# Self-calibration of colormetric parameters in vision systems for autonomous mobile robots

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**Abstract**— *Vision is an extremely important sense for both humans and robots, providing detailed information about the environment. In the past few years, the use of digital cameras in robotic applications has been increasing significantly. The use of digital cameras as the main sensor allows the robot to take the relevant information from the surrounding environment and then take decisions. A robust vision system should be able to detect objects reliably and present an accurate representation of the world to higher-level processes, not only under ideal light conditions, but also under changing light intensity and color balance. In this paper, we propose an algorithm for the self-calibration of the most important parameters of digital cameras for robotic applications. The algorithm extracts statistical information from the acquired images, namely the intensity histogram, saturation histogram and information from a black and a white area of the image, to then estimate the colormetric parameters of the camera. We present experimental results obtained with several autonomous robotic platforms: two wheeled platforms, with different architectures of the vision system, a humanoid robots and an autonomous driving agent. The images acquired after calibration show good properties for further processing, independently of the initial configuration of the camera and the type and amount of light of the environment, both indoor and outdoor.*

**Keywords:** Robotic vision, digital cameras, image processing, camera calibration, colormetric parameters.

## 1. Introduction

In the past few years, the use of digital cameras in robotic applications has been increasing significantly. We can point out some areas of application of these robots, as the case of the industry, military, surveillance, service robots and we start also seeing vision systems in vehicles for assisted driving. The cameras are used as sensors that allow the robot to take the relevant information of the surrounding environment and then take decisions.

To extract information from the acquired image, such as shapes or colors, the camera calibration procedure is very important. If the parameters of the camera are wrongly calibrated, the image details are lost and it may become almost impossible to recognize anything based on shape or color (see for example Fig. 1).

Our experience, as well as the experience of all the researchers that work in the field of computer vision, show that the digital cameras fail regarding the quality of the images acquired under certain situations, even considering the most recent cameras (an example can be found in [1]. The algorithms developed for calibration of digital cameras assume some standard scenes under some type of light, which fails in certain environments. We did not find scientific references for these algorithms.

In this work, we show that the problem can be solved by adjusting the colormetric parameters of the camera in order to guarantee the correct colors of the objects, allowing the use of the same color classification independently of the light conditions (see for example the problem presented in [2]). This allows also a correct processing of the image if other features have to be extracted. We think that this paper presents an important contribution to the field of autonomous robotics.

We propose an algorithm to configure the most important colormetric parameters of the cameras, namely gain, exposure, gamma, white-balance, brightness, sharpness and saturation without human interaction, depending on the availability of these parameters in the digital camera that is being used. This approach differs from the well known problem of photometric camera calibration (a survey can be found in [3]), since we are not interested in obtaining the camera response values but only to configure its parameters according to some measures obtained from the acquired images in robotic applications. The self-calibration process for a single robot requires only few seconds, including the time necessary to interact with the application, which is considered fast in comparison to the several minutes needed for manual calibration by an expert user. Moreover, the developed algorithms can be used in the real-time by the robots while they are operating.

The work that we present in this paper was tested and is being used by several robotic platforms developed in the University of Aveiro, namely in the challenging environment of robotic soccer (where the goal is the development of multi-agent robotic teams), both with welled [4] and humanoid robots [5], and also in autonomous driving vehicles and a service robot [6]. These robots are presented in Fig. 2. In all these applications, the robots have to adjust, in a constrained time, their camera parameters according to the lighting conditions.

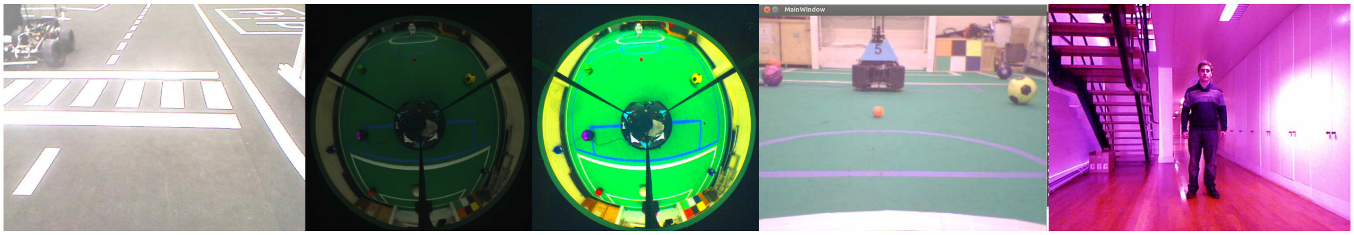


Fig. 1: Images acquired in different scenarios with different robots, using wrong colometric parameters in their digital cameras. From left to right, wrong value of gamma (high), exposure (low), saturation (high), gain (high), white-balance (high both in Blue and Red gains).

