DEMOSAICING LOW RESOLUTION QVGA BAYER PATTERN

Tommaso Guseo and Emanuele Menegatti
Intelligent Autonomous Systems Laboratory (IAS-Lab), The University of Padua

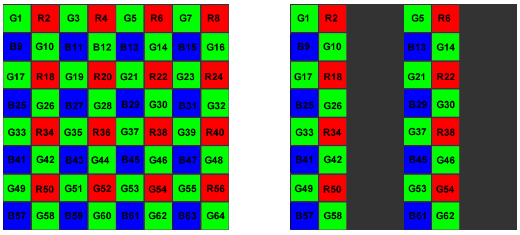
Keywords: Robot vision, demosaicing, QVGA resolution, Bayer pattern.

Abstract: In this paper, we present a solution for the interpolation of low resolution digital images. Many digital cameras can function in two resolution modes: VGA (i.e., 640×480) and QVGA (i.e., 320×240). These cameras use a single sensor covered with a Color Filter Array (CFA). The CFA allows only one color component to be measured at each pixel, the remaining color components must be interpolated, this operation is called demosaicing. There is not a standard way to interpolate the QVGA Bayer pattern and most of the known demosaicing algorithms are not suitable. In this paper, we propose a new solution for the interpolation of QVGA Bayer pattern. Experimental results using digital images and an evaluation function confirm the effectiveness of the interpolation method. The use of the QVGA resolution is important in low-cost and low-power embedded hardware. As an application, we chose the RoboCup domain and in particular our Robovie-M humanoid robot competing in the RoboCup Kid-Size Humanoids League.

1 INTRODUCTION

Color digital cameras are popular today. They can be found also in PDA cellular phone, etc. CMOS digital cameras are more and more often used in autonomous robots to acquire images of the environment surrounding a robot. Most cameras use a single light sensor covered with a Color Filter Array (CFA). The CFA is a colored filter that allows only one color component to be measured at each pixel, the remaining color components must be interpolated: this operation is called demosaicing. Several patterns exist for the CFA, the most common is the Bayer pattern, shown in Fig. 1(a). Many algorithms for demosaicing the Bayer pattern exist in literature. In this paper we focus on low computational cost algorithm that are intended for embedded low power systems. Low cost digital cameras with CFA can acquire images at different resolutions: the most important are high resolution VGA and low resolution QVGA. In low resolution acquisition mode, the Bayer pattern is sampled to reduce the data rate. This reduction is obtained skipping two consecutive columns every four, as shown in Fig. 1(b), obtaining what we call QVGA Bayer pattern. In this paper, we propose a new solution for the interpolation of QVGA Bayer pattern, obtained sampling only columns, based on *periodic reconstruction*. The QVGA resolution is adopted in many devices such as cellular phones and PDAs with inexpensive cameras. The QVGA interpolation algorithm proposed in this paper could also be used to improve the color image acquisition in these handheld devices or for image visualization in small LCDs. We use QVGA low resolution mode in our Kid-Size Humanoid to reduce the data rate and to improve image processing speed, maintaining a large field of view and reducing the resolution. We use QVGA resolution for full field of view and VGA for focalized view reduced to a region of interest of the image, where an object of interest has been detected. We also introduce an evaluation function to compare the different interpolation methods for QVGA; this function shows effectiveness of improvement of quality in interpolation results due to *periodic reconstruction*. The remainder of the paper is organized as follows. In Section 2, we summarize the most common interpolation methods for the Bayer pattern. In Section 3, we present basic interpolation methods for QVGA Bayer pattern and

Guseo T. and Menegatti E. (2007).
DEMOSAICING LOW RESOLUTION QVGA BAYER PATTERN.
In *Proceedings of the Second International Conference on Computer Vision Theory and Applications - IFP/IA*, pages 141-146



(a) VGA mode.

(b) QVGA mode.

