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Digital Standards Converter by Adaptive Intra-Frame Line Interpolation

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Abstract—**This paper introduces a new technique for TV standards conversion called "adaptive intra-frame line interpolation". The configuration and the performance of a digital converter developed by using the technique are also described. In the present converter, an input picture is divided into still and moving areas by measuring frame difference signals, and suitable interpolation parameters are adaptively chosen for each area. This method brings good results to both areas. Especially, the converter has enabled the converted picture to recover high vertical resolution of more than 350 TV lines in still pictures, which has never been obtained by any conventional intra-field line interpolation.**

1. INTRODUCTION

The first TV standards conversion was realized with the image transfer method in which a display tube was combined with a camera. Although the structure of this type of converter is quite simple, the converted pictures usually have impairments in the form of blurring or smearing.

All-electronic converters which could convert NTSC into PAL/SECAM and/or vice versa were subsequently developed utilizing sophisticated analog techniques depending on the availability of ultrasonic quartz delay lines.(1)(2)(3) The analog converters of this type substantially improved the quality of converted pictures. However, they still had some inherent shortcomings such as the necessity of delicate adjustments, large size and high cost.

Recent progress in digital technology, particularly in high-speed and high-density memory elements, has made it possible to overcome the problems and has enabled to realize high accuracy conversion. Some digital converters which have been developed so far demonstrate significant performance improvements over the conventional analog converters.(4)(5)(6) For scanning line conversion in the converters, the past developments employed intra-field processing which was similar to the technique used in the analog type of converters. Looking into the possibilities of improving performance of the converters by utilizing more advanced methods, the authors came to a conclusion that intra-frame (inter-field) line interpolation can yield better performance than conventional intra-field proces-

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sing.[7][8] Furthermore, it was revealed that even higher performance may be achieved in this intra-frame line interpolation by introducing an adaptive application of different processings conformed to both still and moving areas of a picture.[9][10] Based on the study described above, a digital TV standards converter employing the adaptive intra-frame line interpolation has been developed.

This paper reports the conclusions of the study to date along with the results of the above development. The basic problems associated with scanning system conversion are discussed first, then the results of study on the line interpolation technique are described. Finally, an adaptive intra-frame line interpolation method is proposed, and the outline of the developed digital converter using the new line interpolation technique is described together with the obtained performance.

2. SCANNING SYSTEM CONVERSION

TV standards conversion consists of conversions of both the color and scanning systems. The former conversion uses well established video processing technology, but the latter conversion still involves some problems. The scanning system is divided into two main procedures, conversion of number of lines per frame (line conversion) and conversion of number of fields per second (field conversion). The scanning systems discussed here are the 525-lines/60-fields system and the 625-lines/50-fields system. Conversion from the former to the latter is called U/C (up-conversion) and the reverse one is D/C (down-conversion).

2.1 Problem Description

The number of effective scanning lines in the 525/60 system is approximately 500 and that of the 625/50 system is 600 excluding a part of vertical blanking lines. So, the simplest conversion of number of lines may be made by repeating one per five input lines for the U/C and by omitting one per six lines in the D/C. This type of conversion brings about bothering serrations on sloping edges of the converted picture. This distortion may considerably be reduced by interpolation technique. Generally, two or more successive lines of an input field are combined to yield an output line (intra-field line interpolation). Linear combination is made with weights varying inversely with the distances between the desired output line and the input lines.

Considering that a frame (or picture) of TV signal consists of two successive interlacing fields, conventional line interpolation utilizing input lines of one field does not seem to be the best choice to produce an output line. It does not use all of the available information because it disregards interlacing lines in the successive field. This is the primary cause of residual distortion on sloping edges and deterioration of resolution especially in a still picture.