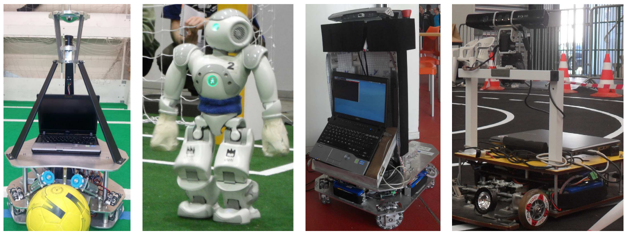


Fig. 2: Robotic platforms used in this work. From left to right, CAMBADA (RoboCup Middle Size league robotic soccer), NAO (RoboCup Standard Platform League soccer robot), CAMBADA@HOME (service robot for elderly and disabled people support - under test on RoboCup @HOME league) and autonomous driving.

This paper is structured in five sections, the first of them being this introduction. Section 2 provides an overview on the most important colormetric parameters of digital cameras and the properties on the image that are related to each one. Section 3 describes the proposed algorithm. In Section 4 the results and their discussion are presented. Finally, Section 5 concludes the paper.

## 2. Configuration of the camera parameters

The configuration of the parameters of digital cameras is crucial for object detection and has to be performed when environmental conditions change. The calibration procedure should be effective and fast. The proposed calibration algorithm processes the image acquired by the camera and computes several measurements that allow the calibration of the most important colormetric parameters of a digital camera, as presented in Fig. 3. Besides the referred parameters, the hardware related parameters gain and exposure are also taken into consideration.

Starting by some definitions, luminance is normally defined as a measurement of the photometric luminous intensity per unit area of light travelling in a given direction. Therefore, it is used to describe the amount of light that goes through, or is emitted from, a particular area, and falls within a given solid angle.

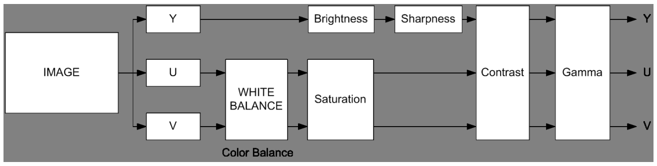


Fig. 3: A typical image processing pipeline (inside the image device) for a tri-stimulus system. This processing can be performed on the YUV or RGB components depending on the system. This should be understood as a mere example.

Chrominance is a numeral that describes the way a certain amount of light is distributed among the visible spectrum. Chrominance has no luminance information but is used together with it to describe a colored image defined, for instance, by an RGB triplet. Any RGB triplet in which the value of R=G=B has no chrominance information.

White balance is the global adjustment of the intensities of the colors (typically red, green, and blue primary colors). An important goal of this adjustment is to render specific colors – particularly neutral colors –correctly; hence, the general method is sometimes called gray balance, neutral balance, or white balance. This balance is required because of different color spectrum energy distribution depending on the illumination source. The proposed algorithm uses a white area as reference to calibrate this parameter. The idea is that the white region should be white – in the YUV color space this means that the average value of U and V should be 127.

The black and white regions can be defined manually beforehand to correspond to regions of the robots in the image or the algorithm can search in the image autonomously for white areas, after setting the camera to auto mode. In the case of the NAO robots, the robot stops and look to a defined position of its own body where these regions are. In the case of the wheeled robots, due to the use of a omnidirectional vision system [7], the own body is seen in the image and a white and black area was placed closed to the mirror. In case of the autonomous driving and service robots, an example of the white areas obtained from the images acquired by their vision systems can be found in Figs. 5 and 4.