Figure 1: Bayer pattern base structure VGA and QVGA mode.

the new one proposed by us. In Section 4 these algorithm are compared using quality evaluation functions.

2 DEMOSAICING BAYER PATTERN

Consider a 2×2 base grid, the Bayer pattern measures the G in two diagonal pixel and the R and B in the others, as shown in Fig. 1(a). The G component is measured twice with respect to R or B because the peak sensitivity of the human visual system lies in the medium wavelengths, corresponding to the G portion of the visible spectrum. The computer vision community has devoted many efforts to the problem of Bayer pattern demosaicing. There are many algorithms to interpolate the Bayer pattern. In this paper, we consider only low computational algorithm. For a comprehensive description of the current state of the art see the work of Gunturk et al. (Gunturk *et al.* (2005)).

The *Nearest Neighbor Replication* method is the simplest algorithm for demosaicing CFA images. It is analyzed in the works of (Parulski (1985)), (Adams and Hamilton (1997)), (Zen *et al.* (1998)) and of (Sakamoto *et al.* (1998)). The algorithm is non–adaptive, i.e. operates in the same way for all pixel of the same components in every images. The value of each interpolated pixel is obtained by copying the value of the nearest pixel in the Bayer pattern image. The nearest pixel can be any one of the pixel in the neighborhood: upper, lower, left and right pixels. This algorithm does not involve any arithmetic operation and therefore this method does not impose a heavy computational cost. However there are many negative aspects: creation of false colors and high chromatic gradient transitions become irregular, this effect is called *zipper effect*.

The *Bilinear Interpolation* is the most used algorithm for demosaicing CFA images. It is analyzed in the works of (Parulski (1985)), (Wu *et al.* (1997)), (Chan *et al.*, 1996), (Tsai *et al.* (1997)), (Zen *et al.* (1998)), (Adams *et al.* (1998)) and also of (Sakamoto *et al.* (1998)). In other works, such as in (Lukin (2004a)). *Bilinear Interpolation* method forms the base for more sophisticated algorithm; in (Malvar (2004)) this method is studied for non–linear interpolation algorithm on rhomboidal grid. The algorithm is non–adaptive. There are two privileged directions (i.e., vertical and horizontal) and pixels are bilinearly interpolated along these directions.

An interpolation algorithm that has good performances in terms of quality of reconstruction is *Linear Interpolation with Laplacian Second–order Correction Terms* that we adopted in our application. The *Linear Interpolation with Laplacian Second–order Correction Terms* is an adaptive algorithm, i.e. it changes the interpolation equation adapting to the image to be interpolated. This algorithm is analyzed in (Hamilton and Adams (1997)) and with modifications in (Adams and Hamilton (1997)) and (Adams *et al.* (1997)). Interpolation of the green component has to be computed before the other components. Consider interpolation of green component in blue pixel, see Fig. 2(a), for example $G5$ in $B5$. Calculate gradient in horizontal (ΔH), and vertical (ΔV) direction

$$\Delta H = |G4-G6|+|B5-B3+B5-B7| \;; \quad (1)$$

$$\Delta V = |G2-G8|+|B5-B1+B5-B9| \;. \quad (2)$$

Then evaluate which interpolation fuction has to be used:

$$\Delta H < \Delta V \quad \rightarrow \quad G5 = \frac{(G4+G6)}{2} + \frac{(2\cdot B5-B3-B7)}{4} \quad (3)$$

$$\Delta H > \Delta V \quad \rightarrow \quad G5 = \frac{(G2+G8)}{2} + \frac{(2\cdot B5-B1-B9)}{4} \quad (4)$$

$$\Delta H = \Delta V \quad \rightarrow \quad G5 = \frac{(G2+G4+G6+G8)}{4} + \quad (5)$$

$$+ \frac{(4\cdot B5-B1-B3-B7-B9)}{8} \;. \quad (6)$$

For red and blue components are possible tree cases, consider Fig. 2(b):