The number of fields can also be converted by omitting or repeating input fields cyclically. The omission (U/C) or the repetition (D/C) occurs approximately every 100 ms or 120 ms.[11] Therefore, occasional jumpings or stoppings are observed in picture motion. In order to reduce this jerkiness, adjacent fields may be combined. Though the jerkiness is considerably reduced by this method, further deterioration in resolution is incurred in the case where the intra-field line interpolation is adopted. For, in this case, another line interpolation (interlace line interpolation) is required to set the type of field, odd or even, in advance of the field interpolation. Consequently, four or more input lines must be combined to obtain one output line, and the number of input lines to be combined changes periodically. This causes line flicker on horizontal edges, which further deteriorates the quality of converted pictures.

2.2 Discussions on Linear Interpolation

The line conversion is regarded as resampling of a picture with a different rate of sampling in vertical direction. Let $\{S_i\}$ be the sequence of samples of input signal and a sample to be located between S_0 and S_1 be S as shown in Fig. 1. We calculate the interpolated value for S, denoted by $\hat{S}$, by a linear combination as

$$\hat{S} = \sum_{-n}^{n} w_i S_i \tag{1}$$

where w_i is a weighting factor and $i = 0, \pm 1, \pm 2, \cdots, \pm n$. Mean square error of the difference between S and $\hat{S}$, which is an evaluating factor of the distortion, is given by

$$\overline{\epsilon^2} = E[(S-\hat{S})^2] = E\left[\left(S - \sum_{-n}^{n} w_i S_i\right)^2\right]. \tag{2}$$

Let us determine those values of weights $\{w_i\}$ which give the least mean square error. They are derived solving the following equation,

$$\frac{\partial \overline{\epsilon^2}}{\partial w_k} = E\left[2\left(S - \sum_{-n}^{n} w_i S_i\right) S_k\right] = 0 \tag{3}$$

where $k = 0, \pm 1, \pm 2, \cdots, \pm n$. In typical television signals the autocorrelation shows a very nearly exponential behavior. Therefore, the correlation function of two samples S_i and S_k is given by

$$E(S_i S_k) = \rho^{|i-k|} \sigma^2 \tag{4}$$

where ρ is the correlation coefficient between adjacent samples, and σ^2 is the autocovariance of a sample. As for the correlation function between S and S_k, we find

$$E(SS_k) = \rho^{|a-k|} \sigma^2, \tag{5}$$

where a is the distance between S and S_o. From equations (3), (4), (5), we have

$$\sum_{-n}^{n} w_i \rho^{|i-k|} = \rho^{|a-k|}. \tag{6}$$

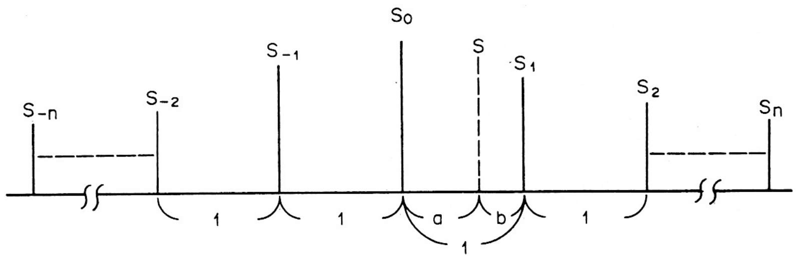


Fig. 1 Sequence of original samples and an interpolated sample.

Solving the above equation for w_i, we obtain

$$\left.\begin{aligned} &w_{-n} = w_{-n+1} = \cdots w_{-1} = 0 \\ &w_n = w_{n-1} = \cdots w_2 = 0 \\ &w_0 = \frac{\rho^a - \rho^{2-a}}{1-\rho^2}, \qquad w_1 = \frac{\rho^{1-a} - \rho^{1+a}}{1-\rho^2}. \end{aligned}\right\} \tag{7}$$

Since the correlation coefficient ρ is close to one, the following relationship is justifiable

$$w_0 \cong b, \qquad w_1 \cong a \tag{8}$$

where $b = 1 - a$. Then, equation (2) is approximated by

$$\overline{\epsilon^2} = 2ab\delta\sigma^2, \tag{9}$$

where $\delta = 1 - \rho$.