The brightness parameter is basically a constant (or offset)

Fig. 4: From left to right, an example of an image acquired in auto mode by the camera the autonomous driving robot, the corresponding white areas obtained autonomously, and the corresponding black areas also obtained autonomously by the proposed algorithm.

that can be added (subtracted) from the luminance component of the image. It represents a measure of the average amount of light that is integrated over the image during the exposure time. If the brightness it too high, overexposure may occur which will white saturate part or the totality of the image. The proposed algorithm considers a black area in the image as reference to calibrate this parameter. In the CAMBADA and SPL robots, these areas are part of the robots and can be defined beforehand. In case of the autonomous driving and service robots, an example of the white areas obtained from the images acquired by their vision systems can be found in Figs. 5 and 4. The concept is that the black area should be black – in the RGB color space, this means that the average values of R, G and B should be close to zero in this region.

Fig. 5: From left to right, an example of an image acquired in auto mode by the camera the autonomous service robot, the corresponding white areas obtained autonomously, and the corresponding black areas also obtained autonomously by the proposed algorithm.

The saturation of a color is determined by a combination of light intensity that is acquired by a pixel and how much this light it is distributed across the spectrum of different wavelengths. Saturation is sometimes also defined as the amount of white that has been blended into a pure color. In the proposed algorithm, we consider the histogram of the Saturation (obtained in the HSV color space) and we force the MSV value of this histogram to 2.5, following the explanation above about the use of the MSV measure regarding the histogram of intensities, calibrating this parameter.

Sharpness is a measure of the energy frequency spatial distribution over the image. It basically allows the control of the cut-off frequency of a low pass spatial filter. This may be very useful if the image is afterward intended to be decimated, since it allows to prevent spatial aliases artifacts. We do not consider this parameter in the proposed calibration algorithm as in the referred applications of the robots we work with the resolution of the images acquired by the camera.

Gain, exposure, gamma and contrast are related and we use the information of the luminance of the image to calibrate them. The priority is to keep gamma out and the exposure to the minimum possible value to reduce noise in the image and the effect of the moving objects in the image. If the light conditions are very hard, the algorithm will calibrate the gamma and exposure time.

Gain is a constant factor that is applied to all the pixels in the image when the image is acquired. Exposure time is the time that the image sensor (CCD or CMOS) is exposed to the light. Gamma correction is the name of a nonlinear operation used to code and decode luminance or TGB tristimulus values. One of the most used definition of contrast is the difference in luminance along the 2D space that makes an object distinguishable. To calibrate all these parameters, it is used the histogram of luminance of the image and a statistical measure to balance the histogram of the acquired image, as presented next.

The histogram of the luminance of an image is a representation of the number of times that each intensity value appears in the image. Image histograms can indicate if the image is underexposed or overexposed. For a camera correctly calibrated, the distribution of the luminance histogram should be centered around 127 (for a 8 bits per pixel image). An underexposed image will have the histogram be leaning to the left, while an overexposed image will have the histogram leaning to the right (for an example see the Fig. 13)).

Statistical measures can be extracted from digital images to quantify the image quality [8], [9]. A number of typical measures used in the literature can be computed from the image gray level histogram. Based on the experiments presented in [10], in this work we used the mean sample value ($MSV$):

$$MSV = \frac{\sum_{j=0}^{4} (j+1) x_j}{\sum_{j=0}^{4} x_j},$$

where $x_j$ is the sum of the gray values in region $j$ of the histogram (in the proposed approach we divided the histogram into five regions). When the histogram values of an image are uniformly distributed in the possible values, then $MSV \approx 2.5$.

A graphical representation of the statistical measures extracted from the image acquired by the camera and its relation to the parameters to be calibrated on the camera is presented in Fig. 6.

## 3. Proposed algorithm

The algorithm configures the most important parameters, as referred above. For each one of these parameters, and

