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On a Motion Analysis Process for Image Sequences from Real World Scenes

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ON A MOTION ANALYSIS PROCESS FOR IMAGE SEQUENCES FROM REAL WORLD SCENES

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Abstract

Interest in the analysis of image sequences developed only quite recently. In their survey of work on dynamic scene analysis Martin and Aggarwal [1] differentiate between three processes, the motion detection process, the attentive process, and the cognitive process. We present an algorithm for the motion detection and the attentive process, working with image sequences from a real world scene. This algorithm does not only provide an estimate for images of moving objects. In addition, it accumulates evidence for the image of stationary scene components. We start from the assumption that the first frame represents the stationary scene component. Once it has been recognized that a subarea of this initial estimate corresponds to a moving object, the greyvalues in this subarea are replaced by later estimates of the stationary background at this position. No knowledge specific to a particular scene is utilized in the algorithm. The results for three scene sequences are presented in detail and the applicability of this algorithm is discussed.

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1. Introduction

Image analysis concentrated up to now mostly on single images or the comparison of image pairs. Interest in the analysis of extended image sequences from other than special application areas like cloud motion detection [2] or heartcycle x-ray films [3-5] developed only quite recently. In their survey of work on dynamic scene analysis, Martin and Aggarwal [1] differentiate between three processes - the "peripheral vision" or motion detection process, the attentive process and the cognitive process. The first of these processes identifies areas in the field of view with persistent changes from frame to frame, so-called nonstationary image components. The second process focusses attention onto one of such image areas in order to investigate it in more detail. The third process relates the observations derived from this subimage sequence to system internal knowledge about the section of the real world covered by the field of view.

Our work is pursued in the context of an attempt to derive scene specific knowledge about a real world scene (its moving objects as well as the stationary fore- and background) using only the TV-frame sequence as input together with a scene-independent knowledge base [6] .

In this paper we present an algorithm for the motion detection and attentive processes in the analysis of a real world scene sequence. This algorithm detects a nonstationary image component as soon as an object image is displaced by a few pixels from its position in the reference frame which initially is taken to be the first frame. After the object image has been totally displaced from its position in the reference frame, the algorithm modifies the reference frame by substituting the greyvalue characteristics of the background from the current frame for those pixels which were occupied by the object image in the reference frame. The remaining nonstationary image component is assumed to correspond to the image of a moving object and a greyvalue representation for this object image may be extracted. In the time interval - time being represented here by framenumber - between the motion detection and the extraction of a greyvalue representation, the algorithm is able to estimate the rate and direction of displacement for a nonstationary image component as well as its size. The algorithm may act on the images of more than one moving object within an image sequence simultaneously as long as the nonstationary image components associated with different objects do not merge. If the image sequence is long enough, greyvalue characteristics of stationary background may be substituted for the images of all moving objects appearing in the first frame - thus rendering the reference frame independent from the particular configuration of moving objects in the first frame of a sequence. Once a greyvalue representation for an object image has been extracted the algorithm may focus attention to this object image.

Earlier stages of development for this algorithm have been reported in [7,8].

2. Active FODP Regions and Their Properties

The signal of a B/W-TV-camera is recorded at our laboratory in real time on an analog TV-disk. Subsequently each TV-frame on the analog disk can be selected under computer control and digitized into 573 rows with 512 columns at 8 bit greylevel resolution. These raw data are condensed into 96x128 pixels by computing the mean and variance for each subarray of four consecutive columns in three consecutive rows of digitizings from one halfframe. Only digitizings from one halfframe (field) are used. Otherwise the images of faster moving objects may show a significant displacement in successive rows taken from the two interlaced fields of a full TV-frame - thus introducing an additional variance into the sample. For every TV-frame in the sequence, each pixel is compared to the data of the first condensed frame at the same pixel coordinates by means of the following likelihood ratio

$$\frac{\left(\frac{s_{first} + s_{current}}{2} + \left(\frac{m_{first} - m_{current}}{2} \right)^2 \right)^2}{s_{first} \cdot s_{current}} \qquad (1)$$

m and s denote the mean greyvalue and its variance for the measurements from the first and the current condensed frame at this pixel position. This expression is formed in analogy to one given by Yakimovsky [9] to determine whether two neighbouring test areas can be thought of being measurements from identical or from differing normal distributions for greylevels. Here, the measurements are not taken from two neighbouring areas of the same TV-frame but rather from the same area of two TV-frames to be compared - an idea which comes quite natural when working with the Yakimovsky algorithm on sequences of TV-frames [10,11]. The numerator corresponds to the square of the variance for the sample formed by combining the measurements from the first and the current frame at this rasterposition. We substitute a minimum value of 20 for all variances that appear in equation (1) to account for the noise in the TV-signal input to the ADC. This approach has been shown to yield good results [7] with the same threshold t for this likelihood ratio at all TV-frame sequences processed so far.

If the likelihood ratio equals or exceeds the chosen threshold t, it is decided to attribute the measurements for this pixel of the current frame to a different normal greylevel distribution than that of the first frame. This is called a "mismatch". An accumulative "difference picture" with 96x128 positions is generated which is referred to in the following under the name "First Order Difference Picture" or FODP. Each position contains the number of mismatches between the reference frame (initially the first condensed frame) and the second frame up to the current frame. A group of at least N 4-connected entries in the difference picture is denoted "active region". Figs. 1a and 1b show two frames of a sequence and fig. 2 shows the FODP generated from the first five frames of this sequence. The following parameter values have been used during the analysis of all TV-frame sequences. The threshold t in equation (1) has been set to 4.0. The minimum number N of pixels constituting a FODP-region has been chosen to be 10. This corresponds to 10*24 = 240 raw TV-data pixels or about 0.1 % of an entire TV-frame. Previous investigations have shown that the mismatch results are insensitive to the precise choice of the threshold t if a lower bound of 20 is placed on all three variances appearing in equation (1).

In order to find a possible relationship between the changes in the TV-frame sequence from a scene and the entries in the corresponding FODP, let us consider an idealized situation. A homogeneous rectangular object is moving with constant velocity parallel to the image plane, in the direction of scan lines, before a homogeneous background differing significantly in greylevel from the object. Due to the displacement of the object, part of the background which was open to the camera till the previous frame is covered by the front end of the object. On the other hand part of the background which till the previous frame was covered by the object is uncovered at the rear end of the object. This covering and uncovering of background components by object components results in nonzero entries in the difference picture. Let us consider figs. 3a-d and let the TV-frames be numbered from 0 onwards, the reference frame being the 0th frame. Now after the 1st frame there will be "1" entries in the difference picture towards the rear and the front end of the object due to uncovering and covering, respectively, of background by the object. Since the object motion is assumed to be unidirectional, after the 2nd frame 1 entries become 2 and new 1 entries are generated due to further uncovering and covering of background by the object. The 3rd frame results in updating of 1s to 2s, 2s to 3s and generation of new 1s. This process continues until the object image has moved over a distance D equivalent to the diameter of its projection along the direction of displacement in the image plane. After the object has moved over this distance D, new 1 entries will result only at the front end of the object, since the trailing edge of the object henceforth only uncovers background previously covered by the leading edge of the object. Before the object has moved over this distance D there are two clusters of nonzero entries in the difference picture. When the object image has been displaced by this distance D, these two clusters will merge and form a single region. The entries in the FODP at those pixel positions where the object was in the first frame and at those pixel positions where the object is in the current frame will keep increasing with increasing number of frames. In between the entries will remain constant at those pixel positions where the object has been in some intermediate frame but was neither there in the first nor is there in the current. This situation is shown in fig. 4i. In the present case of motion along the scan lines, the entries of a row in a cluster will form a monotonic sequence. These entries show decreasing values in the direction of displacement of the object image. If the object image is moving in the direction perpendicular to the scan lines in the image plane, then the monotonicity in the entries of an active region will be along columns. If the object image is moving obliquely to the scan lines then the monotonicity in the entries of the active region resulting from this motion will be along rows as well as along columns.

In real world scene sequences a moving object may be of arbitrary shape, having many different greylevel regions, and may be accompanied by a shadow, moving in any possible direction, occluding (and getting occluded by) other moving objects. Due to motion in varying directions, the shape and size of the object image may change. It seems that even in such complex situations an approximate idea about the object and its motion may be formed by observing the active regions of a difference picture. If an object does not change its direction of motion abruptly - which is the case with most of the real world objects - then the active regions in a difference picture have the following properties:

(i) The cluster of nonzero entries in a difference picture will increase in the direction of image displacement as more frames are observed.

(ii) A row or a column of this cluster may contain one or more monotonically increasing or decreasing sequence of entries.

(iii) If a moving object corresponds to more than just a few neighbouring pixels then its motion may result in more than one active region within the difference picture. All these active regions will have merged together by additional mismatches after the object image has been displaced by its extension D along the direction of displacement.

