Evaluation of light sources for machine vision

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Received 3 September 1996; accepted 17 September 1997.

Luo, X., Jayas, D.S., Crowe, T.G. and Bulley, N.R. 1997. **Evaluation of light sources for machine vision.** Can. Agric. Eng. **39**:309-315. Using a color machine vision system, three types of light sources, incandescent, halogen, and fluorescent lamps were evaluated. The fluorescent lamp was also tested with a light controller incorporated as part of its power supply. Output gray levels from the three bands of the camera (red, green, and blue) were recorded for a range of lamp supply voltages and for an 8 h period with constant lamp supply voltages. Illumination uniformities over the field of view (FOV) of the camera were also examined. Given a 1 V change from the rated supply voltage, the maximum changes among the three color components occurred in the blue (1.8%), blue (1.3%), green (0.5%), and green (0.5%) bands for the incandescent, halogen, fluorescent, and controlled fluorescent lamps, respectively. Under constant lamp voltages for an 8 h period, the lamp outputs decreased by 4.7, 5.0, 7.7, and 1.2%, for the incandescent, halogen, fluorescent, and controlled fluorescent lamps, respectively. The illumination levels over the FOV were uniform, with average column intensities varying by less than 2.1, 2.1, 3.1, and 3.1% of the overall image intensity means, for the incandescent, halogen, fluorescent, and controlled fluorescent lamps, respectively. The average row intensity variations were less than the average column intensity variations.

Un système de vision artificielle couleur a été utilisé pour évaluer trois types de sources lumineuses, incandescente, halogène et fluorescente. La lampe fluorescente a aussi été testée avec un régulateur de lumière intégré au bloc d'alimentation. Les niveaux de gris des trois bandes de la caméra (rouge, verte et bleue) à la sortie de l'appareil ont été enregistrés pour des tensions de secteur variables et pour une période de 8 hr où la tension était maintenue constante. L'uniformité de l'éclairage dans le champ de vision de la caméra a aussi été examinée. Pour un écart de 1 V de la tension nominale, les changements les plus importants parmi les trois composantes de couleur furent pour les bandes bleue (1.8%), bleue (1.3%), verte (0.5%), et verte (0.5%) pour les lampes incandescente, halogène, fluorescente, et fluorescente contrôlée, respectivement. Pour une tension constante sur une période de 8 hr, les intensités lumineuses des lampes ont diminué de 4.7, 5.0, 7.7 et 1.2 %, pour les lampes incandescente, halogène, fluorescente, et fluorescente contrôlée, respectivement. L'intensité de l'éclairage à l'intérieur du champ de vision était uniforme, avec une intensité des colonnes variant par moins de 2.1, 2.1, 3.1, et 3.1% des moyennes d'intensité globale de l'image, pour les lampes incandescente, halogène, fluorescente, et fluorescente contrôlée, respectivement. Les variations moyennes d'intensité des rangées étaient moins importantes que celles des colonnes.

INTRODUCTION

High quality image acquisition is the first and the most important step in machine vision applications. The image of an object, as captured by a machine vision system, is not only a function of the spectral properties of the object surface, but also is a function of the illumination spectral distribution and the camera's spectral response. The camera's spectral response is fixed if the same camera is used for imaging, however illumination may vary with time in both intensity and color due to changes in supply voltage, lamp deterioration, and ambient temperature. As a result, images of an object taken at different times may appear differently, making comparison and analysis of images taken at different times difficult, especially when color or reflectance information is involved. The problem may be eliminated by adjusting the illumination each time an image is acquired, but this may become impractical in industrial applications of machine vision. Consistent illumination over an 8 h working shift is usually desired.

Many researchers have reported on illumination for machine vision systems, but the objectives of these research projects were focused on either manipulating illumination to obtain a clear image (Paulsen and McClure 1986) or developing algorithms to map spectral reflectance data onto an absolute coordinate system (Lee 1988; Gershon and Jepson 1989; Brainard and Wandell 1990; Green and Ismail 1990; Tominaga 1992; Hetzroni and Miles 1994). Little attention has been paid to developing practical illumination systems for industrial machine vision applications.