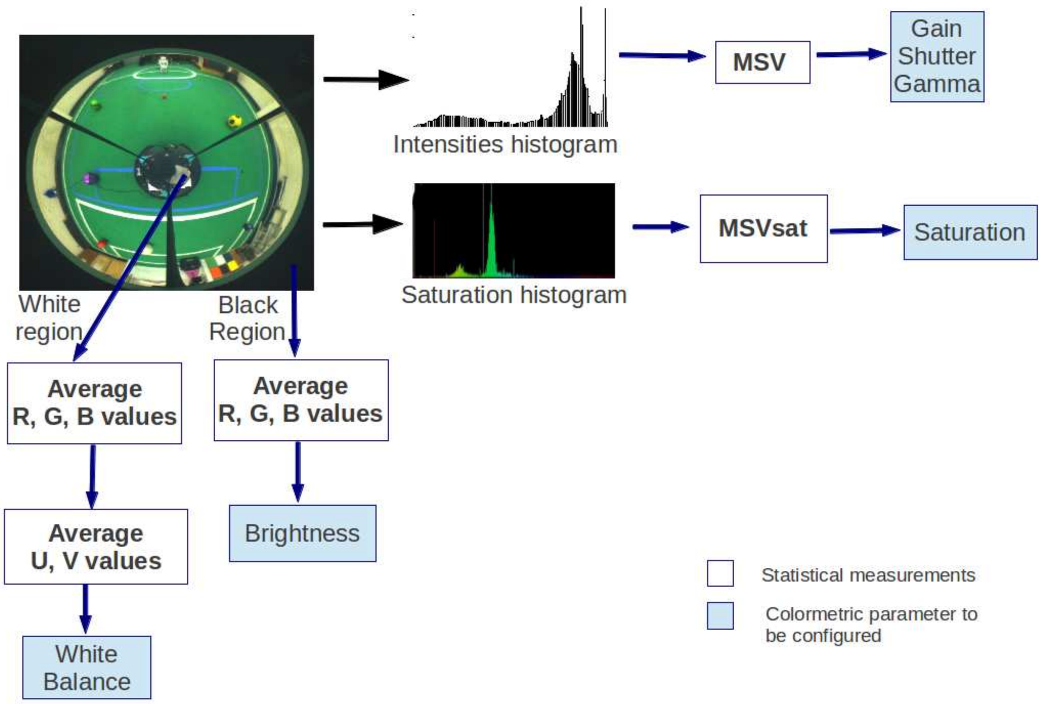


Fig. 6: A graphical representation of the statistical measures extracted from the image acquired by the camera and its relation to the parameters to be calibrated on the camera.

that are available on the camera, a PI controller was implemented. PI controllers are used instead of proportional controllers as they result in better control having no stationary error. The constants of the controller have been obtained experimentally for both cameras, guaranteeing the stability of the system and an acceptable time to reach the desired reference.

The algorithm presented next starts by the configuration of the parameters related to the luminance on the image, namely gain, exposure and gamma, by this order if necessary. To improve the quality of the image, i. e. to have the less noise as possible, the exposure should be as much as possible. On the other hand, the gamma should be the one that gives the best dynamic range for the intensity and we only want to change it is the gain and exposure alone cannot get good results.

When the image acquired have enough quality in terms of luminance, considering that the MSV for the histogram of intensities is between 2 and 3, the algorithm starts calibrating the other parameters, namely white-balance, saturation and brightness, according to the ideas expressed in the previous section. The algorithm stops when all the parameters have converged. This procedure solves the problem of the correlation that exists between the parameters.

```
do
  acquire image
  calculate the histogram and the MSV value of Luminance
  if MSV != 2.5
    if exposure and gain are in the limits
      apply the PI controller to adjust gamma
    else if gain is in the limit
      apply the PI controller to adjust exposure
    else
      apply the PI controller to adjust gain
    end
    set the camera with new gamma, exposure and gain values
  end
  if MSV > 2 && MSV < 3
    calculate the histogram and MSV value of saturation
    calculate average U and V values of a white area
    calculate average R, G and B values of a black area
    if MSVsat != 2.5
      apply the PI controller to adjust saturation
      set the camera with new saturation value
    end
  if U != 127 || V != 127
    apply the PI controller to adjust WB_BLUE
      apply the PI controller to adjust WB_RED
      set the camera with new white-balance parameters
    end
    if R != 0 || G != 0 || B != 0
      apply the PI controller to adjust brightness
      set the camera with new brightness value
    end
  end
while any parameter changed
```

## 4. Experimental results

To measure the performance of the proposed self calibration algorithm, experiments have been made in four robotic platforms: the CAMBADA robots (RoboCup Middle Size league robotic soccer robots) and NAO robots (RoboCup Standard Platform League soccer robot), in indoor scenarios, a wheeled service robot and an autonomous driving agent. In all the cases, the images acquired after the proposed autonomous colormetric calibration have good properties, both in terms of objective and subjective analysis.