(iv) After the object image has moved over the distance D, there will be only one active region for this object. This active region may be considered to consist of three subregions:

a) The subregion where the object was located in the first frame. The location, size, and shape of this subregion will remain the same for subsequent difference pictures.

b) The subregion where the object is located in the current frame.

c) The subregion where the object has been during its course of motion but neither was there in the first frame, nor is there in the current frame.

The mismatch entries in the subregions a) and b) will keep increasing with increase in number of observed frames , but in the subregion c) the number of mismatch entries at each pixel will remain constant and only the size of this subregion will continue to grow with further TV-frames.

As a preliminary filter mechanism against mismatch entries due to noise we reject an FODP-entry which has no 8-connected neighbours for the current frame and where no mismatches at all are observed in a 3-by-3 square centered at the corresponding position for the preceding and the following frame.

3. Computation of Active FODP Region Descriptors

The properties of a region are chosen to be based on the properties of individual rows and columns of the region [12]. In this report - unless otherwise stated - AND, OR, and NOT will be used as in fuzzy set theory [13], i.e.

$$A \text{ AND } B = \text{MIN}\,[\,A,\ B]$$

$$A \text{ OR } B = \text{MAX}\,[\,A,\ B]$$

$$\text{NOT}\,(A) = 1.0 - A$$

$$A \;¤\; B = A + B - A * B$$

Let a sequence which may be a row or a column of an active region be represented as a[1] , a[2] , ... , a[n] . It is assumed that this sequence is a row or a column of an active region whose leading and trailing zeros have been suppressed. For this sequence the following quantities are computed:

a) ASC and DESC denoting the number of ascending and descending subsequences; LASC[I] and LDESC[I] denoting the lengths of the Ith ascending and descending subsequence, respectively.

Constant terms are not allowed to break the monotonicity of a sequence. In the present implementation it is decided that if a constant subsequence appears at the start or end of an ascending or descending subsequence, this constant subsequence is merged with the ascending or the descending subsequence. Ascending and descending subsequences are evaluated independently from each other. Therefore, a single FODP-entry or a constant subsequence may appear simultaneously at the end of an ascending and at the start of a descending subsequence or vice versa. Let us consider a sequence

1 2 3 4 4 4 5 6 6 7 6 6 6 5 4 3 3 2 7 5 4

The first ascending subsequence in the above sequence is 1 2 3 4 4 4 5 6 6 7. The first descending subsequence is 7 6 6 6 5 4 3 3 2 and a second descending subsequence is 7 5 4 . These conventions are illustrated using the above sequence for which we now have: ASC=1 , LASC[1]=10 , DESC=2 , LDESC[1]=9 , LDESC[2]=3.

b) In the sequence 2 3 0 0 2 4 5 0 6 4 2 there are two gaps (a subsequence of zero entries) having lengths 2 and 1. The number of gaps and their lengths will be denoted by GAP and LGAP[I], respectively.

c) The average difference in successive entries of ascending and descending subsequences is denoted by FDA and FDD, respectively.

On the basis of the above variables the following properties of a sequence are computed. Each individual sequence within the region under consideration is classified as ascending if it contains more ascending than descending subsequences, it is classified as descending if the opposite condition prevails, and it is classified as nonmonotonous if the numbers of ascending and descending subsequences equal each other or no such subsequences have been detected. The value of F1

F1 = (ABS(ASC-DESC) / (ASC+DESC))**K1 .... (2)

depends on the difference in numbers of ascending and descending subsequences. This difference is taken as an approximate measure for the monotonicity of a sequence. If a sequence has at most a few short gaps then this will result in high values of FILL defined as

FILL = F2 AND F3 .... (3)

with

F2 = (1.0 + GAP)**(-K2) .... (4)

F3 = ((LASC[I] + LDESC[I]) / LENGTH)**K3 .... (5)

The constants in equations (2) - (5) have been set to :

K1 = 1 ; K2 = 0.5 ; K3 = 1 .

As a measure of confidence in the values of F1 and FILL for a sequence, the variable CON is set to FA

FA = Max(LASC[I] / LENGTH) .... (6)

for an ascending sequence, it is set to FD

FD = Max(LDESC[I] / LENGTH) .... (7)

for a descending sequence, and it is set to zero otherwise.

The following properties will be computed for a region on the basis of its sequence properties in horizontal (from rows) and vertical (from columns) directions.

MONOTONICITY: A function similar to F1 is used to measure the MONOTONICITY of the region. At a positive value of MONOTONICITY, the region is labelled as ascending, whereas a negative value will result in a descending label. The MONOTONICITY of an active region gives the direction of displacement of the image. Normally for an object all sequences of the active region should show monotonicity in the same direction, resulting in a high value of MONOTONICITY for this region. A small value of MONOTONICITY for an active region indicates that there might be high noise in the picture or that the active region is due to two overlapping objects moving in different directions.

A small value of MONOTONICITY for an active region may also be due to drastic changes in the direction of motion of an object. In such a situation, individual rows (or columns) may have high monotonicity but in different directions, resulting in a small value of MONOTONICITY for the active region. Under the premise that moving objects do not change their direction of motion abruptly , the spatial distribution of new mismatches within an active region should reflect the separation between original and current object position when subareas of an active region show markedly differing MONOTONICITY. As will be seen later, such a situation is properly identified and handled.

FILLNESS: Taken as the average FILL of sequences. FILLNESS will be high if number and lengths of the gaps in an active region are small. A high value of FILLNESS for an active region indicates either that this region is one of the two image regions corresponding to the rear and front end of a fairly homogeneous moving object, or that the image of the object responsible for this region has been displaced by its projected diameter D. For a nonhomogeneous moving object there will be several active regions, which may join each other much before the object image is displaced by the distance D. In such a situation, the FILLNESS of the region - resulting from a merger of two or more regions - may be poor. One may find some exceptions to this conclusion , but in most cases the above observation will hold.

VEL: Let us consider two ascending sequences:

S1: 1 2 3 4 5 6

S2: 2 4 6 8 10 12

The sequence S1 is from an active region which is due to an object image being displaced to the left by one pixel from frame to frame. If the image is displaced by one pixel during the interval of two frames then the active region will show a sequence S2. Thus, the difference between the successive entries of an active region is the inverse of the rate of displacement of the object image expressed in terms of pixels per frame. This property allows to estimate the rate of displacement for the image of a moving object causing this region. If the region is labelled as an ascending region then VEL is taken as the average FDA; if the region is labelled as descending then VEL is taken as the average FDD.

CONF: If MONOTONICITY is greater than 0.5, CONF is taken as the average CON of the sequences, otherwise this measure of confidence in active region descriptors is set to zero.

CONF represents the confidence in the estimates based on the above mentioned properties. The low values of MONOTONICITY may be due to inconsistency in the nature of individual sequences of the region. This inconsistency could have been caused by high noise and hence the above sequence properties may not be expected to result in good estimates for MONOTONICITY, FILLNESS, and VEL for such an active FODP-region. CONF may also be low if the sequences of the active region contain many subsequences such that no single sequence is long in comparison to the length of the entire sequence. This situation indicates the presence of nonhomogeneous or nonrigid objects. No good estimates may be obtained in this situation and hence due care should be taken when hypothesizing on the basis of such property values for an active region.

In the following sections, MONOTONICITY, FILLNESS, VEL, and CONF of a region in horizontal and vertical directions are represented by using H_, and V_, respectively, as a prefix to the property names.

4. SODP Region Properties

In the preceding section we discussed some properties of the FODP which are useful for estimating attribute values of a nonstationary image component and its displacement characteristics. The FODP contains a high amount of information since it represents the mismatch history of pixels.

In addition to the FODP, a so-called "Second Order Difference Picture" (SODP) is derived for each frame after the second one. A SODP for the nth (n > 2) frame is a binary picture having 1 entries in only those pixel positions where the difference pictures obtained for the (n-1)th and nth frame have different entries. A set of 4-connected "1" entries in the SODP is called a SODP-region. Analysis of SODP-regions associated with an active FODP-region may yield important clues for identifying the different subregions of a FODP-region discussed in paragraph (iv) of section 2.