1. interpolate red or blue component in green position when nearest same color components are in the same column. Consider $R4$ in $G4$, interpolation is done with (7)

$$R4 = \frac{(R1+R7)}{2} + \frac{(G4-G1+G4-G7)}{4} \;; \quad (7)$$

2. interpolate red or blue component in green position when nearest same color components are in the same row. Consider $R2$ in $G2$, interpolation is done with (8)

$$R2 = \frac{(R1+R3)}{2} + \frac{(G2-G1+G2-G3)}{4} \;; \quad (8)$$

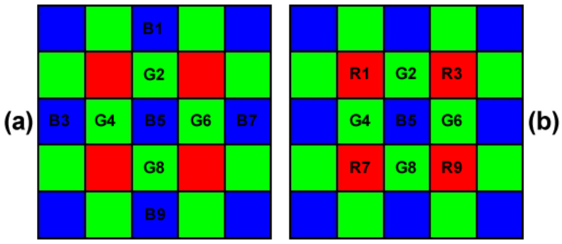


Figure 2: Linear Interpolation with Laplacian Second–order Correction Terms in VGA Bayer pattern.

3. interpolate red or blue component in blue or red position. Consider $R5$ in $B5$. Define diagonal gradient in negative direction ΔN (9) and in positive direction ΔP (10).

$$\Delta N = |R1 - R9| + |G5 - G1 + G5 - G9| \quad (9)$$
$$\Delta P = |R3 - R7| + |G5 - G3 + G5 - G7| \quad (10)$$

Then evaluate which interpolation fuction has to be used:

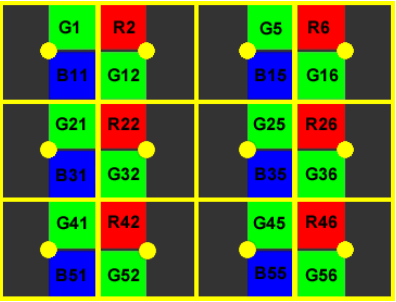
$$\Delta N < \Delta P \quad \rightarrow \quad R5 = \frac{(R1+R9)}{2} + \frac{(2 \cdot G5 - G1 - G9)}{4} \quad ; \quad (11)$$
$$\Delta N > \Delta P \quad \rightarrow \quad R5 = \frac{(R3+R7)}{2} + \frac{(2 \cdot G5 - G3 - G7)}{4} \quad ; \quad (12)$$
$$\Delta N = \Delta P \quad \rightarrow \quad R5 = \frac{(R1+R3+R7+R9)}{4} + \quad (13)$$
$$+ \quad \frac{(4 \cdot G5 - G1 - G3 - G7 - G9)}{8} \quad . \quad (14)$$

3 DEMOSAICING QVGA BAYER PATTERN

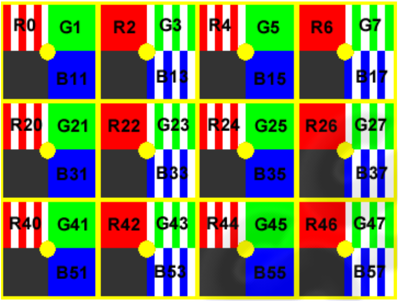
As we already said in the introduction, the QVGA Bayer pattern is obtained sampling the Bayer pattern skipping two columns every four, see Fig. 1(b). To the best of our knowledge, there is not a standard way in literature to interpolate the QVGA Bayer pattern. In this paper we propose a new interpolation method.

The main idea originates from an original work of (Tang and Lee (2004)) about interpolation of classical Bayer pattern. In that work, Tang and Lee proposed a vertex based interpolation method instead of center based interpolation method.

Similarly, we based our interpolation algorithm for QVGA on vertex interpolation mode (i.e. the interpolated pixels are centered on the vertex of the Bayer pixels). This is sketched in Fig. 3(a). The interpolated pixel is the yellow square binding 2x2 Bayer pixels. The yellow dot represents the center of the interpolated pixel. With respect to the VGA Bayer pattern, the QVGA Bayer pattern has the following peculiarities:



(a) QVGA structure.