The objective of this study was to evaluate three types of commonly used light sources, namely incandescent, halogen, and fluorescent lamps in the following aspects: (1) sensitivity to lamp voltage variations, (2) stability with time, and (3) uniformity over the field of view (FOV) of the camera.

MATERIALS AND METHODS

Machine vision system

The hardware of the machine vision system consisted of a 3-chip CCD (coupled charge device) color camera (DXC-3000A, Sony, Japan) with a zoom lens of 10-120 mm focal length, a camera control unit (CCU-M3, Sony, Japan) which enabled selectable manual or automatic iris and video signal gain control and white/black balance of the camera, a personal computer (PC) (386/20MHz, UNISYS) with 8 MB of RAM and 80 MB hard disk, a color frame grabbing and processing board (DT2871 & DT 2858, DATA Translation, Marlboro, MA) which was installed in the PC extension slot, and a light chamber (Fig. 1 (a)). The software included a library of subroutines (Aurora, DATA Translation, Marlboro, MA) and application programs developed using the C language in the Department of Biosystems Engineering at the University of Manitoba.

Mounted over the lighting chamber on a stand which provided easy vertical movement, the camera captured images of objects in the light chamber. The camera provided three parallel analog video signals, namely red (R), green (G), and blue (B) corresponding to the three NTSC (National Television System Committee) color primaries and a sync signal to the camera control unit at a speed of 30 frames per second. The camera control unit performed the time-division multiplexing, dc restoration of the RGB signals, and timing signal generation for the frame grabber. The frame grabber digitized the RGB analog video signals into three 8-bit 512 x 480 digital images and stored them in three on-board buffers. The acquired digital images were then transferred to the hard disk for storage. The image resolutions were 0.206 mm/pixel and 0.161 mm/pixel in the horizontal and vertical directions, respectively.

Light sources

Three types of light sources, incandescent, halogen, and fluorescent lamps, were evaluated. The incandescent light sources were eight 40-W bulbs (Soft White, GE Lighting Canada, Mississauga, ON). The halogen light sources were eight 46-W bulbs (Power Par 20, Duro-Test Co., Fairfield, NJ). The fluorescent light source was a 305-mm diameter, 32-W circular lamp (FC12T9/CW, Philips, Singapore).