Let us consider figs. 4. Fig. 4a shows an object image in the reference frame and fig. 4b some frames later. The FODP- and SODP-regions due to this displacement of the object image are given in figs. 4c and 4d , respectively. Fig. 4h shows the object image after it has been displaced by a distance greater than its D with figs. 4i and 4j representing the associated FODP- and SODP-region. It has been explained in section 2 that in an ideal case initially there are two regions due to the displacement of the object image. For both these FODP-regions there will be corresponding regions in the SODP. As the displacement of the object image increases, the size of these FODP- and SODP-regions also increases. After the object image is displaced by its distance D, both these FODP-regions join and henceforth there is only one FODP-region. However, there will be two SODP regions; one will be at the reference frame position of the object image and another at the current frame position of the object image. The SODP-region at the reference frame position of the object image neither increases its size nor changes its position as more frames are observed. The SODP-region at the current frame position of the object image changes its size, shape and location according to the current size, shape and position of the object image. Since the high recording rate of TV-frames justifies the assumption of only small changes in the image of a moving object from frame to frame, the SODP-region corresponding to the object image in the current frame will change its size only slowly. In general the changes in SODP-region size during the building-up phase will be larger than after the moment where the object image has been displaced by its projected diameter D along the direction of displacement. We assign different names to these different SODP-regions: the growing region due to covering of background by the object image is called an 'object-growing' or O_GROW region. The growing region due to uncovering of background by the object is called a 'background-growing' or B_GROW region. The region at the reference frame position of the object image after the object image has been displaced by a distance greater than D is called a STATIC region; and the SODP-region at the current frame position of the object image - after the object image has been displaced by a distance greater than D - is called a MOBILE region.

To see an additional advantage of being able to classify a SODP-region into one of these four categories, let us consider the situation shown in figs. 5a-d. Here two object images of width L, 01 and 02, are displaced by d raster units in the same direction from a position corresponding to fig. 5a into a position corresponding to fig. 5b. The resulting FODP-regions R1 through R4 for these object images are given in fig. 5c. FODP-region R2 is about to merge with R3 and similarly FODP-region R3 with R4. Since regions R3 and R4 are due to the same object, their merging is not problematic for the algorithm; this situation has been discussed already. However, joining of the regions R2 and R3 will result in a single FODP-region for images of two different objects which were never touching or occluding each other in the real world scene. This may complicate the analysis since the estimates derived from this FODP-region may not be consistent. Thus, if possible, such merging of FODP-regions due to images of different objects should be prevented. If we substitute the greyvalues for the background from the current frame and reinitialize the FODP-pixels corresponding to region R3 then the problem may be solved since region R3 is due to uncovering of background. Correct classification of SODP-regions S1 through S4 (see fig. 5d) associated with FODP-regions R1 through R4 , respectively, will allow to detect a situation like the one shown in fig. 5c. In order to classify SODP-regions into the above four categories we exploit the following observation. If the contour of an SODP-region coincides with the contour of an object image in the reference frame then this SODP-region will belong to the categories B_GROW or STATIC. If , however , the contour of a SODP-region coincides with the contour of an object image in the current frame then this SODP-region belongs to the categories O_GROW or MOBILE. It should be mentioned that this observation allows to differentiate between O_GROW and MOBILE regions on the one hand and B_GROW as well as STATIC regions on the other hand. In fact, this is the distinction desired since an O_GROW region subsequently becomes a MOBILE region and a B_GROW region subsequently becomes STATIC.

A likelihood ratio analogous to (1) is used to decide wether there is an edge between neighbouring pixels from the same condensed frame (either in the reference frame or in the current frame) where one pixel has a rasterposition just under the contour of a SODP-region and the other pixel is its neighbour just outside the SODP-region. The ratio of edge length - i.e. number of edges between neighbouring pixels - for a SODP-region in the current frame to the edge length for this same SODP-region determined for the reference frame is denoted by CURREF. Consider region S2 of fig. 5d. This SODP-region of category O_GROW has an edge length (L + 2d) in the current frame whereas in the reference frame this region has an edge length L, resulting in a value of

$$\mathrm{CURREF} = (L + 2d) / L .$$

For a B-GROW region like S1 this ratio can be seen to result in

$$\mathrm{CURREF} = L / (L + 2d) .$$

After the object image O1 has been displaced by its projected diameter D, this ratio for a STATIC SODP region will be

$$CURREF = 0 / (2L + 2D)$$

and for a MOBILE SODP-region this ratio will be

$$CURREF = (2L + 2D) / 0 .$$

Thus the value of CURREF for an O_GROW region is expected to be greater than 1. For B_GROW regions it will be smaller than 1. For MOBILE regions it will be very much higher than 1 and for STATIC regions very much smaller than 1. Moreover, the size of SODP-regions in the categories STATIC and MOBILE will remain almost constant as more frames are observed. The sizes of O_GROW and B_GROW regions, however, will be increasing. The appendix indicates a set of functions formulated in an attempt to compute SODP-region attributes that correspond to these observations. Although results obtained with these functions generally support our hypotheses, alternative forms and the choice of parameters have still to be investigated in more detail.

When a FODP-region has grown to the stage where its SODP-region is about to split into a STATIC and a MOBILE subregion the 4-connection between these two subregions may depend only on a few entries. In order to postpone a - maybe due to noise slightly premature - splitting of a SODP-region we attach all groups of 4-connected SODP-entries that do not exceed the SODP-region threshold (currently set to the same value N = 10 chosen for FODP-regions) to 8-connected neighbouring SODP-regions which have already passed that threshold.

5. Estimation of Nonstationary Image Components and Their Displacement per Frame

Starting with the third frame, the following procedure is repeated for each subsequent frame . The active regions of the FODP are found. A set called ACTSET is formed which initially includes all active FODP-regions in this frame. For each active region in ACTSET, the number of related regions of 4-connected entries in the SODP is determined. If both H_FILLNESS and V_FILLNESS for an active FODP-region exceed a FILLNESS threshold (currently chosen as 0.75) and if there are exactly two SODP-regions for this active FODP-region then it is concluded that the nonstationary image component has been displaced by more than its projected diameter D. If these conditions are satisfied the first time for an active FODP-region, the details of this active FODP-region and of both SODP-regions are entered into a list of objects denoted as OBJ_LIST. Using the displacement direction derived from

MONOTONICITY it is estimated which of the two SODP regions corresponds to the current position and which to the reference frame position of the nonstationary object image. The O_GROW and B_GROW attributes could be used to confirm this estimate although it has not yet been done for the experiments reported in section 6 . If this FODP-region had already been entered previously into the OBJ_LIST then these estimates are updated.

Once all entries in ACTSET have been treated in this manner the OBJ_LIST is examined. An OBJECT_CONFIDENCE is determined based upon the following consideration. The number SIM of pixels in the intersection of the STATIC SODP-regions from the preceding and the current frame is counted for this object. Likewise the number NONSIM of pixels is counted where these STATIC SODP-regions do not overlap. Then the similarity between these two STATIC SODP-regions is defined as (SODP-regions of size 1 contribute two counts to NONSIM if they do not overlap, but only one count to SIM if they overlap)

SIMIL_STATIC = 2 * SIM / (2*SIM + NONSIM) .

If SIMIL_STATIC exceeds the value 0.7, a value SIMIL_MOBILE is determined analogously for the MOBILE SODP-regions from the preceding and the current frame for this object. These two similarity estimates are combined to yield

SIMIL = SIMIL_STATIC AND SIMIL_MOBILE .

Based on this similarity measurement the OBJECT_CONFIDENCE - initialized to zero when an object is detected - will be updated according to

OBJECT_CONFIDENCE(current) =
OBJECT_CONFIDENCE(previous) # SIMIL .

If this OBJECT_CONFIDENCE exceeds a threshold currently set at 0.95 - i.e. if sufficient confidence has been gained in the estimates for any nonstationary image component - then the reference frame is modified at the original position of this nonstationary image component. The greyvalues and their variances for pixels in the reference frame corresponding to this nonstationary image component are replaced by greyvalue characteristics of corresponding pixels from the current frame. The mismatch count in the FODP is reset to zero for each pixel position of the nonstationary image component where greyvalues of the current frame are substituted into the reference frame.

The above procedure gives us the initial and current positions of nonstationary image components and the paths of all nonstationary image components that have been displaced by at least their projected diameter D. It also yields approximate horizontal and vertical displacement estimates per frame for each nonstationary image component.

6. Results

The algorithm discussed in the preceding sections has been implemented as a PASCAL program for a DECSystem KI-10. This program has been applied to several TV-frame sequences from downtown street intersections with moving cars and pedestrians. Results from our experiments with three sequences are presented here.

Three frames out of 26 frames from sequence A are shown in figs. 1a-c reproduced from raw digitizings by a facsimilewriter interfaced to our laboratory computer-network [14]. Fig. 6a presents a greyvalue reproduction of the condensed reference frame obtained from the TV-frame depicted in fig. 1a. After having processed the 9th frame the bright moving car in the center of this picture sequence is detected as an object. Figs. 7 show the FODP and SODP at this stage. After having processed two additional frames, enough confidence has been gained to modify the reference frame. The result is given in fig. 6b. This happens prematurely since parts of the moving object's image remain at its initial position. As will be seen, this premature decision is corrected later on automatically. After the 16th frame the pedestrian southwest of the car in the center is recognized as an object - see figs. 8 - and the reference frame is modified after having processed frame 18. Figs. 9 present the FODP and the SODP at this stage and fig. 6c shows a pictorial representation of the reference frame after substitution of background greyvalues at the initial position of the pedestrian. As can be seen in figs. 8 the partial substitution of background greyvalues at the initial position of the car results in continuing accumulation of mismatch entries which are recognized as a STATIC SODP-region after frame 18 has been processed - see fig. 9 . Two frames later the reference frame is updated at the remaining pixels of the original car position, resulting in fig. 6d.