(b) QVGA periodic reconstruction.

Figure 3: Base structure of QVGA and periodic reconstruction.

1. in each yellow square one color component is missing;
2. the vertical periodicity of the grid is of 2 pixels, while the horizontal is of 4 pixels;
3. in the yellow squares along the same column is missing always the same color component;

In the next paragraphs, we will show how the *Nearest Neighbor Replication* algorithm and the *Bilinear Interpolation* algorithm could be applied to the QVGA Bayer pattern. We will see that both algorithms perform poorly, basically because they do not use a periodic pattern for the color components. We propose a new method called *Periodic Reconstruction Interpolation* in which some of the color components are interpolated to obtain a periodic color pattern, that is equally repeated in every yellow square of the QVGA image, as depicted in Fig. 3(b). Interpolated pixels are always painted with the corresponding color and white bar pattern.

The *Nearest Neighbor Replication* algorithm is the simplest non–adaptive algorithm for demosaicing QVGA images. The green component does not need to be interpolated; every yellow square contains a green pixel of the QVGA Bayer pattern. The red and the blue pixels are obtained by replicating, respectively, the nearest right pixel and the left near-

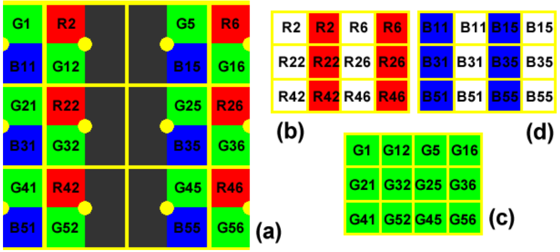


Figure 4: Nearest Neighbor Replication in QVGA Bayer pattern.

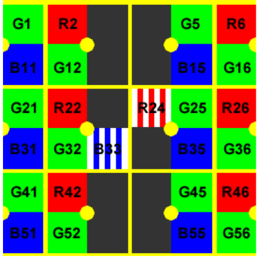


Figure 5: Bilinear interpolation in QVGA Bayer pattern.

est pixel, as shown in Fig. 4. The pros and cons of this method are the same as the algorithm presented in VGA mode: low computational cost, presence of false color and *zipper effect*.

The *Bilinear Interpolation* algorithm is a non–adaptive algorithm for demosaicing QVGA images, that makes an average on vertical and horizontal direction. The green component, as in *Nearest Neighbor Replication* algorithm, is not interpolated. For the interpolation of red and blue components, see Fig. 5, is not possible to have an exactly bilinear interpolation, because the color information in vertical direction is always absent. The interpolation method uses a weighted mean based on the distance. For a red pixel, for example $R24$, the value is obtained with (15)

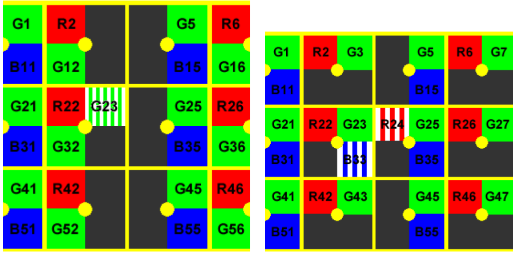
$$R24 = \frac{(4 \cdot R22 + 4 \cdot R26 + 3 \cdot R2 + 3 \cdot R6 + 3 \cdot R42 + 3 \cdot R46)}{20} \quad , \qquad (15)$$

and for a blu pixel, as $B33$, consider Eq. (16)

$$B33 = \frac{(4 \cdot B31 + 4 \cdot B35 + 3 \cdot B11 + 3 \cdot B15 + 3 \cdot B51 + 3 \cdot B55)}{20} \quad . \qquad (16)$$

Unfortunately this algorithm blurs the image by averaging over all pixels without any appropriate weighting. Even this algorithm is affected by the *zipper effect*.