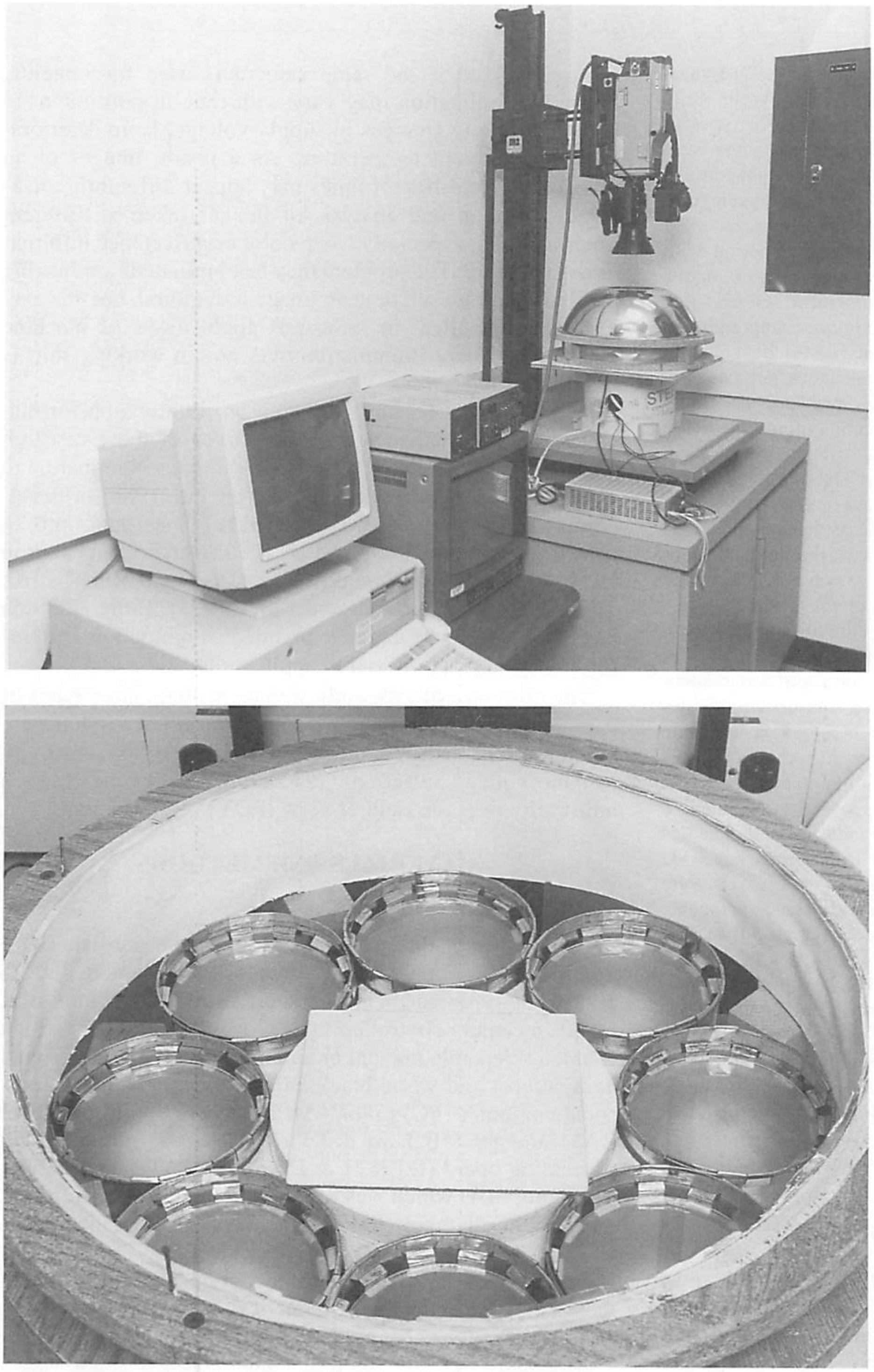

Fig. 1. Machine vision system: (a) arrangement of system components (top) and (b) incandescent or halogen bulbs (bottom).

A light chamber was used to provide uniform diffuse illumination over the FOV of the camera for imaging. For testing the incandescent and halogen light sources, the eight bulbs were oriented vertically in a ring around a 150 mm x 150 mm object plane in the centre of the light chamber (Fig. 1 (b)). For testing the fluorescent light source, the lamp was placed around and just below the surface of the object plane (Fig. 1 (c)). As a light diffuser, a steel bowl of approximately 400-mm diameter, painted white and smoked with magnesium oxide on the inside was inverted and covered the light bulbs and the object plane such that the object plane was only exposed to diffuse light. The steel bowl had a 125-mm diameter opening in its top (in the inverted position) through which the camera acquired images.

A voltage regulator (Sola Canada Inc., Toronto, ON) supplied stable AC power (±0.1 V) to the three types of light sources and the voltage to the lamps was adjusted by a variac. The fluorescent lamp was also tested with a light controller (FX0648-2/120, Mercron, Richardson, TX) incorporated in its power supply. The light controller automatically detected the illumination level in the light chamber through a photodiode light sensor and adjusted the AC frequency to the lamp to maintain a stable level of illumination under varying conditions. The frequency of the AC power output of the controller varied between 140 kHz at the minimum light levels to 60 kHz at full power.

Fig. 1. Machine vision system: (c) fluorescent bulb.

Testing procedures

Illumination standardization A Kodak white card with 90% reflectance (E152-7795, Eastman Kodak Co., Rochester, NY) was used as the white reference to standardize the illumination level in each test. The lamp voltage was set to the rated value V_R (120 V for the incandescent and the fluorescent lamps and 122 V for the halogen lamps). Then the image of the white card was acquired and the mean gray-level values of the *R*, *G*, and *B* color images over a small central area (50 x 50 pixels) were computed and used as the illumination-level indicators. By manually adjusting the iris control and performing white-balance with the camera control unit, all three values were adjusted to 250 ± 1.

