point $P4$ and $P5$ with vertex $P1$; and 5) the normalized angle α_2, which is defined by points $P2$ and $P3$ with vertex $P1$. The features vector is defined as $V = (a/A, l/L, h/H, \alpha_1/2\pi, \alpha_2/2\pi)$.

An initial question may be posed: *Why are these characteristics in particular selected?* the answer is straightforward in principle: the set of characteristics are comparable to the primary differentiable physical attributes used by human experts for the recognition of mussels in real scenarios. Additionally, information on these five characteristics is available for the development of the current classification system, which is well suited for the needs of the specific target in the Chilean scenario. In practical terms, classification based on the five morphological characteristics was sufficiently robust for high accuracy recognition in laboratory conditions, and more than acceptable performance has been reported in a field test at marine farms in the Bio Bio and Los Lagos regions. Other types of characteristics, such as color and texture features are not considered as primary physical attributes for differentiation due to some degree of visual similarity between species but will be examined with more accuracy in future work with spectral analysis.

F. DIMENSIONALITY REDUCTION OF THE FEATURE VECTOR

To obtain additional insights into the contribution of the features and properly differentiate the classes, a principal components analysis (PCA) is performed [16]. PCA is a standard technique for the statistical treatment of data, and it can reduce the dimensionality of the feature space to an uncorrelated basis through an orthogonal transformation. This new basis of vectors called principal components corresponds to the largest variability in the incoming dataset. In the present case, a two-dimensional distribution of classes is exhibited in Fig. 7 for the Bio-Bio region only (for academic purposes) and it shows good spatial distribution. Therefore, in this example, the four classes are sufficiently differentiable at a glance. Eventually, the distribution of points will improve if the resolution of the vision system is increased as will be explained hereinafter.

III. RESULTS AND DISCUSSION

Four machine learning strategies were implemented via the Labview toolkit to display the classification results and facilitate discussion: Support Vector Machine (SVM) [11]; Neural Network Algorithm (aNN) (see [12], [13]); Logistic Regression Algorithm (L.R.) and K-Nearest Neighborhood (k-NN) (see [14], [15], [17], [18]). With these four classifiers, the performance of the system at the laboratory scale can be analyzed.

A. CLASSIFICATION RESULTS IN THE LABORATORY

Single-valve samples were used for laboratory testing under the assumption of shell symmetry (i.e., considering the top or

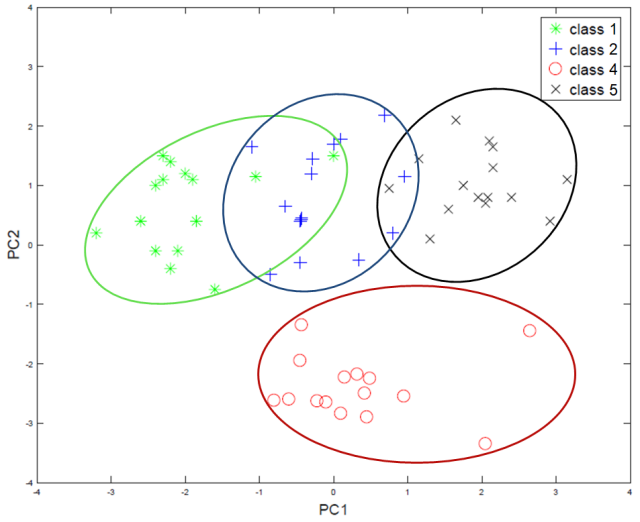

FIGURE 7. First two principal components for the Bio-bio region: Class 1 (green '∗' symbol bounded by a green ellipse), Class 2 (blue '+' symbol bounded by a blue ellipse), Class 4 (red '∘' symbol bounded by a red ellipse), and Class 5 (black '×' symbol bounded by a black ellipse).

TABLE 3. Sensitivity test for the Bio-Bio region.

Bio Bio	Size	Class 1	Class 2	Class 4	Class 5
		%	%	%	%
SVM	B	93.3	80.0	66.6	100.0
	C	80.0	100.0	86.6	100.0
	D	73.3	100.0	93.3	100.0
aNN	B	93.3	80.0	73.3	100.0
	C	93.3	100.0	86.6	100.0
	D	73.3	100.0	93.3	100.0
L.R.	B	93.3	80.0	73.3	100.0
	C	80.0	93.3	86.6	100.0
	D	73.3	100.0	86.6	100.0
k-NN	B	91.3	95.6	91.3	95.6
	C	95.6	100.0	95.6	100.0
	D	82.6	100.0	91.3	100.0

bottom shell equivalent for analysis). Tables 3 and 4 show the statistical performance of the classifier system for the Bio-Bio and Los Lagos regions, respectively, quantified as the number of individuals correctly classified to each species over the total number of evaluated individuals (true-positive sensitivity). Four classifiers were used to classify the samples by size and class in both Tables. The results are presented as the percent recognition (%) of true-positive values from the entire set of samples (N≈500) extracted from both regions. The classes are split by their size rank, and five ranks are separated every 10 mm, with the first rank (A) ranging from 1 to 10 mm and the final rank (E) ranging upwards from 40 mm without an upper bound. Although a collection of thousands of samples extracted in a variety of sizes and ranks is available, the results of Tables 3 and 4 are focused on ranks B, C, and D only. The number of specimens per class and rank is $N = 95$ with 80 and 15 used for training and recognition purposes, respectively. Following the nomenclature of Table 2, *M. galloprovincialis* is Class 1, *S. algosus* is Class 2, *A. ater* is Class 3; *M. chilensis* is Class 4, and *Ch. chorus* is Class 5.

TABLE 4. Sensitivity test for the Los Lagos region.