A thorough analysis of the *Nearest Neighbor Replication* and *Bilinear Interpolation* algorithms when used for the interpolation of QVGA Bayer pattern shows that they do not correctly interpolate the green component. This problem arises from the non–periodic interpolation domain (i.e., the distance between two green pixels varies along the grid). This results in a wrong attribution to green components. We propose first to interpolate the green components to construct the periodic grid of Fig. 3(b), from this the name *Periodic Reconstruction Interpolation*, and then to interpolate the red and blue components.



(a) Green. (b) Red and Blue.

Figure 6: Periodic Reconstruction Intepolation in QVGA Bayer pattern.

The green component in every yellow square is obtained as the average of the nearest green Bayer pixels weighted by their distances. As an example consider pixel $G23$, as shown in Figure 6(a). The interpolation is obtained by (17)

$$G23 = \frac{(3 \cdot G21 + 4 \cdot G12 + 4 \cdot G32 + 3 \cdot G25)}{14} \quad . \qquad (17)$$

To limit the low-pass filter effect due to the average operation, we perform it only on pixel closer than two pixels from the interpolation center.

The next step is to create a periodic structure also for these components. Consider Fig. 6(b) where green pixels have been already interpolated by the Eq. (17). We propose an adaptive algorithm for interpolation of red and blue pixels.

Consider red pixel $R24$. We define diagonal gradients in negative direction as ΔN (18) and in positive direction as ΔP (19) and the horizontal gradient as ΔO (20).

$$\Delta N = |R2 - R46| + |G25 - G3 + G25 - G47| \; ; \qquad (18)$$

$$\Delta P = |R6 - R42| + |G25 - G7 + G5 - G43| \; ; \qquad (19)$$

$$\Delta O = |R22 - R26| + |G25 - G23 + G25 - G27| \qquad (20)$$

The value of every interpolated pixel is calculate with Algo 3.1 depending on which of the gradient is maximum. The interpolation of blue pixel is done in the same way.

Algorithm 3.1 QVGA Periodic Reconstruction Interpolation.

```
for all $i$ is pixel has to be interpolated do
    $A = max(\Delta N, \Delta P, \Delta O)$
    if $(A == \Delta N)$ then
        $R24 = \frac{(R2+R46)}{2} + \frac{(2 \cdot G25 - G3 - G47)}{4}$
    else if $(A == \Delta P)$ then
        $R24 = \frac{(R6+R42)}{2} + \frac{(2 \cdot G25 - G7 - G43)}{4}$
    else if $(A == \Delta O)$ then
        $R24 = \frac{(R22+R26)}{2} + \frac{(2 \cdot G25 - G23 - G27)}{4}$
    else
        $R24 = \frac{(4 \cdot R22 + 4 \cdot R26 + 3 \cdot R2 + 3 \cdot R6 + 3 \cdot R42 + 3 \cdot R46)}{20}$
    end if
end for
```

4 ALGORITHM QUALITY EVALUATION

To compare the quality of the images reconstruction with different algorithms, in addition to the visual comparison of the reconstructed images, we use the *dependency index* developed in (Guseo T. (2006)). This index is based on the concept of entropy, see (Guseo R. (2006)).