Sensitivity to lamp voltage variations The lamps were turned on and the illumination standardization procedure was performed after 3 h. Then the lamp voltage was gradually changed from (V_R - 1.0 V) to (V_R +1.0 V) with a step of 0.1 V by adjusting the variac. At each of the 21 steps, the image of the same white card was acquired immediately following the voltage adjustment and the mean *R*, *G*, and *B* values over the small central area were calculated and recorded. The *R*, *G*, and *B* values at the different lamp voltages were then divided by the *R*, *G*, and *B* values at the rated lamp voltage V_R and defined as the voltage-dependent relative intensities, *Rv*, *Gv*, and *Bv*, respectively. The same test was repeated five times for each type of light source and the average *Rv*, *Gv*, and *Bv* of the five tests were plotted versus the lamp voltage.

Stability with time The illumination standardization was performed immediately after switching on the lamps. The image of the same white card was captured repeatedly and the mean *R*, *G*, and *B* values over the small central area were computed and recorded every 10 min for 8 h. The lamp voltage was maintained at the rated value V_R all the time. The mean *R*, *G*, and *B* values at the different times were then divided by the mean *R*, *G*, and *B* values when the system was just switched on and defined as the time-dependent relative intensities, *Rt*, *Gt*, and *Bt*, respectively. The same test was repeated five times for each type of light source and the average *Rt*, *Gt*, and *Bt* of the five tests were plotted versus time.

Uniformity over FOV Again, illumination standardization was performed and the image of the same white card was captured. Mean *R*, *G*, and *B* values were calculated for each row (down the image) and each column (across the image) in the image. The row means of *R*, *G*, and *B* images were then divided by the overall mean *R*, *G*, and *B* values and defined as the row-dependent relative intensities, *Rr*, *Gr*, and *Br*, respectively. Similarly, the column means of *R*, *G*, and *B* images were divided by the overall mean *R*, *G*, and *B* values and defined as the column-dependent relative intensities, *Rc*, *Gc*, and *Bc*, respectively. For each light-source type, ten images of the same white card with different orientations and viewing regions were acquired and analysed. Average *Rr*, *Gr*, and *Br* and average *Rc*, *Gc*, and *Bc* of the ten tests were plotted versus the row and column numbers, respectively.

RESULTS AND DISCUSSION

Sensitivity to lamp voltage variations

Figure 2 shows the average *Rv*, *Gv*, and *Bv* of the five replicate tests with the lamp voltages in the range of V_R - 1.0 V to V_R +1.0 V for the different light sources. Data for each curve were consistent with standard deviations for the three color bands and for the 21 voltage levels being less than 0.0016, 0.0016, 0.0025, and 0.0020 for the incandescent, halogen, fluorescent, and controlled fluorescent lamps, respectively.

The results showed that the output intensities of the R, G, and B components varied linearly with the lamp voltage for all of the light sources. Given a 1 V change from the rated supply voltage, the maximum changes among the three color components occurred in the blue (1.8%), blue (1.3%), green (0.5%), and green (0.5%) bands for the incandescent, halogen, fluorescent, and controlled fluorescent lamps, respectively.

The *Rv*, *Gv*, and *Bv* values were affected differently by a voltage change for a given lamp type. Slopes were different among the colors for the incandescent and halogen bulbs (Figs. 2 (a) and 2 (b)) but were nearly identical for the fluorescent lamp (Fig. 2 (c)). These results indicated that lamp voltage changes from the rated supply voltage caused slight color shifts in the light outputs of the incandescent and halogen bulbs and little change in the spectral output from the