As shown above, if the autocorrelation function is of exponential shape, only two neighboring samples are sufficient for linear interpolation. The weighting factor of each sample should be proportional to the inverse of the distance from the point to be interpolated.

2.3 Intra-Frame Line Interpolation

The essential point in scanning system conversion is how to minimize the deterioration of picture quality caused by line and field conversions. If output lines are obtained by combining the adjacent two lines in an input frame, then the distance between the input lines to be combined is reduced to one-half of that in the case of intra-field line interpolation. Therefore, the accuracy of the line interpolation will be considerably improved.

Since the correlation coefficient between the nearest points on the closest lines in a field is ρ, the correlation coefficient of the points on the closest lines in a frame is $\sqrt{\rho}$. Then, in the case of intra-frame line interpolation, equation (10) becomes

$$\overline{\epsilon^2} \cong ab\delta\sigma^2 \tag{10}$$

which is one-half of the value given by equation (9).

Another estimation was given that the equivalent pass bandwidth of the intra-frame line interpolation becomes twice that of the intra-field line interpolation.[8]

Fig. 2 shows the methods of intra-frame line interpolation adopted in this converter. LI_1 illustrates the method in which

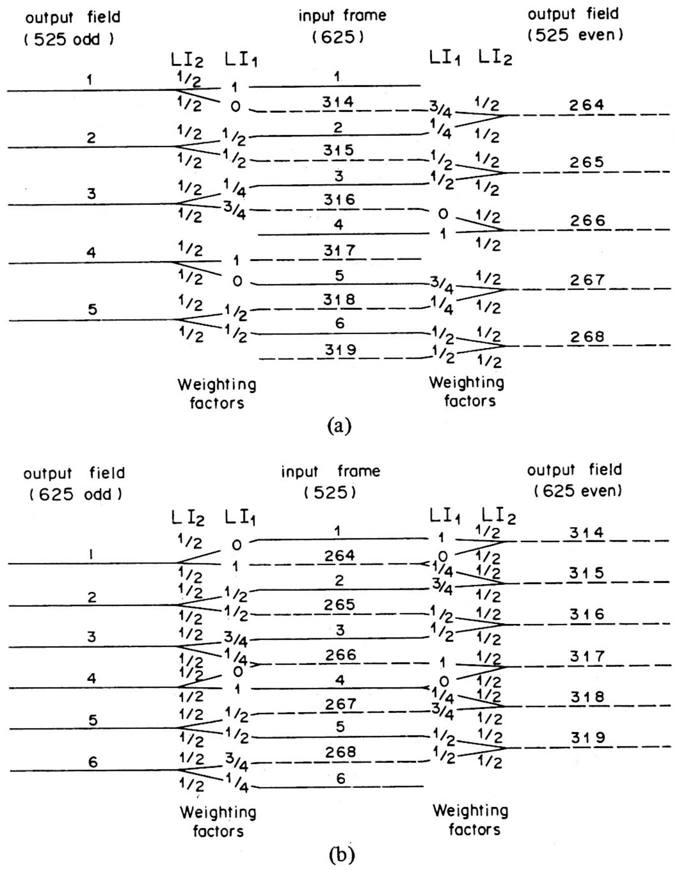
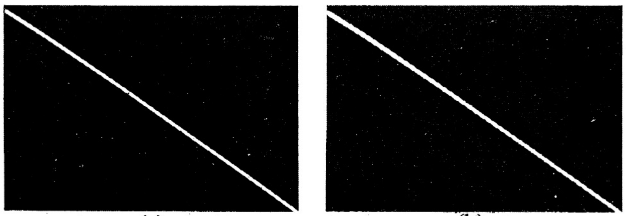


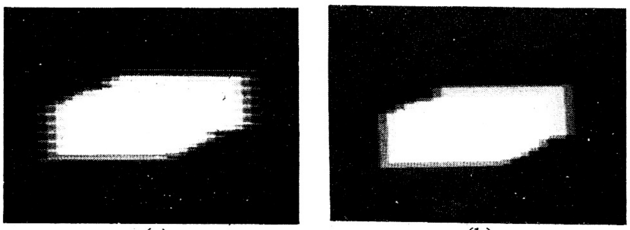
Fig. 2 Intra-frame line interpolation. Weighting factors in LI_1 vary depending on the distance between input and output lines, whereas those in LI_2 are constant. a) Down conversion. b) Up conversion.