The experiment that follows have been conducted using the cameras of the robots with different initial configurations inside a laboratory with both artificial and natural light sources. In Fig. 7, the experimental results are presented when the algorithm starts with the parameters of the camera set to lower value and Fig. 8 presents experiment results when the camera parameters are set to higher values. As it can seen, the configuration obtained after using the proposed algorithm is approximately the same, independently of the initial configuration of the camera.

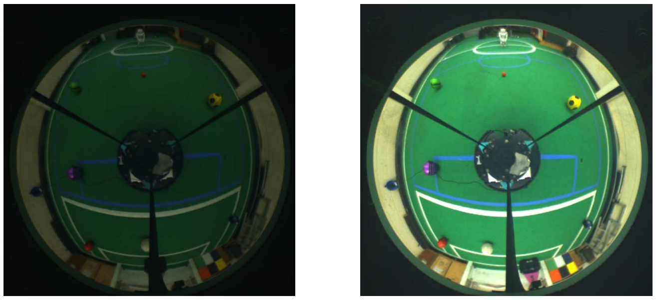


Fig. 7: Some experiments using the proposed automated calibration procedure. From left to right, an image captured with some of the parameters of the camera set to lower values, the corresponding image obtained after applying the proposed calibration procedure.

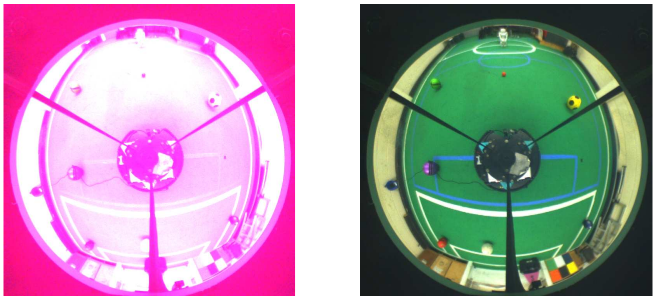


Fig. 8: Some experiments using the proposed automated calibration procedure. From left to right, an image captured with some of the parameters of the camera set to higher values and the corresponding image obtained after applying the proposed calibration procedure.

In Fig. 9 and 10 there are presented the variation of the camera parameters related to the experiment described above. As we can see, the convergence of the parameters is fast. It took less than 100 cycles to the camera converges to the correct parameters in order to obtain the images presented in Fig. 7 and Fig. 8. In this experiment, the camera was working at 30 fps that means a calibration time below 3 seconds. These are the worst case scenarios in calibration. Most of times, in practical use, the camera can start in auto mode and the algorithm applied after that. An example of this situation is presented in the video, where the lamps of the laboratory are switched on and off after the camera calibrated. In these situations, the camera converges in a reduced number of cycles.

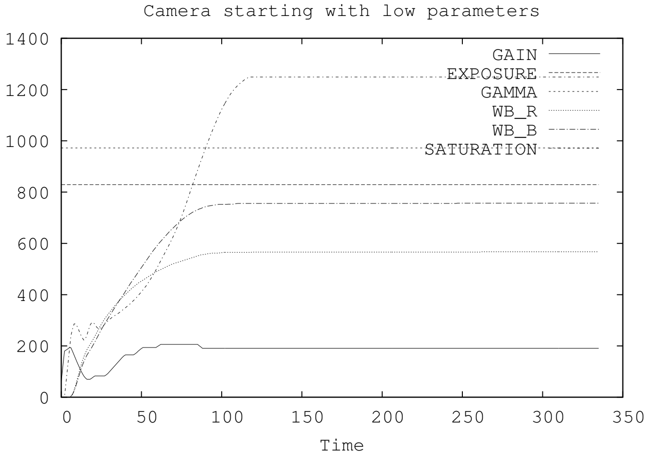


Fig. 9: A graphic showing the variation of the parameters of the camera when it started with higher values. We can see a fast convergence of the parameters.