Los Lagos	Size	Class 3	Class 4	Class 5
		%	%	%
SVM	B	100.0	93.3	100.0
	C	100.0	93.3	80.0
	D	100.0	93.3	60.0
aNN	B	93.3	86.6	100.0
	C	100.0	93.3	86.6
	D	100.0	93.3	86.6
L.R.	B	93.3	93.3	100.0
	C	100.0	93.3	93.3
	D	100.0	93.3	80.0
k-NN	B	95.6	95.6	91.3
	C	95.6	91.3	91.3
	D	100.0	95.6	86.9

From the perspective of mussel visual examination experts, the percent of true-positive recognition values is defined as *sufficient* if it reaches 70%, *high* if it ranges from 80% to 90%, *excellent* if it reaches the 95%, and *human-expert comparative* if it reaches 98%. From our results, the lowest percentage values (under 80 percent) obey loss of sensitivity due to the limited resolution of the camera system (∼2 Mega pixels). To improve these numbers, a minimum region of interest (ROI) per mussel of 100 × 100 pixels is sufficient for high sensitivity. Instrumentally, the field of view, the focal length of the camera lens, and sensor distance are parameters that directly affect the image resolution. In simpler terms, the higher the resolution of the camera sensor, the better the sensitivity. In practice, these laboratory results with a 2 Mega pixel camera are auspicious for all classes in the full-size rank from 1 mm to 30 mm. Thus, the use of the system in field test was justified. Finally, although it is not conclusive which machine learning tool is the more recommended for practical uses, a deep understanding of the machine learning strategy used in each case will be investigated in the future.

In this diagnostic it is important to mention that a secondary specificity can be defined as the number of individuals correctly excluded as belonging to each specie over the total number of evaluated individuals (true-negative sensitivity). Nevertheless, this treatment was not carried on because the geographical separation was considered to - precisely - avoid the appearance of specimens not belonging to the geographical zone selected in the software. In practice, by selecting a group (zone) properly in the software there will be never appear a "foreign" specimen because it physically does not grow in that zone.

B. EVALUATION IN THE CHILEAN SEAFOOD COMPANY

The field-reported performance with two-shell mussels are satisfactory and close to the laboratory results reported with single shells. These measurements were performed using specially fabricated acrylic trays that allow a flat layout of the specimens. Sensitivity was validated empirically under the judgement of visual examination experts working at marine farms and Chilean seafood companies located in Coliumo in the Bio Bio region, Hualaihué and Chiloé Island in the Los Lagos region. The only requirement for users in this on-field

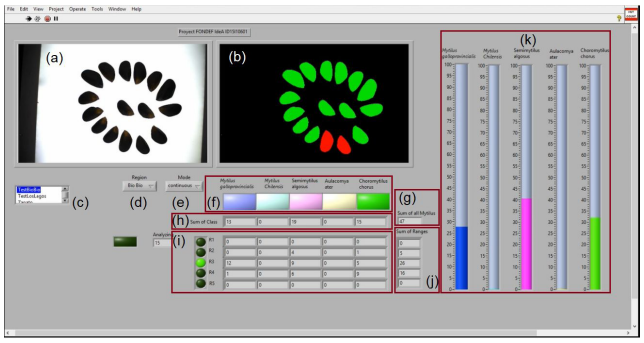

FIGURE 8. User interface. (a) Entry image. (b) Mask generation. (c) Training images selector. (d) Zone selector (Bio Bio or Los Lagos). (e) Run mode selector (continuos or manual). (f) Color code by class. (g) Sum of all individuals. (h) Sum of all individuals by class. (i) 5 × 5 matrix (class by rank). (j) Sum of all indivuals by size. (k) Cumulative percentage bars by class.

test was a simple sample preparation protocol, consisting of washing and flatly disposing mussels on trays. The goal at this stage was both, to get feed-back based in the experience of non trained users, and to evaluate the degree of concordance between visual identifications and the automatic system. Secondary attributes were also putted to evaluation, such as software operation and manipulation of the user interface (Fig. 8). In particular, Sorting by size rank and automatic and fast counting are additional attributes of the developed system that were highly appreciated by users. Under normal conditions, a single sample of dozens of specimens can be classified within 5 to 10 seconds, and high-speed performance (on the order of milliseconds) can be achieved when the vision interfaces (Fig. 8(a) and (b)) are switched-off and the computer is run internally.

For clarity, a multimedia file (musselClassifier.avi) accompany this manuscript, it shows the main features and functionalities of the user interface depicted in Fig. 8.

IV. CONCLUSIONS AND PROSPECTS

In this work, an automatic mussel classifier system was presented. To the best of our knowledge, this can be the first successful attempt at the automatic classification of mussel specimens with machine learnings tools. The results provide a solid base of experimental proofs of the developed system, which shows a high level of true-positive recognition with four machine learning strategies. Moreover, system performance was positively evaluated in a field test. On this last aspect, it is a mandatory task to quantify the evaluation of human experts with a concordance correlation coefficient for future industrial applications. At this scale, classification of tons of specimens in real-time demand the integration of the machine vision system with hardware units, such as conveyor belts and mechanical actuators. Additionally, other architectures can be implemented in the classification method to minimize computational costs, which is a mandatory task at the industry as well.

In an improved version of this system, we will study the effect of adding new characteristics on the classification results, such as color and texture. Moreover, additional strategies in the classification method will be approached in the future for the classification of more complex samples, such as those with impurities, in random disposition and worldwide mussel species.

Finally, in addition to the economic benefits, this system can provide rich statistical information in real-time, which might facilitate rapid decision-making for the benefit of seafood quality by rapid selectivity, thus improve sustainability with more efficiency crops.

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