two input lines nearest to output lines are weighted depending on the ratio of the distances from each output line with the minimum step size ¼. This step size is accurate enough to represent the ratio of distances.[10] LI_2 represents the method in which all weighting values are fixed at ½. As seen from the figure, these methods enable one to easily produce either odd or even field from an input frame, so the interlace line interpolation procedure previously mentioned may be omitted. Moreover, the adjacent fields which are line converted by these methods are entirely the same for a still picture so that it will be totally free from such degradation caused by the field interpolation as mentioned in 2.1. As a result, the final output lines are synthesized out of at most two lines for still pictures and the details of the pictures are not lost. For moving pictures, the final output line is composed with three different lines extracted from three successive fields. However, there is



(a) (b)

Photo. 1 Converted slant line (625/50 output for 525/60 input. a) Obtained by LI_1 in which weighted factors for interpolation depend on the distances between input and output lines. b) Obtained by LI_2 in which the weighting factors are kept constant.



(a) (b)

Photo. 2 Converted moving window (625/50 output for 525/60 input). a) Obtained by LI_1. b) Obtained by LI_2.

no problem because detail components of TV signal are usually small and the human visual sensitivity is low for moving pictures.

Photo. 1 shows converted pictures of sloping lines obtained by the method LI_1 and LI_2. With LI_1, a perfect straight line is obtained and the deterioration of resolution is hardly observed. With LI_2, the deterioration of resolution is also small, but a slight serration remains. Thus, as far as still pictures are concerned, there is no problem for pictures converted by LI_1, but a noticeable phenomenon appears on the edges of moving objects. Photo. 2 shows a converted picture of a white window which passes along a diagonal line of the screen in two seconds. Vertical edges of the moving window derived by LI_1 are distorted in a teeth-like pattern whose length is proportional to the speed of the motion. This distortion is caused by periodical changes of the weighting values in the vertical direction. This does not appear with LI_2 in which the weighting values of each line are constant.

2.4 Adaptive Intra-Frame Line Interpolation

TV programs include various motions from still to violent, and in most cases they appear in the same scenes. Although LI_1 provides an extremely good result with still pictures, it cannot be applied to moving scenes. On the other hand, LI_2 is inferior to LI_1 for still pictures, but it is acceptable for all kinds of pictures and gives a much better result than the conventional intra-field line interpolation. Thus, adoption of LI_2 may be an effective solution.(8) However, if a picture is divided into still areas and moving areas, and LI_1 can be adaptively applied to the former and LI_2 to the latter, it is possible to fully utilize the advantages of both methods. The authors named this method an "adaptive intra-frame line interpolation."(9)

Moving and still areas of a picture can be separated by detecting frame differences in the manner similar to the inter-frame coding. To perform this operation, a memory to store at least one frame is needed. Since a converter must have at least one frame memory for field conversion, this memory can be used also for that purpose.

3. OPERATION OF THE CONVERTER

3.1 System Design

The important point in implementing a converter is how to design a large capacity memory which can store at least one frame signal. Necessary capacity of the memory depends on a desired conversion process. To realize the adaptive intra-frame line interpolation and field conversion, three field memories (FLMs) are installed in the converter. High-speed and high-density MOS-RAMs are available for composing these memories. Refresh control necessary in the dynamic MOS memory can be easily accomplished by cyclically writing or reading the memory. Therefore, the refresh cycle can be omitted and the effective operating speed of the memory can be accordingly increased.(12)

Color transcoding between NTSC and PAL/SECAM is accomplished by demodulating the incoming composite color signal into luminance and two color difference signals, and by modulating them into the desired color system after scanning system conversion. There are two types of demodulation methods. One uses an ordinary video color decoder, and the other a digital processer. In this converter, the former method is adopted in order to easily cover two-way conversion between NTSC and PAL or SECAM.