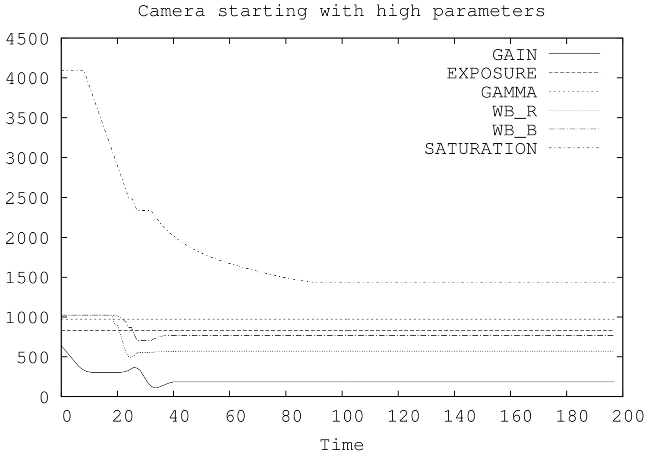


Fig. 10: A graphic showing the variation of the parameters of the camera when it started with higher values. We can see a fast convergence of the parameters.

In the NAO robot, we work with the cameras at 15 fps due to the limitations on the processing capabilities, which leads to times close to 10 seconds. However, due the fact that the NAO robots do not have graphical interface with the user, the proposed algorithm is very useful to calibrate the two cameras of the robots.

In Fig. 11 we present an image acquired with the camera of a CAMBADA robot in auto mode and in Fig. 12 we present an image acquired with the camera of a NAO robot in auto mode. The results obtained using the camera with the parameters in auto mode are overexposed and the white balance is not correctly configured, both for the welled and NAO robots. The algorithms used by the digital cameras that are on the robots (we tested also some more models and the results are similar) is due several reasons explained next. In the case of the omnidirectional vision system, the camera analyzes the entire image and, as can be seen in Fig. 11, there are large black regions corresponding to the robot itself. Moreover, and due to the changes in the environment around the robot as it moves, leaving the camera in auto mode leads to undesirable changes in the parameters of the camera, causing problems to the correct feature extraction to object detection.

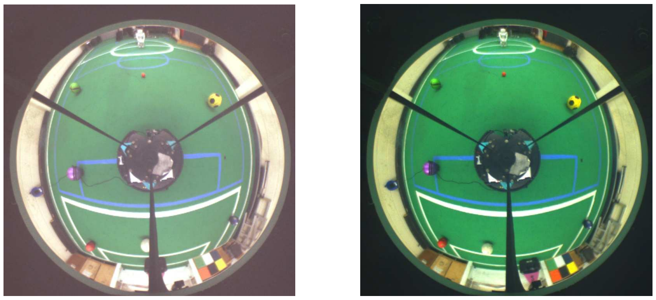


Fig. 11: From left to right, an example of an image acquired with the camera of the wheeled robot in auto mode, an image in the same robot after the proposed algorithm.

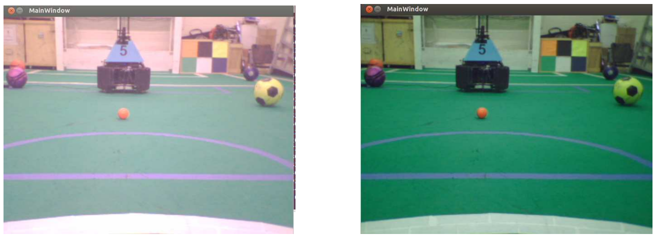


Fig. 12: From left to right, an example of an image acquired with the camera of NAO in auto mode and an image in the same robot after the proposed algorithm.

The good results of the automated calibration procedure can also be confirmed by the histograms presented in Fig. 14. The histogram of the image obtained after applying the proposed automated calibration procedure (Fig. 13) is centered near the intensity 127, which is a desirable property, as visually confirmed in Fig. 11. The histogram of the image acquired using the camera in auto mode (Fig. 13) shows that the image is overexposed, leading to the majority of the pixels to have saturated values.