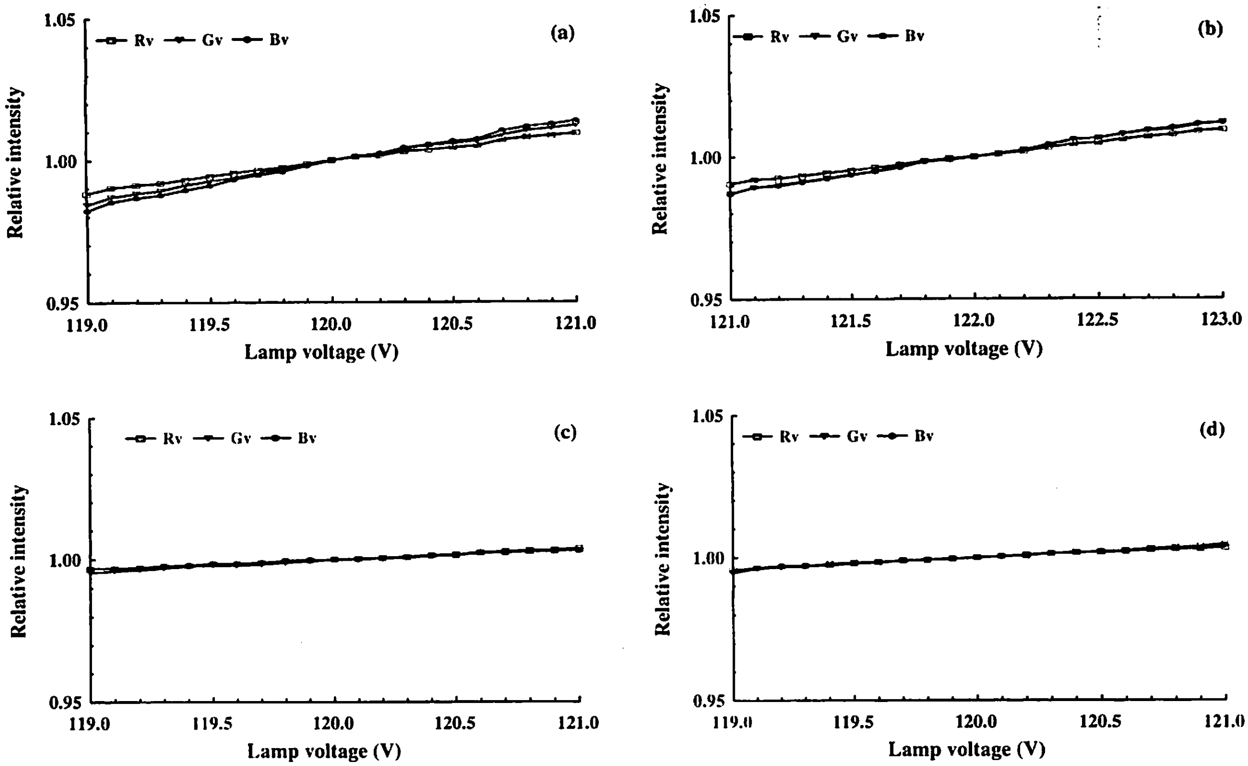

Fig. 2. Light sensitivities to lamp voltage variations for incandescent (a), halogen (b), fluorescent (c), and controlled fluorescent (d) lamps.

fluorescent lamp.

Incorporating the light controller in the power supply for the fluorescent lamp (Fig. 2 (d)) did not show any improvement, because the changes in the light output caused by the changes in the lamp voltage were within the control accuracy of the light controller.

Stability with time

Figure 3 shows the average *Rt*, *Gt*, and *Bt* of the five replicate tests over a duration of 8 h for the different light sources. Data for each curve were consistent with standard deviations for the three curves and for the 48 time intervals being less than 0.007, 0.011, 0.020, and 0.011 for the incandescent, halogen, fluorescent, and controlled fluorescent lamps, respectively.

The results (Figs. 3 (a), 3 (b), and 3 (c)) showed that there were significant changes in the outputs from the three light sources over 8 h. The three color components of the light changed differently with maximum differences of 0.63, 0.91, and 5.62% in the red, 4.68, 4.98, and 7.65% in the green, and 2.54, 2.99, and 6.35% in the blue, for the incandescent, halogen, and fluorescent lamps, respectively. This indicated that not only the light intensities but also the light colors changed.

The general trends of the curves showed that the major variations occurred within the first 3 h. This may have been due to the ambient temperature changes in the light chamber, which increased after the light sources were switched on.

The light levels of the incandescent and halogen bulbs varied in a similar way such that the G components varied the most, followed by *B* then *R*. The *R* components were actually quite stable with less than 0.1% variations over 8 h. All of the three color components of the fluorescent tube dropped significantly over the 8 h. As with the incandescent and halogen lamps, the *G* component dropped the most, followed by the *B* and *R* components.