The original and reconstructed images to be compared has to be considered as a linear array. In bivariate case the dependency index ${}_{P|F}\tilde{D}$ is defined as (21), where P represent the pixel's position in the linear array and F indicates the original and reconstructed image. ${}_{F}H$ and ${}_{P}H$ is denoted the marginal entropy respect figure (F) and position (P), with ${}_{PF}H$ the joined entropy and with ${}_{PF}I$ the information between original and reconstructed figure.

$$ {}_{P|F}\tilde{D} = \frac{{}_{PF}I}{{}_{P}H} = \frac{{}_{F}H + {}_{P}H - {}_{PF}H}{{}_{P}H}. \qquad (21) $$

In the trivariate case, where third qualitative variable is color (C) we consider the *partial dependency index without effect of color* (22)

$$ {}_{P|F}\tilde{D}_C = \frac{{}_{P|C}H - {}_{P|FC}H}{{}_{P|C}H} = \frac{{}_{PC}H - {}_{C}H - {}_{PFC}H + {}_{FC}H}{{}_{PC}H - {}_{C}H}. \qquad (22) $$

The dependency indexes are for construction normalized in the range $[0,1]$. If two images are very similar the dependency index tends to 0.

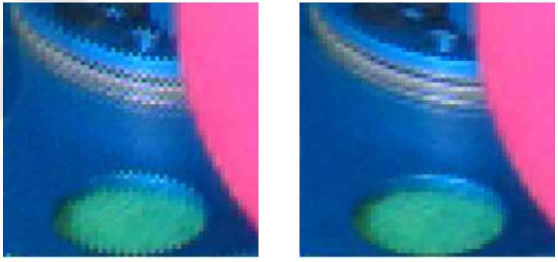
We use dependency indexes ${}_{P|F}\tilde{D}_{(R)}$, ${}_{P|F}\tilde{D}_{(G)}$ and ${}_{P|F}\tilde{D}_{(B)}$ for bivariate case for each single components and ${}_{P|F}\tilde{D}_{(T)}$ for image in all components. We use partial dependency index without effect of color ${}_{P|F}\tilde{D}_C$ for trivariate case.

To assess to interpolation quality of different algorithm proposed, consider the Tab. 1 the which are listed dependency indexes. Periodic Reconstruction has ${}_{P|F}\tilde{D}_{(G)}$ index that is half than other methods. This represent a good improvement in interpolation quality. In Fig. 7 interpolation algorithms have been visually compared . It is visible the presence of *zipper effect* an false colors in Fig. 7(b) and Fig. 7(c) corresponding to *Nearest Neighbor Replication* and *Bilinear Interpolation* alortithm. The Fig. 7(d) obtained with Periodic Reconstruction algorithm has sharp edges and no *zipper effects*.

Table 1: Comparison between interpolation methods on QVGA Bayer pattern, all values are in 10^{-5}.

	Dependency index				
	${}_{P\|F}\tilde{D}_{(R)}$	${}_{P\|F}\tilde{D}_{(G)}$	${}_{P\|F}\tilde{D}_{(B)}$	${}_{P\|F}\tilde{D}_{(T)}$	${}_{P\|F}\tilde{D}_C$
Neighbor	10.4765	5.8445	23.1138	10.2245	11.0308
Bilinear	10.9063	5.8445	22.6590	10.2537	11.0618
Periodic	7.3436	2.4420	15.2124	6.8667	7.5032

(a) Original (b) Neighbor



(c) Bilinear (d) Periodic

Figure 7: Visive comparison between QVGA interpolation methods.

5 CONCLUSION

The use of QVGA format is important in low cost and low computational power systems as embedded PCs, PDAs and cellular phones. In this paper we present a new interpolation method for QVGA Bayer pattern: *Periodic Reconstruction Interpolation*. The improvement of quality of the images reconstructed with proposed method is demonstrated using *dependency indexes*.

The platform on which this method is implemented is Robovie-M by VStone with a Renesas CPU at 40Mhz and a RAM of 256k–Word of 16–bit. The digital camera used is a CMOS camera (an OV3620 by Omnivision). Acquiring the 240 × 240 Bayer pattern with a QVGA resolution and interpolating it with the *Periodic Reconstruction Interpolation*, enables the robot to allocate memory space for three images to be used for image processing operations that cannot be done in place. We reached a performance of 2 fps on the 40Mhz CPU that has also to control 22 motors during image processing time.