3.2 Outline of Operation

A block diagram is shown in Fig. 3. The input composite color signal is divided by the video decoder into a luminance signal Y and two color-difference signals R-Y (or I) and B-Y (or Q), each being digitized by the A-D converter. Each pulse train is multiplexed and written into the FLMs through the buffer memory which is used to avoid simultaneous access of writing and reading, giving priority to the latter. The FLMs can store three fields of Y, R-Y and B-Y, except for their horizontal and vertical blankings. Corresponding signals in the same position of a picture are read out from each field stored in the FLMs in synchronism with the local output synchronous signals. Therefore, the memory cycle of the FLMs is divided into four phases, the first of them is assigned for writing and the other three are for readings. The sampling rate is unchanged throughout the entire conversion process. The difference of line time between input and output signals (about 0.5 μs) is adjusted by curtailing or adding to the horizontal blanking time.

Since the field rates of input and output are different, an overlap of the writing and reading operations sometimes occurs in an FLM. Output from such an FLM should be prohibited since contiguity of the picture is disturbed over the time when the overlap occurs. Therefore, it is arranged that when the overlap is forecasted, no reading takes place from the start to end of the particular field memory. This overlap occurs once per six or seven output fields in D/C and once per five or

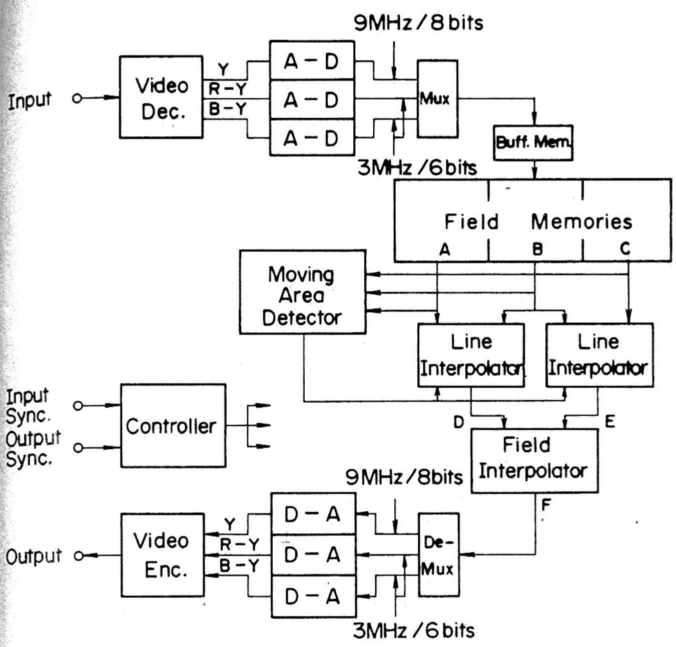


Fig. 3 Simplified block diagram of the digital standards converter by adaptive intra-frame line interpolation.

six output fields in U/C.[11] Two (sometimes one) intermediate fields are derived from three (sometimes two) input fields as shown in Fig. 4a. At this time, the line interpolators are controlled by the moving area detector to work in either the LI_1 or LI_2 interpolation mode.

Field interpolation to smooth picture motion is accomplished by combining two intermediate fields with suitable weights as shown in Fig. 4b. An output from the field interpolator circuit is divided into three parallel signals, Y, R-Y and B-Y. After D-A conversion, they are modulated into a desired composite color signal by a video encoder.

Table 1 shows the main parameters of this converter.

3.3 Moving Area Detector

The moving areas of a picture can be detected by using the frame difference of picture elements. The moving area detector selects two outputs of three FLMs to obtain the frame difference. The following detection algorithm is used to avoid erroneous operation due to noise on the input signal.

Detection algorithm: A picture element is defined as a moving element when its frame difference exceeds a threshold L. If N ($N \leqslant 10$) or more moving elements are counted within ten successive elements, then these ten elements are defined to be a moving area.