The premature modification of the reference frame can be avoided by raising the FILLNESS threshold from 0.75 to 0.88. Everything else equal this will postpone the detection of this object until after frame 13 has been processed. The reference frame will then be modified after frame 15. Figs. 10 show the FODP and the SODP corresponding to this stage after frame 15. Using this higher FILLNESS threshold will lead to correct detection of the pedestrian after having processed the 16th frame - i.e. at the same frame as with the lower FILLNESS threshold. However, such a high value for the FILLNESS threshold prevented the correct detection of the moving object in series B. Therefore, all frames have been processed with the somewhat smaller value of 0.75 .

It should be pointed out that the moving car at the center of these TV-frames is slightly occluded in its initial position by another - turning - car that slowed down to let the pedestrian pass.

Other cars and pedestrians have not been analysed in the same manner since the number of frames is not sufficiently large to observe the displacement of these objects by more than their projected length D along the direction of displacement. It should be noted that all these other objects are highly nonhomogeneous and are moving almost perpendicular to the line of sight.

30 frames of sequence B - see fig. 11 - have been processed. In this sequence a car is turning right. The car is partially occluded by a tree during the observed frames. Fig. 12a presents the FODP after 18 frames of this sequence have been processed and fig. 12b presents the corresponding SODP. It can be seen that a single SODP-entry still establishes the 4-connection between the two SODP-subregions corresponding to the initial and the current position of the car image. After having processed frame 19 of this sequence this SODP-region splits apart and the resulting STATIC and MOBILE SODP-regions are accepted by the algorithm as the initial and current position of the moving object's image. After two additional frames the reference frame is modified at those pixels corresponding to the STATIC SODP-region. Fig. 13a presents the reference frame before and fig. 13b after this modification. Fig. 14a shows the FODP after having processed the 22nd frame of this sequence and fig. 14b the associated SODP.

Once the separation of subregions corresponding to type a) and b) of section 2 (iv) has been verified in the SODP, these separated subregions in the SODP may be treated as a mask to obtain a greyvalue representation for the nonstationary image component from the initial and the current TV-frame. Fig. 15a presents a greyvalue representation extracted from the corresponding frame at the locations of nonzero SODP-region entries shortly before the STATIC and MOBILE SODP-subregions separate and fig. 15b shows the greyvalue representation of the object image corresponding to the MOBILE SODP-region after separation. As can be seen, the shadow is considered part of the moving object since its image is displaced together with the object image. These masks can subsequently be used to determine the greyvalues of the object image from different frames. Even if neither of these masks and their corresponding greyvalue images are individually a satisfactory representation of the object image, taken together they may provide enough information to refine the coarse descriptions obtained from an individual frame.

The sequence C represents a complex situation - see fig. 16. The motion of the objects at the street intersection could not be properly analysed by the present algorithm. The main reason for the failure of the current version of our algorithm to cope with these events at the street intersection is the absence of any knowledge about occlusion of moving objects . There are three cars (two of which are of the same greyvalue) and a pedestrian crossing at the street intersection and partially occluding each other within 30 frames or 1.2 seconds realtime .

7. Discussion

Results similar to those for series A and B have been obtained for two other TV-frame sequences from street intersections. Taken together, these results indicate that this approach may allow to extract images of moving objects from real world TV-frame sequences based solely on the assumption that compact objects are displaced smoothly in front of a sufficiently contrasting background. The incorporation of this approach into a more comprehensive system [6] is currently being implemented.

Further research is required to investigate alternative formulations for computing some of the FODP- and SODP-region attributes and to study the influence of the various parameters used in their computation. The essential parameters of our approach as it has been reported here are the mismatch threshold t , the minimum value for the variances used in equation (1) , the minimum acceptable size for FODP- and SODP-regions, the FILLNESS threshold and the OBJECT_CONFIDENCE threshold. Among these five parameters the FILLNESS and the OBJECT_CONFIDENCE thresholds as well as their associated concepts need more attention. Such investigations require extensive experiments with larger sequences of TV-frames. The resulting bottleneck in processing capacity is likely to be felt for any approach to detailed understanding of image sequences.

In our first approach [7] we continuously updated the estimate of the reference frame by incorporating data that had been judged compatible with the reference data. Our current version only modifies the reference frame at those rasterpositions where it has been explicitly decided to replace a region considered to be the image of a moving object in the reference frame.

The evaluation of greyvalue differences between TV-frames in order to classify different observed change characteristics can be refined. Further work in this direction will be necessary to cover the ground between two extreme approaches: on the one hand observing changes in isolated small image areas which are subsequently aggregated into groups - see also [15]; on the other hand first segmenting each image frame, with subsequent - symbolic - change analysis on the basis of resulting segments. Recent results for this latter approach have been reported in [11 , 16 , 17 , 18].

The last remark regards the required processing time. We need about 60 seconds CPU-time for the KI-10 to process an entire raw digitized TV-frame with about 300 KBytes which is recorded within 40 msec real-time. The PASCAL-program is executed with runtime checks and other debugging aids. No effort has been spent yet on identifying the bottlenecks and optimizing these parts, e.g. by coding them in assembler language. Depending on the point of view, this processing time can be considered as being still three orders of magnitude beyond real-time processing or as an encouraging step towards realtime motion analysis .

8. Appendix

The following functions are used for assigning labels to a given SODP-region :

$$\text{O\_GROW} = ((\text{CURREF}-1)/20)**0.25 \tag{8}$$

$$\text{B\_GROW} = (1-\text{CURREF})**0.5 \tag{9}$$

If the size of the SODP-region has not changed by more than 10 percent then

$$\text{STATIC} = (1-\text{CURREF}) \tag{10}$$

$$\text{MOBILE} = (\ (\text{CURREF}-1)\ /\ 20\ )**0.5 \tag{11}$$

Otherwise

$$\text{STATIC} = 0 \text{ and } \text{MOBILE} = 0 \tag{12}$$

Negative values for any of the above functions are replaced by zero.

So far , the value of each property for a SODP-region is computed on the basis of only one frame. In order to incorporate past values it is decided that in the nth frame the property P(n) will be taken to be

$$P(n) = (P(n-1)*0.75)\ ¤\ P \tag{13}$$

where P(n-1) is a property in the (n-1)th frame and P is the corresponding property computed using above functions from the current frame.

In order to prevent the merging of FODP-regions corresponding to images from two different objects, the following procedure is applied. Using the location and velocity estimates of FODP-regions from the current frame it is predicted whether a FODP-region trailing another FODP-region might catch up and merge with the leading FODP-region in the next frame. For this purpose it is determined whether the O_GROW value of the trailing FODP-region exceeds its B_GROW value and the B_GROW value of the leading FODP-region exceeds its O_GROW value. If both these relations turn out to be satisfied, it is assumed that a configuration corresponding to the example of fig. 5 in the latter part of section 4 prevails: the image of a new object is about to cover the area occupied by the image of a different moving object in the reference frame. In this case the pixels corresponding to the image of the moving object in the reference frame are replaced by pixels representing background in the current frame just before the new object image shifts into this area. The corresponding entries in the FODP are reset to zero.

9. Acknowledgement

The financial support of the Deutsche Akademische Austauschdienst (DAAD) and the Hansische Universitaets-Stiftung to the first author is gratefully acknowledged, so is the help of Mrs. and Mr. Schenkel in implementing part of the algorithm, and Mrs. R. Jancke in the preparation of the manuscript for this report. We thank especially B. Neumann and B. Radig for many fruitful discussions about the evaluation of image sequences and their comments on a draft version of this report. Moreover, they provided - together with H. Kemen and L. Dreschler - the facilities to generate greyvalue reproductions of intermediate and final results on a digital display and on a facsimilewriter which proved very advantageous during the final phases of this investigation.

10. References

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11. Figure Captions

Fig. 1: Frame 90 (fig. 1a), 94 (fig. 1b), and 114 (fig. 1c) from the TV-frame sequence A consisting of frames 90 through 115. It represents a street intersection with traffic.

Fig. 2: The difference picture FODP up and including frame 94, with frame 90 as the reference frame for sequence A.