Incorporating the light controller in the power supply for the fluorescent lamp (Fig. 3 (d)) showed a significant improvement in the light stability. The intensity variations in the *R*, *G*, and *B* components were reduced to 0.45, 1.20, and 0.53%, respectively. Again the *G* component decreased the most, followed by *B* then *R*.

Uniformity over FOV

Figure 4 shows the average *Rc*, *Gc*, *Bc*, *Rr*, *Gr*, and *Br* of the ten images of the Kodak white card under the three light source types. Across the width of the FOV (column number), the maximum intensity variations among the three color components were 2.1, 2.1, and 3.1% of the overall image intensity means, for the incandescent, halogen, and fluorescent lamps, respectively. Down the depth of the FOV (row number), the maximum intensity variations among the three color components were 1.0, 1.2, and 1.5% of the overall image intensity means, for the incandescent, halogen, and fluorescent lamps, respectively.

In spite of the different light sources and position and orientation of the white card, the *Rc*, *Gc*, and *Bc* curves (Figs. 4 (a), 4 (b), and 4 (c)) have similar patterns. The *Rr*, *Gr*, and *Br* curves showing variations down the depth of the FOV (Figs. 4 (a'), 4 (b'), and 4 (c')) also have common trends. This indicated that there were response variations in each direction of the three color sensor arrays.

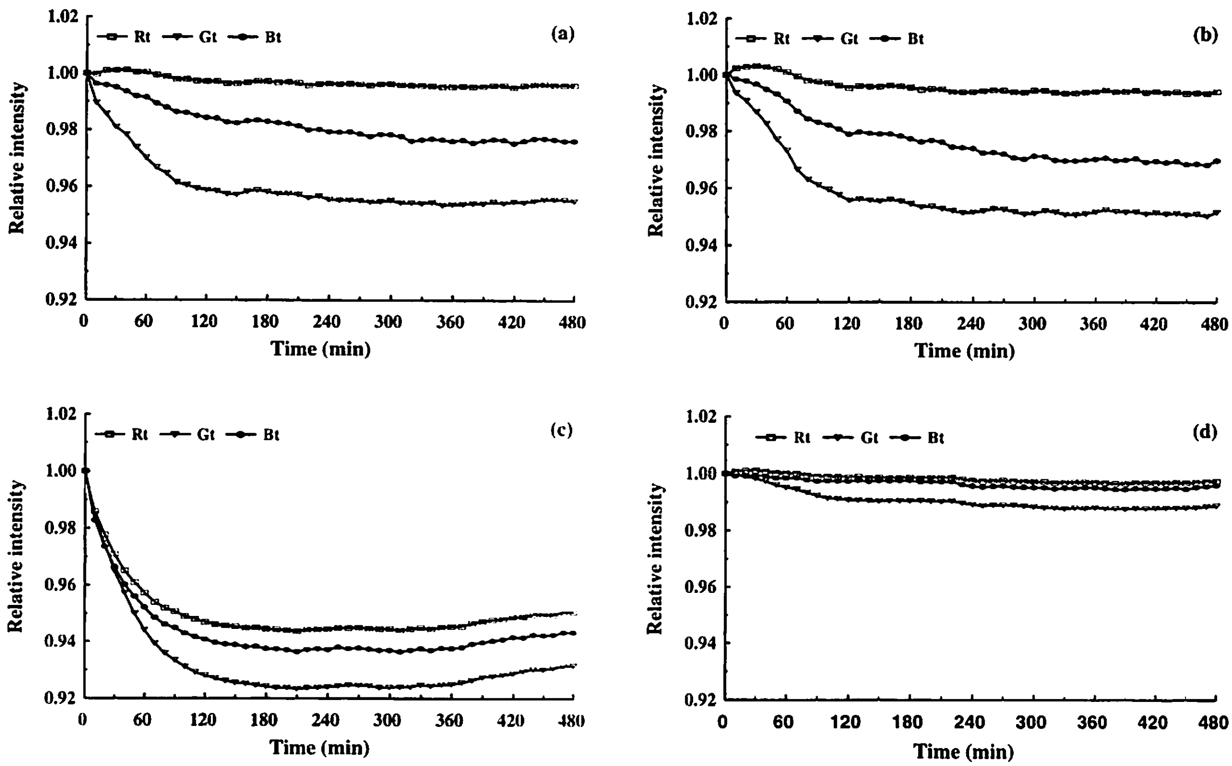

Fig. 3. Light stabilities with time for incandescent (a), halogen (b), fluorescent (c), and controlled fluorescent (d) lamps.