Optimum values of detection parameters L and N are closely related to S/N of input signals. Too small L and N will result in erroneous detection of a still area as a moving area for low S/N inputs. On the contrary, large L and N will reduce detection sensitivity and result in teeth-like distortion on edges of a moving object. Solid lines in Fig. 5 show limits to determine whether or not serrated distortion is recognized on the sloping edges of a test pattern. These lines are greatly affected by the S/N of input signals. Combination of L and N values in the region above each curve bring a good result to each input S/N. On the other hand, dotted lines in Fig. 5 show a boundary

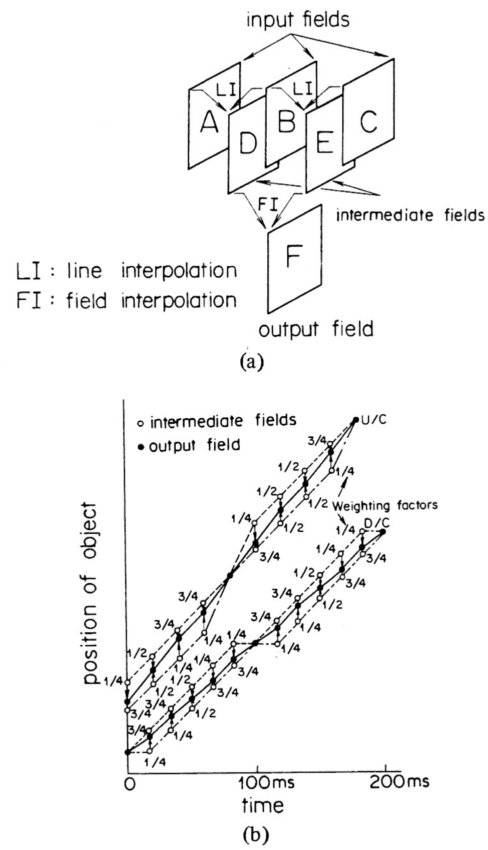


Fig. 4 Reproduction of output field. a) Relationship among input, intermediate and output fields. b) Movements in output picture smoothed by field interpolation.

TABLE 1

Conversion	625/50 ⇄ 525/60		
Video signal	Y	R-Y (I)	B-Y (Q)
Sampling frequency	9 MHz	3 MHz	3 MHz
Number of bits per sample	8 bits	6 bits	6 bits
Number of pel per line	492	164	164
Memory word	216 bits		
Cycle time	500 nsec		
Memory capacity	(8 Kw x 216 bits) x 3		
Memory devices	Dynamic MOS-RAM (1K bits)		

which divides an L-N plane into desirable and undesirable regions for a motion picture. A combination of L and N must be selected in the region below this boundary in order to obtain a good result for the motion picture. The teeth-like distortion can be most sensitively seen when its speed is about w per second, where w is the screen width of a picture monitor. This distortion is hardly affected by the input S/N. From the above results and on the assumption that this converter is used in the INTELSAT system whose S/N is 49 dB (weighted), L