Fig. 3: aa', bb', cc', and dd' represent the successive positions of a moving object image in the 0th, 1st, 2nd, and 3rd frame respectively. The numbers above the leading and trailing part of the moving object image indicate the number of mismatches determined after comparing the 1st, 2nd, 3rd, frame with the 0th frame.

Fig. 4a: Object image in the reference frame.

Figs. 4b, 4c, 4d: Object image, FODP, and SODP after a few frames.

Figs. 4e, 4f, 4g: Object image, FODP, and SODP, respectively, after the object image has been displaced exactly by its diameter D projected onto the direction of displacement .

Figs. 4h, 4i, 4j: Object image, FODP, and SODP, respectively, after the object image has been displaced by more than its diameter D projected onto the direction of displacement .

Fig. 5a and 5b: Two object images, O1 and O2, moving in the same direction.

Fig. 5c: FODP for object images O1 and O2 after a few frames. The FODP-regions R2 and R3 may join after a few more frames, so do R3 and R4.

Fig. 5d: SODP-regions corresponding to this situation.

Fig. 5e: Superposition of SODP-region S1 and S2 with the object image in the reference frame position. Heavy edges indicate where SODP-region boundaries coincide with edges of the object image.

Fig. 5f: Superposition of SODP-region S1 and S2 with the object image in the current frame position.

Fig. 6 : Greyvalue representation of the condensed reference frame for series A at different stages of the analysis. (a) the initial frame - see fig. 1a - in condensed form ; (b) after - premature - modification at the initial position of the bright moving car in the center ; (c) after substituting background greyvalues at the initial position of the pedestrian southwest from this car ; (d) after clearing up the remaining pixels left over from incomplete substitution of background greyvalues at the original position of the moving car in the center .

Fig. 7 : The FODP (a) and the SODP (b) after having processed the 9th frame of series A. The object corresponding to the car in the center has been detected at this frame.

Fig. 8 : FODP (a) and SODP (b) after 16th frame of series A. First detection of the object corresponding to the pedestrian southwest of the bright car in the center. Note how some mismatch entries accumulate at the incompletely modified original position of the moving car at the center.

Fig. 9: FODP (a) and SODP (b) after the 18th frame of series A. The incompletely modified reference frame area is recognized as a STATIC SODP-region at this stage.

Fig. 10 : FODP (a) and SODP (b) after having processed 15 frames of series A with increased FILLNESS threshold of 0.88 . This postpones the detection of the object corresponding to the car at the center until its image has been completely displaced from the position occupied in the first frame of this series. The STATIC and MOBILE SODP-regions in fig. 10b clearly show the shape of the moving car.

Fig. 11: Frame 435 (a) and 461 (b) from the TV-frame sequence B representing a right turning van. This sequence starts with frame 433 . 30 frames of this sequence have been processed.

Fig. 12 : The FODP (a) and SODP (b) for the sequence B after 18 frames of this sequence have been analysed. The image of the turning van has been displaced almost by its distance D.

Fig. 13 : Greyvalue representation of the reference frame for series B before (a) and after (b) the reference frame has been modified by substituting greyvalues from the background of frame 21 at the initial position of the image of the moving van.

Fig. 14: FODP (a) and SODP (b) after having processed 22 frames of series B, i.e. one frame after the replacement of the van image at the original position in the reference frame.

Fig. 15 : Greyvalue representation of the van image shortly before (a) and after (b) it has been detected as the image of a moving object.

Fig. 16 : Frame 10 (a), frame 26 (b), and frame 40 (c) from the TV-frame sequence C representing a complex scene at a street intersection.

BILD. 090 Series A

Fig. 1a

BILD. 094 Series A

Fig. 1b

25TH FRAME OF SERIES A **BILD.114** Series A

Fig 1c

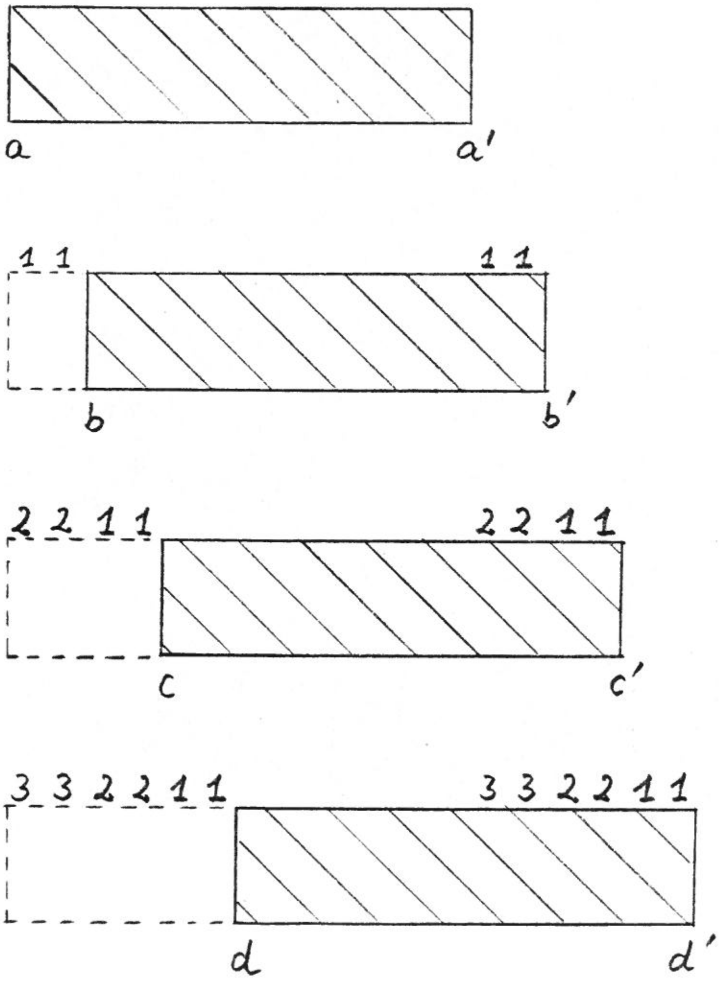
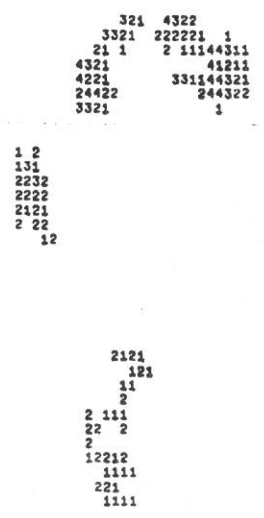


Fig. 3



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         21 1    2 11144311
       4321           41211
       4221       331144321
       24422         244322
       3321            1

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2232
2222
2121
2 22
   12

           2121
             121
            11
            2
        2 111
        22  2
        2
        12212
          1111
         221
          1111
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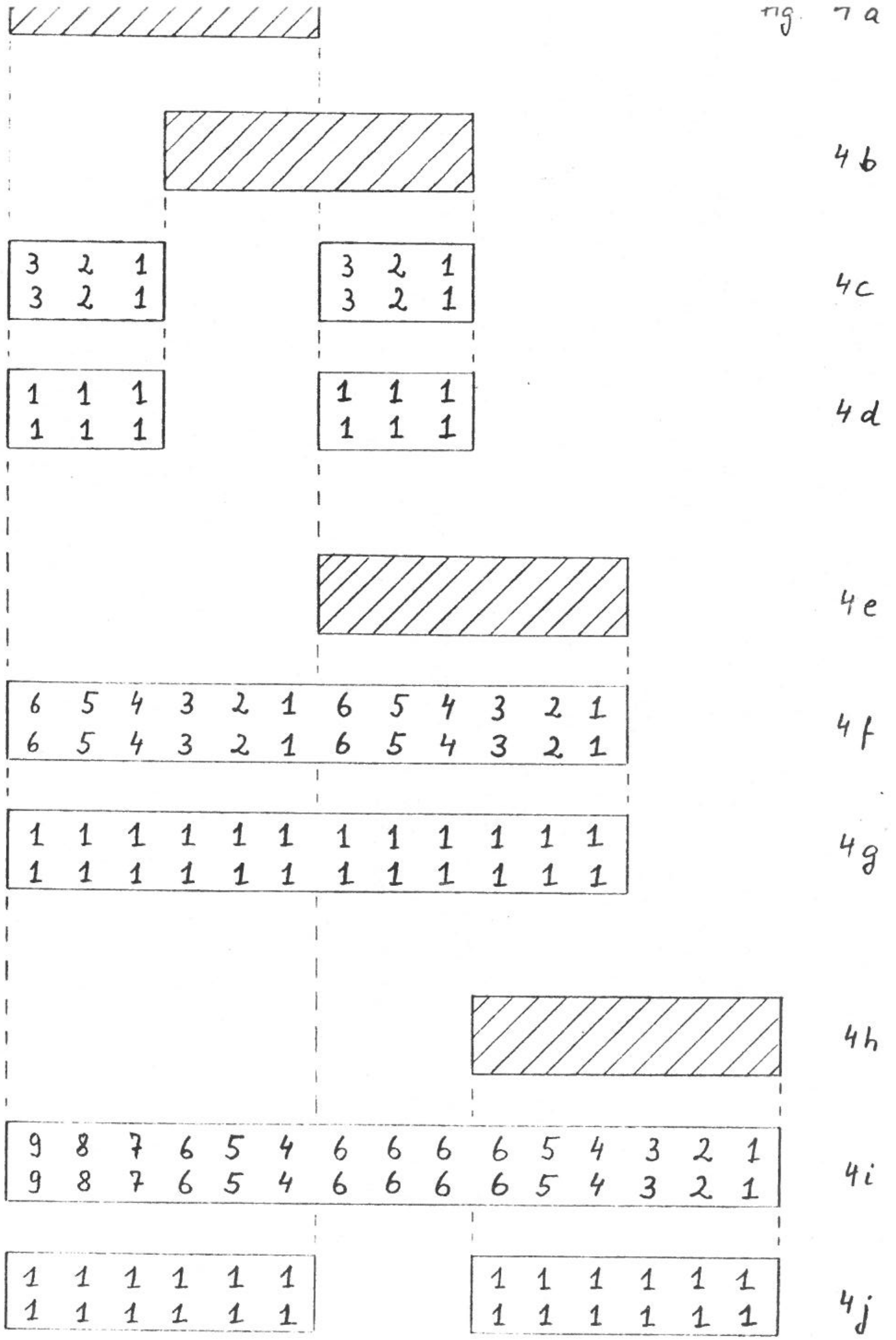
CPU-ZEIT FUER DRUCKEN DER FOOP-BEREICHE   6.86 S