The illumination uniformity was basically determined by the configuration of light sources. As they were arranged in a similar configuration, the incandescent and halogen bulbs produced an almost identical light distribution over the FOV (Figs. 4 (a), 4 (a'), 4 (b), and 4 (b')). The fluorescent and controlled fluorescent lamps produced an identical light distribution (Figs. 4 (c) and 4 (c')) with lower intensities at the edge and slightly higher intensities near the centre of the FOV. The obvious drop in light intensities at the right edge of the FOV (high column numbers) was due to the power lead junction of the fluorescent lamp.

The test results showed that the greatest intensity variations always occurred at the edges of the FOV because of the variations in the camera's responses as well as the configuration of the light sources. This suggests that when taking images, objects should be placed as close to the centre of the FOV as possible. If a 64-pixel wide strip near each of the edges of the FOV is neglected, the intensities varied by less than 1% of the mean for all the three light source types.

In general, the fluorescent lamp with the light controller was affected the least by lamp voltage variations and time, but was poorest in uniformity over the FOV due to the power lead junction. This disadvantage could be overcome by using two or more lamps mounted together with the power lead junctions uniformly located around the object plane.

CONCLUSIONS

The test results showed that:

1) The light output of the fluorescent lamp was less sensitive to supply voltage variations than the light outputs of the incandescent and halogen lamps and incorporating the light controller in the power supply for the fluorescent lamp did not show any improvement.
2) The light outputs of all the three types of light sources (incandescent, halogen, and fluorescent) changed with time significantly, especially in the first three hours, with maximum intensity variations of 0.63, 0.91, and 5.62% in the red, 4.68, 4.98, and 7.65% in the green, and 2.54, 2.99, and 6.35% in the blue, for the incandescent, halogen, and fluorescent lamps, respectively; incorporating the light controller in the power supply for the fluorescent lamp improved the light stability significantly, with the intensity variations reduced to 0.45% in the red, 1.20% in the green, and 0.53% in the blue.
3) Three types of light sources produced acceptable uniform illuminations, with average row and column intensities varying by less than 2.10, 2.11, and 3.06% of the overall intensity means, for the incandescent, halogen, and fluorescent (with or without the light controller) lamps, respectively.
4) Overall, the fluorescent lamp with the light controller gave the best performance, with the lowest sensitivity to lamp voltage variation (0.50% for 1 V variation in the lamp voltage), the smallest intensity variation with time (less than 1.20% over 8 h), and the acceptable uniformity over the FOV (less than 3.06% intensity variation across and down the FOV).