At the moment of writing, we are applying the proposed method to omnidirectional images. We are evaluating an extension of *Periodic Reconstruction Interpolation* to other patterns, for example to pattern implemented in STMicroelectronics cameras, obtained skipping also two rows with the same ratio.

REFERENCES

Adams, J.E. and Hamilton, J.F.: Design of practical color filter array interpolation algorithms for digital cameras, *Proceedings of SPIE* **3028** (1997) 117–125.

Adams, J.E. et al.: Adaptive color plane interpolation in single color electronic camera, U.S. Patent 5 506 619 (1997).

Adams, J.E., Parulski, K. and Spaulding, K.: Color Processing in Digital Cameras, *IEEE Transactions on Microeletectronic*, **18 6** (1998) 20–31.

Chan, W. et al.: A Mega-Pixel resolution PC Digital Still Camera, *Proceedings of SPIE*, **2654** (1996) 164–171.

Gunturk, B.K., Glotzbach, J., Altunbasak, Y., Schafer, R.W. and Mersereau, R.M.: Demosaicking: Color Filter Array Interpolation, exploring the imaging process and the correlations among three color planes in single-chip digital cameras, *IEEE Signal Processing Magazine*, **10 53** (2005) January 44–54.

Guseo, R: *Statistica*, terza ediz., Cedam, Padova (2006).

Guseo, T.: *Architettura Software per Robot Umanoide Autonomo*, Tesi di laurea, University of Padova, Padova (2006).

Hamilton, J.F. and Adams, J.E.: Adaptive color plane interpolation in single sensor color electronic camera, U.S. Patent 5 629 734, (1997).

Lukin, A. and Kubasov, D.: An Improved Demosaicing Algorithm, *Graphicon.2004 conference proceedings*, Faculty of Applied Mathematics and Computer Science, State University of Moscow, Russia (2004).

Malvar, H.S., He, L. and Cutler, R.: *High-quality linear interpolation for demosaicing of Bayer-patterned color images*, Microsoft Research One Microsoft Way, Redmond, WA, USA, (2004).

Maris, M.: Attention-based navigation in mobile robots using a reconfigurable sensor, *Robotics and Autonomous Systems*, **34** (2001) 53–63.

Okuno, H.G., Nakadai, K., Lourens, T., Kitano, H.: Sound and Visual Tracking for Humanoid Robot, *Applied Intelligence* **20** (2004) 253–266.

Parulski, K.A.: Color Filters and Processing Alternatives for one-chip cameras, *IEEE Transactions on Electron Devices*, **32 8** (1985) August.

Reece, D.A., Shafer, S.A.: Control of perceptual attention in robot driving, *Artificial Intelligence* **78**, (1995) 397–430.

Sakamoto, Tadashi, et al.: Software pixel interpolation for digital still cameras suitable for a 32-bit MCU, *IEEE Transactions on Consumer Electronics*, **44 4** (1998) November 1342–1352.

Tang, B. and Lee, K.F.: An efficient color image acquisition system for wireless handheld devices, *IEEE ICASSP 2004*, **3** (2004) 105–108, Multimedia Architecture Lab Motorola Labs, Schaumburg, Illinois, USA.

Tsai, Y.T. et al.: Optimized Image Processing Algorithms for a Single Sensor Camera, *IEEE Pacific Rim Conference on Communications, Computers and Signal Processing*, **2** (1997) 1010–1013.

Vijayakumar, S., Conradt J., Shibata, T. e Schaal, S.: Overt Visual Attention for a Humanoid Robot, *Proc. International Conference on Intelligence in Robotics and Autonomous Systems*, IROS (2001).

Wu, X. et al.: Color Restoration from Digital Camera Data by Pattern Matching, *Proceedings of SPIE*, **3018** (1997) April 12–17.

Zen, Hidemori, et al.: A New digital signal processor for progressive scan CCD, *IEEE Transactions on Consumer Electronics*, **44 2** (1998) May 289–295.