Fig. 2



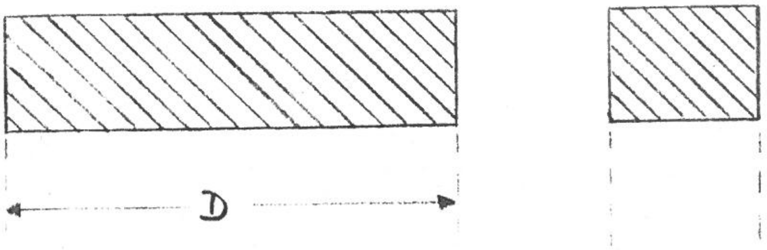
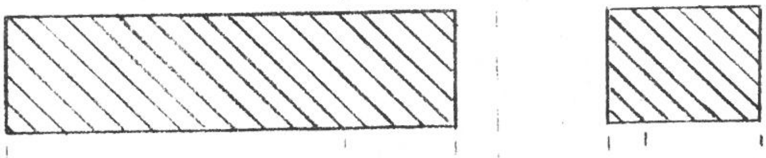
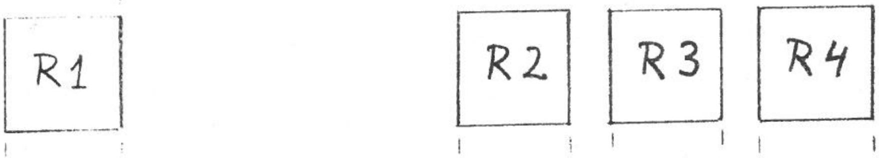


Fig. 5a



5b



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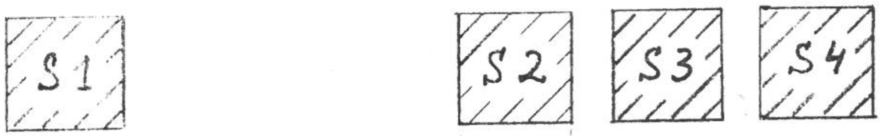

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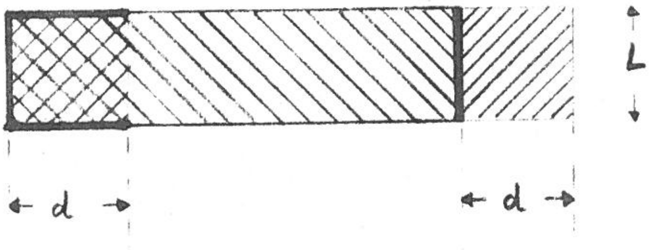

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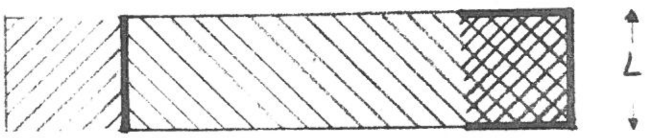