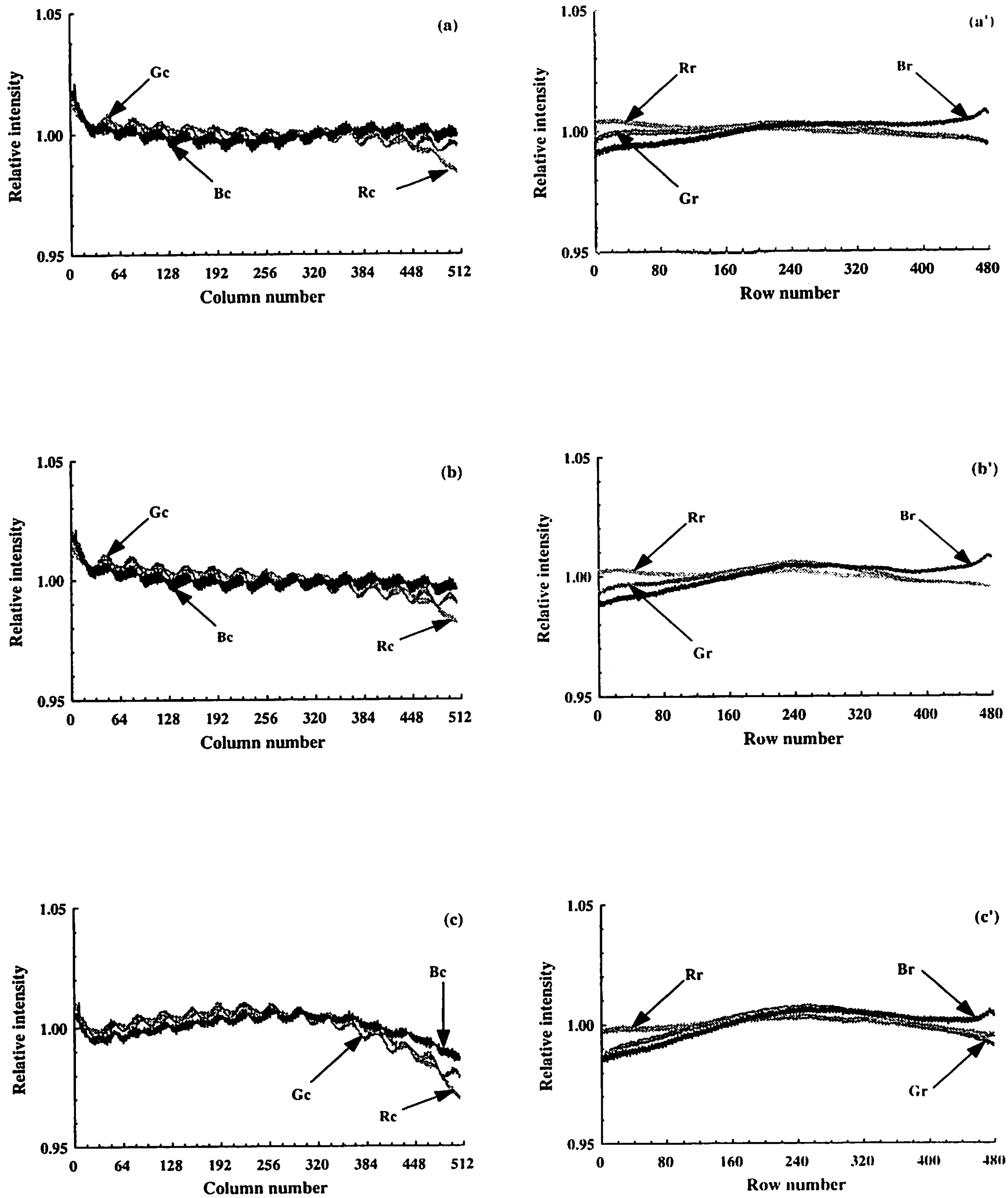

Fig. 4. Illumination uniformities across (column) and down (row) the field of view for incandescent [(a) and (a')], halogen [(b) and (b')], and fluorescent [(c) and (c')] lamps.

ACKNOWLEDGEMENTS

We thank Prince Rupert Grain Ltd., Natural Sciences and Engineering Research Council of Canada, Agriculture and Agri-Food Canada, and University of Manitoba Graduate Fellowship Committee for partial funding of this study.

REFERENCES

Brainard, D.H. and M.B. Wandell. 1990. Calibrated processing of image color. *Color Research and Application* 15(5):266-271.

Gershon, R. and A.P. Jepson. 1989. The computation of color constant descriptors in chromatic images. *Color Research and Application* 14(6):325-334.

Green, R.J. and S.J. Ismail. 1990. Colour error reduction in video systems. *IEEE Transactions on Broadcasting* 36(1):99-107.

Hetzroni, A. and G.E. Miles. 1994. Color calibration for RGB video images. ASAE Paper No. 94-3007. St. Joseph, MI: ASAE.

Lee, Jr. R.L. 1988. Colorimetric calibration of a video digitizing system algorithm and applications. *Color Research and Application* 13(3):180-186.

Paulsen, M.R. and W.F. McClure. 1986. Illumination for computer vision systems. *Transactions of the ASAE* 29(5):1398-1404.

Tominaga, S. 1992. Color classification of natural color images. *Color Research and Application* 17(4):230-239.