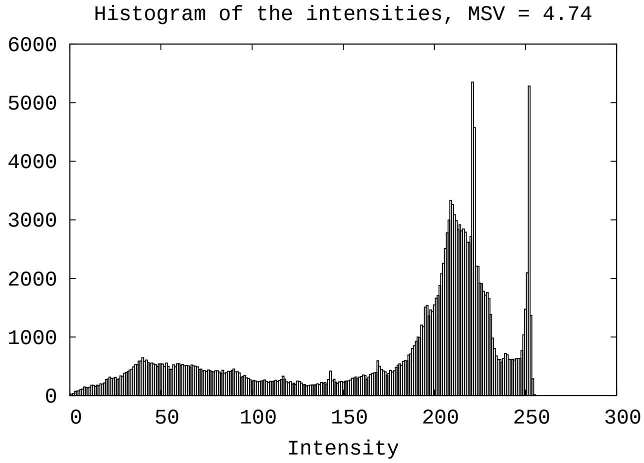
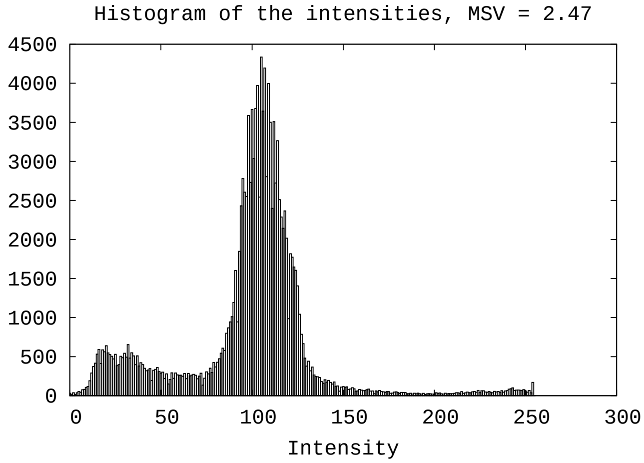


Fig. 13: The histogram of the intensities of the images presented in Fig. 11. This is the histogram of the image obtained with the camera parameters in auto mode.



a) b)

Fig. 14: The histogram of the intensities of the images presented in Fig. 11. This is the histogram of the image obtained after applying the automated calibration procedure.

It is expected that robots can perform their tasks under natural lighting conditions and in an outdoor environment. This introduces new challenges. In outdoor environments, the illumination may change slowly during the day, due to the movement of the sun, but also may change quickly in short periods of time due to a partial and temporally varying covering of the sun by clouds. In this case, the robots have to adjust, in real-time, the camera parameters, in order to adapt to new lighting conditions.

The proposed algorithm was also tested outdoors, under natural light. Figure 15 shows that the algorithm works well even with different light conditions. It confirms that the algorithm can be used in non-controlled lighting conditions and under different environments.

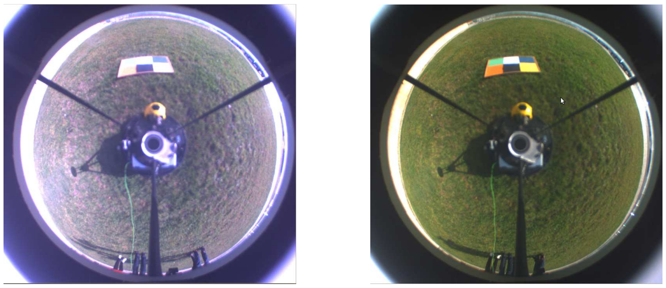


Fig. 15: On the left, an image acquired outdoors using the camera of a CAMBADA robot in auto mode. As it is possible to observe, the colors are washed out. That happens because the camera's auto-exposure algorithm tries to compensate the black around the mirror. On the right, the same image with the camera calibrated using the implemented algorithm. As can be seen, the colors and their contours are much more defined.

The algorithms developed by the industry for calibration of digital cameras assume some standard scenes under some type of light. However, besides the user manuals of the cameras tested, we did not find scientific references for these algorithms.

## 5. Conclusions

We propose an algorithm to autonomously configure the most important parameters of a digital camera. This procedure requires a few seconds to calibrate the colometric parameters of the digital cameras of the robots, independently of the initial parameters of the cameras, as well as the light conditions where the robots are being used. This is much faster than the manual calibration performed by an expert user, that even having as feedback the statistical measures extracted from the digital images that we propose in this paper needs several minutes to perform this operation.

The experimental results presented in this paper show that the algorithm converges independently of the initial configuration of the camera. These results allow the use of the same color ranges for each object of interest independently of the lighting conditions, improving the efficiency of the object detection algorithms .

The calibration algorithm proposed in this paper is also used in run-time in order to adjust the camera parameters during the use of the robots, accommodating some changes that can happen in the environment or in the light, without affect the performance of the vision algorithms.

As a future work, we would like to extend this work to more robotic applications in non-controlled environments, as well as to present more detailed results regarding its use in more models of digital cameras with different type of lens, that also affects the calibration of these parameters.

## 6. Acknowledgements

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