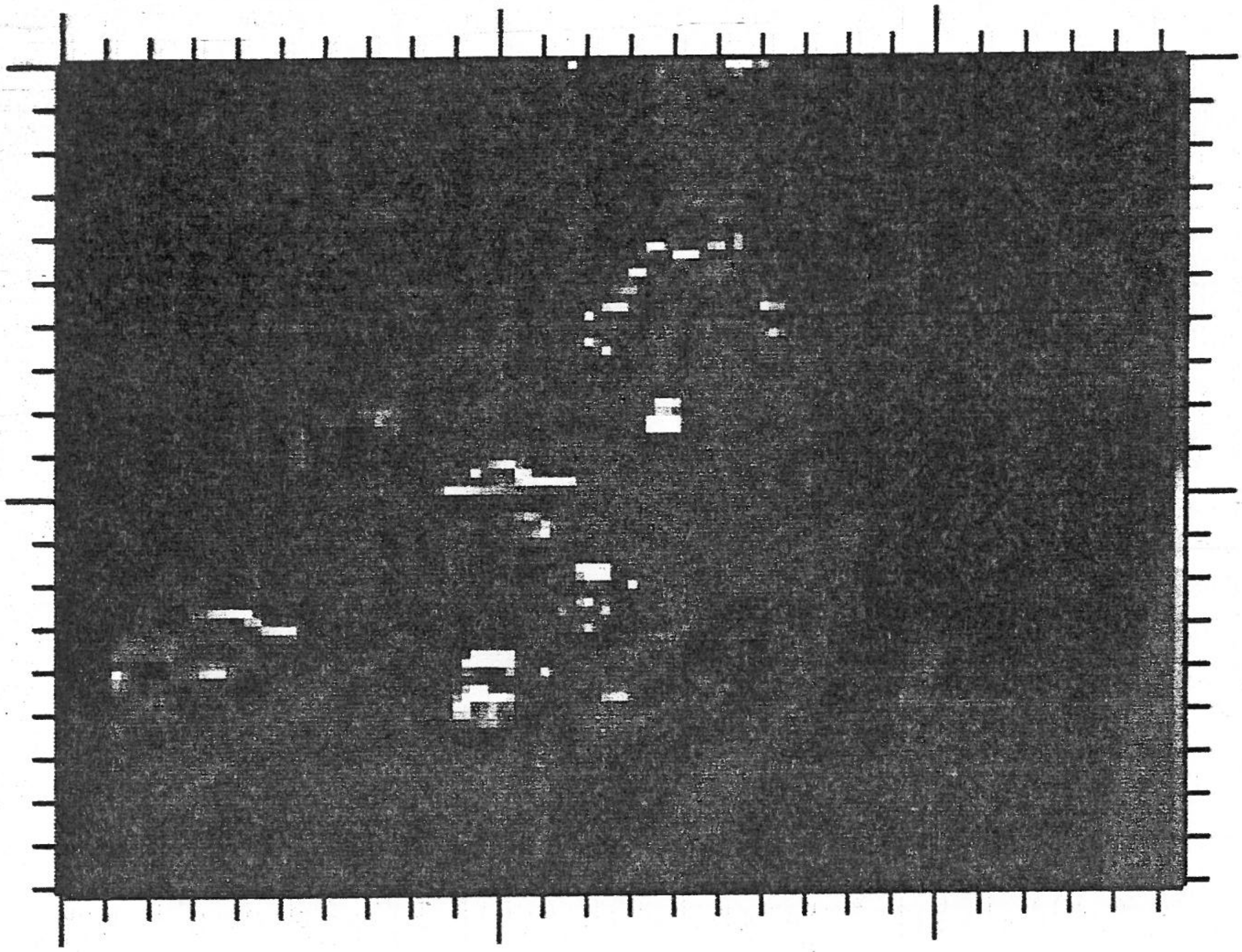
5f

REFERENCE PICTURE OF SERIES A : MODIFIED AFTER 18TH FRAME

Fig. 6c

REFERENCE FRAME OF SERIES A : MODIFIED AFTER 20TH FRAME

Fig. 6d



REFERENCE PICTURE OF SERIES A : INITIAL FRAME

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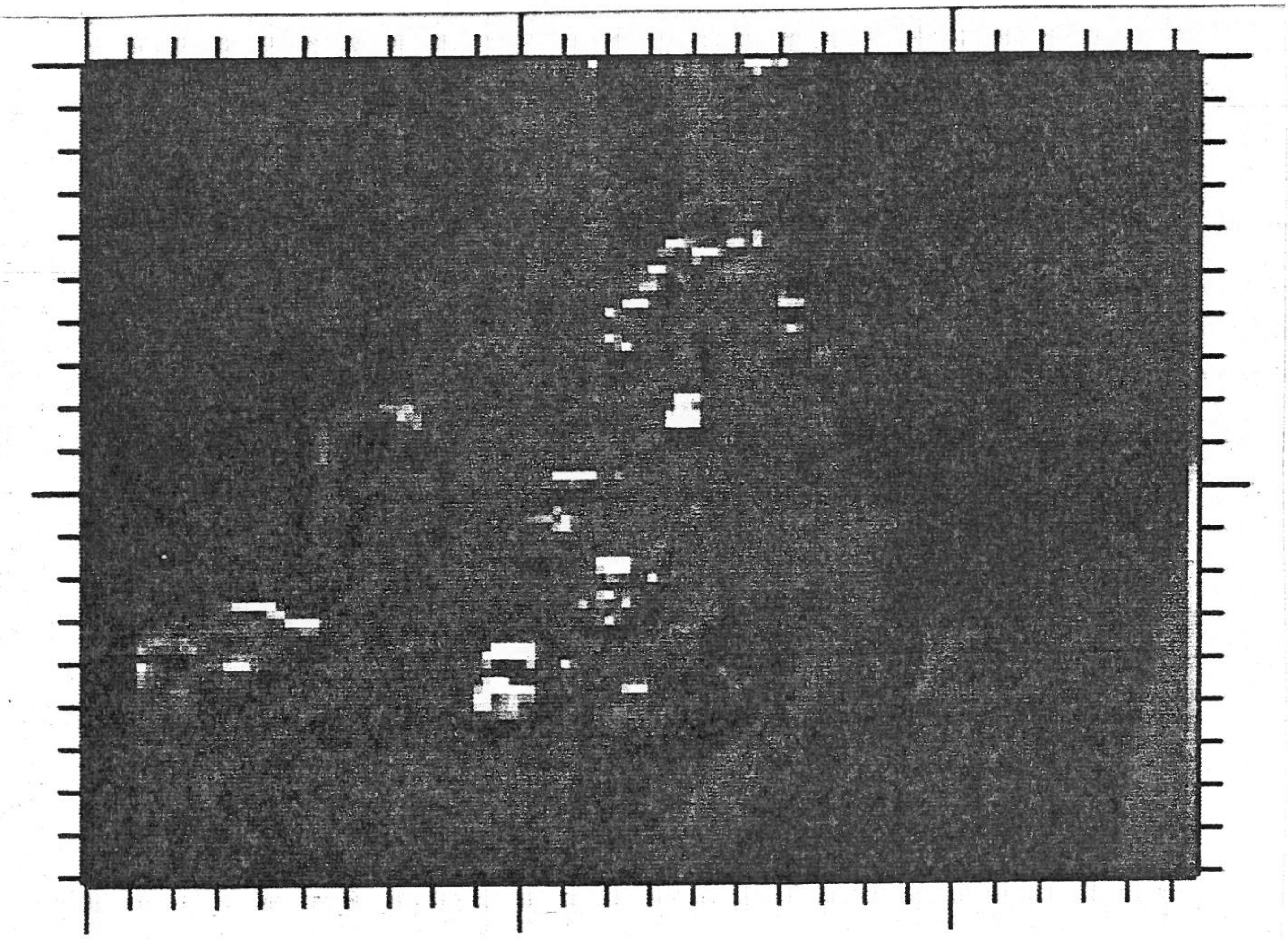
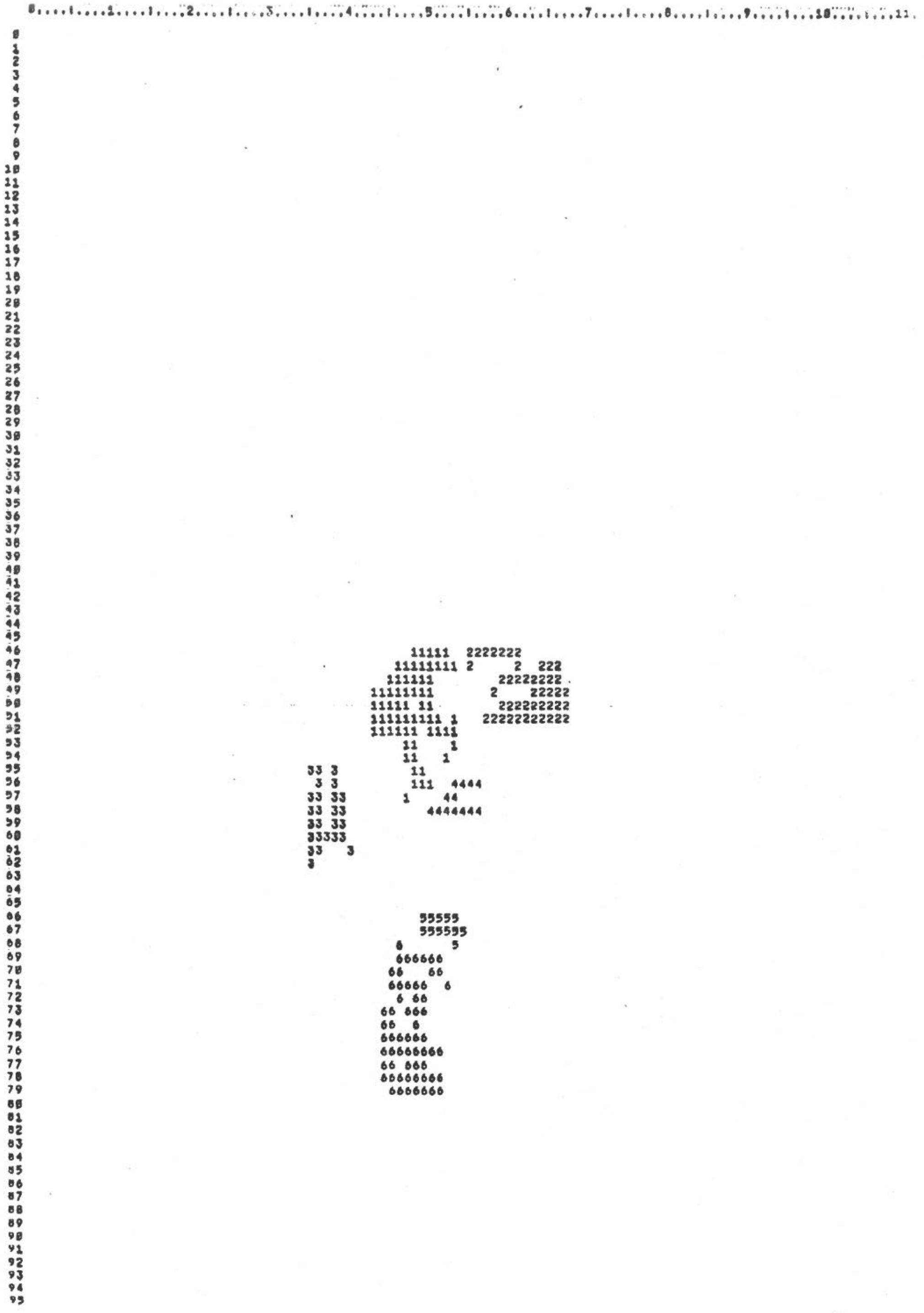