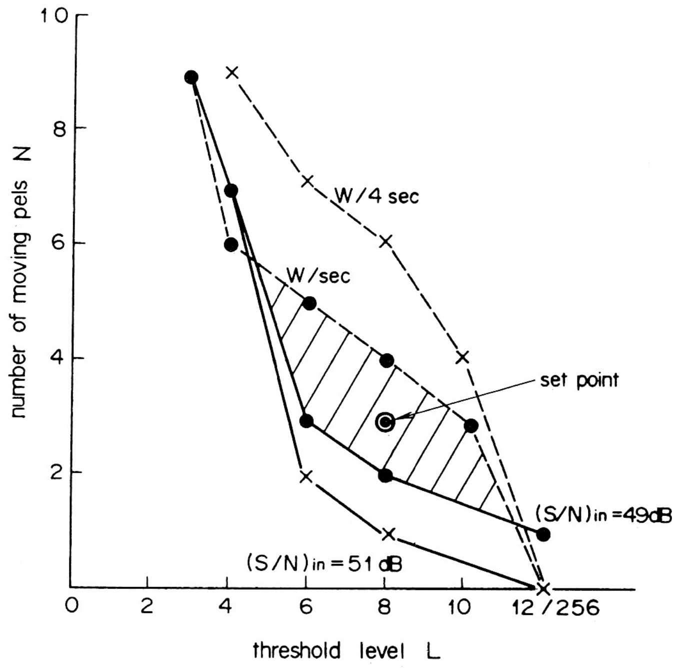


Fig. 5 Area where the values of L and N should be set. Combination of L and N values must be in the area above the rigid curves for still pictures, and it must be in the area below the dotted curves for moving pictures. Consequently, the combination must be set in the hatched area.

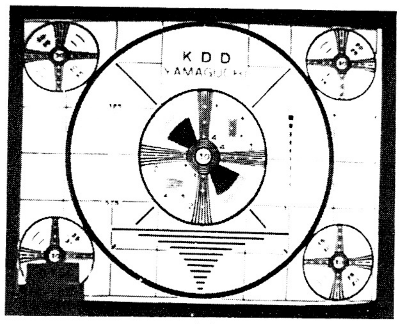
and N are determined: L is $1/2^5$ of the peak video value and N is 3 as shown in Fig. 5.

4. PICTURE QUALITY

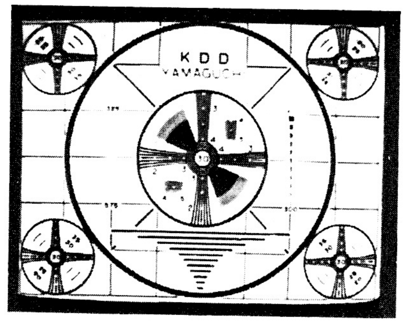
Photos. 3 through 5 show converted pictures of test patterns and moving objects in TV broadcast programs. For the test patterns, the line interpolation is accomplished only by LI_1 in adaptive operation. Therefore, in Photos. 3a and 4a, serrated distortion on the sloping edges and moiré do not appear, whereas they are observed in Photos. 3b and 4b by the LI_2. The recovered vertical resolution is more than 350 TV lines, which has never been obtained by conventional intra-field interpolation. This is the most essential effect of the intra-frame line interpolation. Although the horizontal resolution is a little less than the vertical one, it can be improved by increasing the sampling frequency of input signal if desired. For motion pictures, the teeth-like distortion which can be seen in Photo. 5a disappears in Photo. 5b. Thus, the effect of the adaptive operation is remarkable. Moreover, as was expected, the line flicker on horizontal edges of the picture produced by the conventional intra-field line interpolation are hardly visible in this system.

Since the frame difference signal for moving area detection is obtained only from the luminance signal, the moving area cannot be detected for a signal which has a frame difference only in the color components. Such a signal, however, seems to exist very rarely. Therefore, it poses no problem practically.

Subjective tests of the converted pictures were conducted. Twenty-six observers were experts who were working (or had

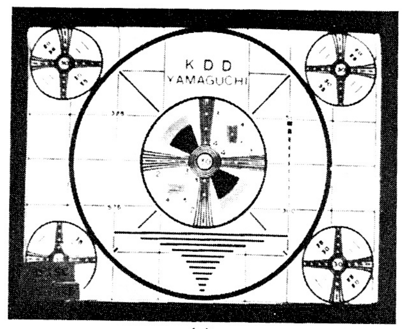


(a)

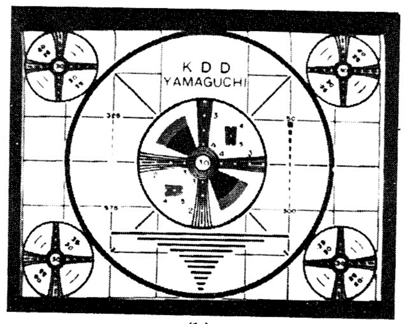


(b)

Photo. 3 Converted test pattern (625/50 output for 525/60 input). a) Obtained by the adaptive operation. b) Obtained by LI_2.

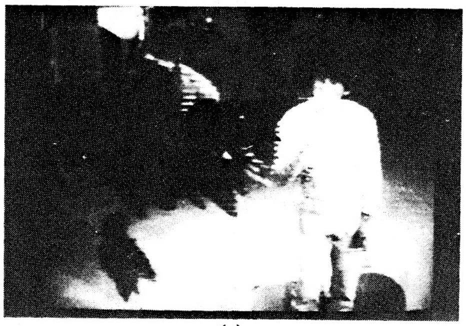


(a)

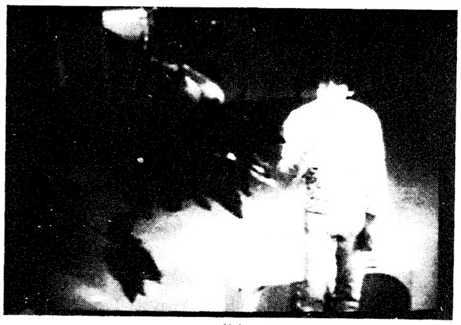


(b)

Photo. 4 Converted test pattern (525/60 output for 625/50 input). a) Obtained by the adaptive operation. b) Obtained by LI_2.



(a)



(b)

Photo. 5 Converted moving objects (625/50 output for 525/60 input). a) Obtained by LI_1. b) Obtained by the adaptive operation.

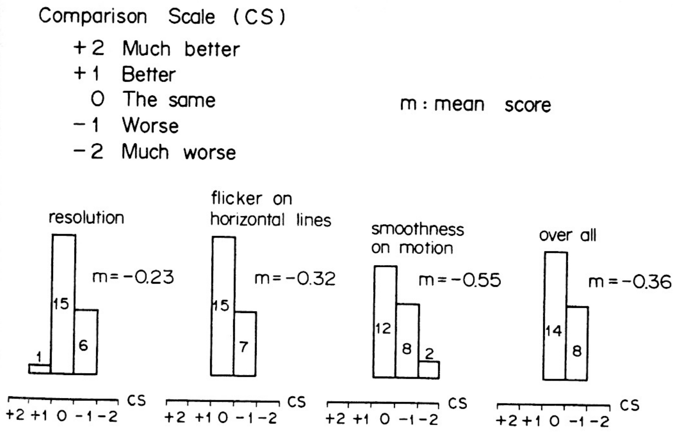


Fig. 6 Results of subjective assessment test for conversion from NTSC to PAL. Actual TV programs (singing and dancing) were used as test data.

worked) in earth stations of satellite communication systems. The evaluation scale and observation conditions were based on the C.C.I.R. Recommendation 500. Fig. 6 shows an evaluation of a PAL picture converted from a NTSC picture. We can conclude from this result that the degree of deterioration by the present converter is, totally, less than 0.5 in five grades.(10)

5. CONCLUSIONS

A digital TV standards converter which utilizes an adaptive intra-frame line interpolation has been described.

The experimental model of the converter, which was developed in April 1974,(8) was improved for practical use and put into field trial for one year. The test results indicate that well-trained observers can hardly recognize the residual distortion of sloping edges or line flicker on the horizontal edges in a still picture. The intra-frame line interpolation method has remarkably enabled the converter to recover high vertical resolution of more than 350 TV lines. Since March 1977, the converter has been put in commercial use for the INTELSAT TV link.

The converter is made up of three racks: the digital processing and control rack, FLM rack and the monitoring rack. The memory devices used for these FLMs are 1 kbit dynamic MOS-RAM. Nowadays, however, the development of 16 kbit or 64 kbit memory devices has made it possible to compact the whole converter into a small rack if desired.

By using the frame memory in common, the standards converter can effectively be integrated with other digital processing for TV signals such as frame-to-frame coding, frame synchronizing, or noise reduction.

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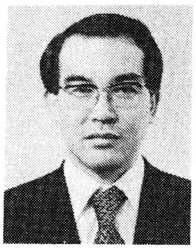

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