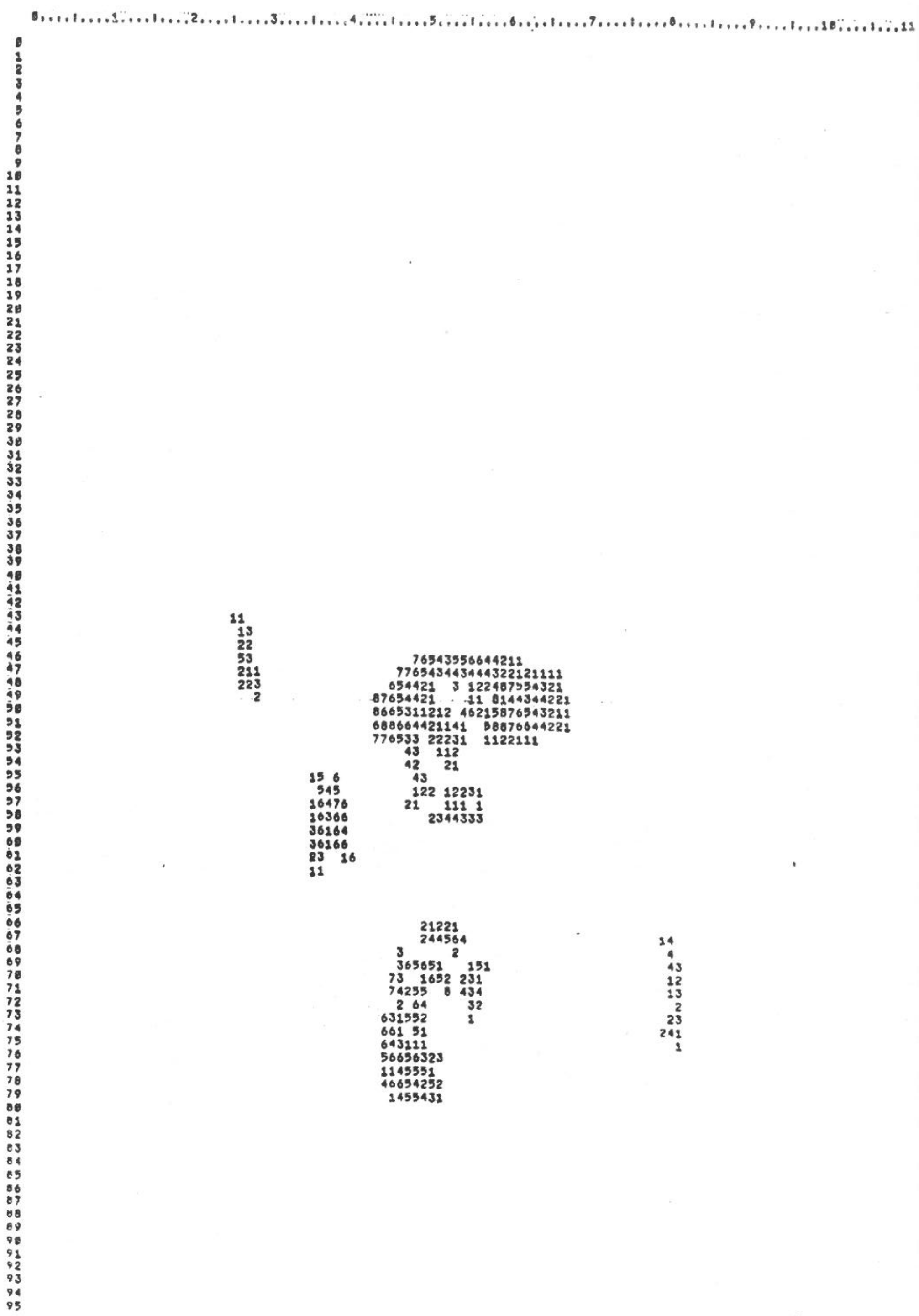
REFERENCE PICTURE OF SERIES A : MODIFIED AFTER 11TH FRAME

Fi
6



CPU-ZEIT FUER DRUCKEN DER SODP-BEREICHE 9,46 S

Fig. 7b



CPU-ZEIT FUER DRUCKEN DER FODP-BEREICHE 7,25 S

Fig. 7a

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42                                   13 456
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44                                    815 87
45                                    5C 5B                       43321
46                                                           77654321
47                                                          3121 1176553311
48                                                   45432 FECCBA9876943311
49                                                   5443    211     554321
50                                                    5532 FEDCBA9887554321
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56                                  4588C               8A1
57                                  50BAED              4 52
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59                                 15AA7D9         121
60                                 27A98DD         79989974
61                                 269B4 1D          313
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65                                                   1
66                                                 9899872
67                                                 9B8CDB                       5A
68                                              A63543 91 551                   3B
69                                              ADCDC83631B8                    3B6
70                                             EA1 3782 2A161                 3  76
71                                             EB9CC7 F26A8 1                 2  39
72                                             63 96   9 A292                 5A1 7
73                                            DABCC9   927 51                 6A 6A
74                                            DD8 54   7                       2657
75                                            DBA88844                        2 6 1
76                                            BDDCDA9A1                       CB27
77                                            887666224                       22366
78                                            BDDCB9C97                       1 12
79                                            13BCCBA3                         572
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CPU-ZEIT FUER DRUCKEN DER FODP-BEREICHE    6.99 S
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Fig. 8a

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56                                 2   3
57                                 22 333         4
58                                 22 333          4 44444
59                                222 333         444
60                                222 333         44444444
61                                222 3  3          444
62                                 22 33
63                                 2
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66                                                5555555
67                                                555555
68                                             555555 55
69                                             55555555
70                                            555
71                                            555555
72                                            55 5
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76                                           55555555
77                                           555    55
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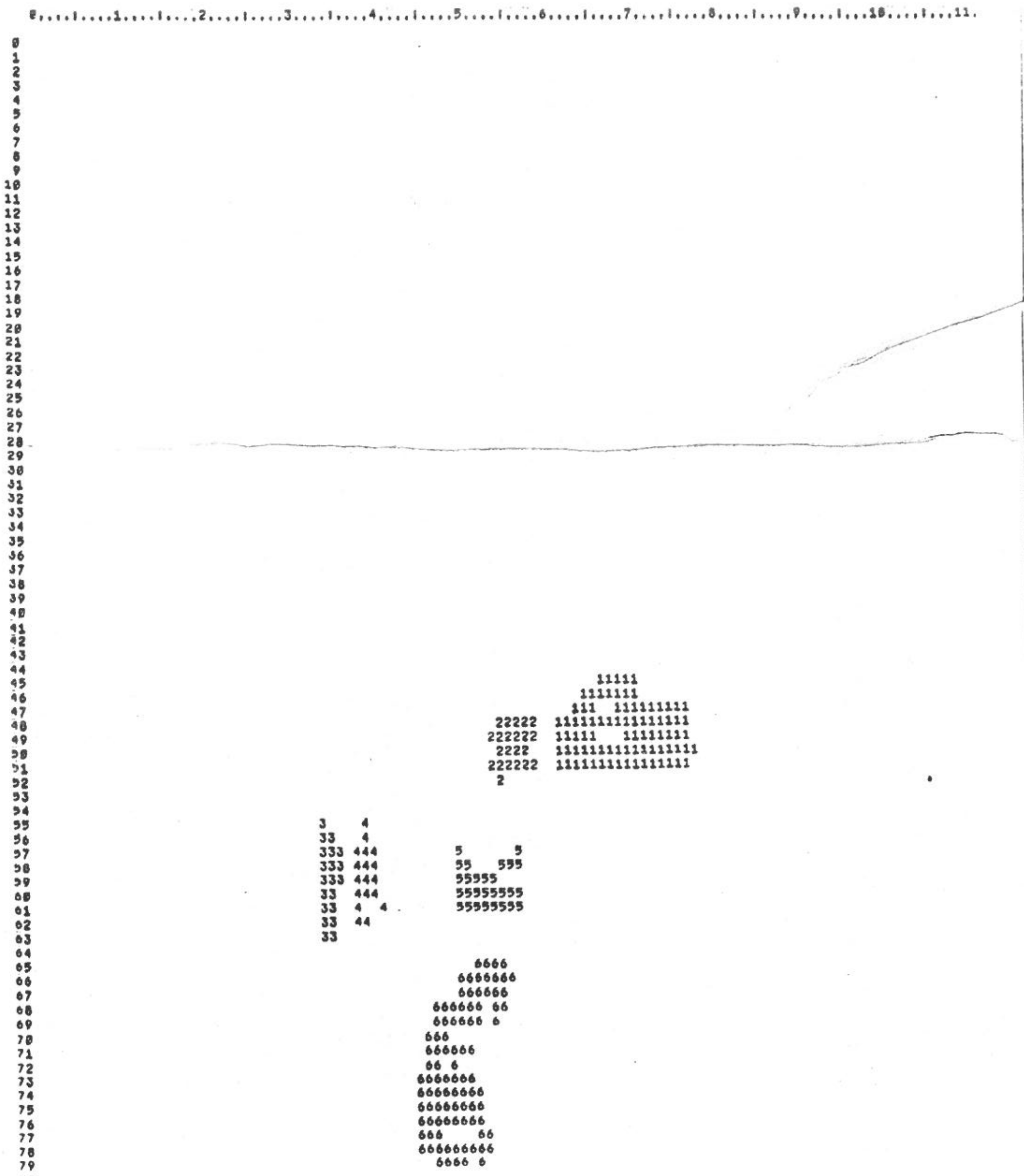
CPU-ZEIT FUER DRUCKEN DER SODP-BEREICHE    9.35 S
```

Fig. 8



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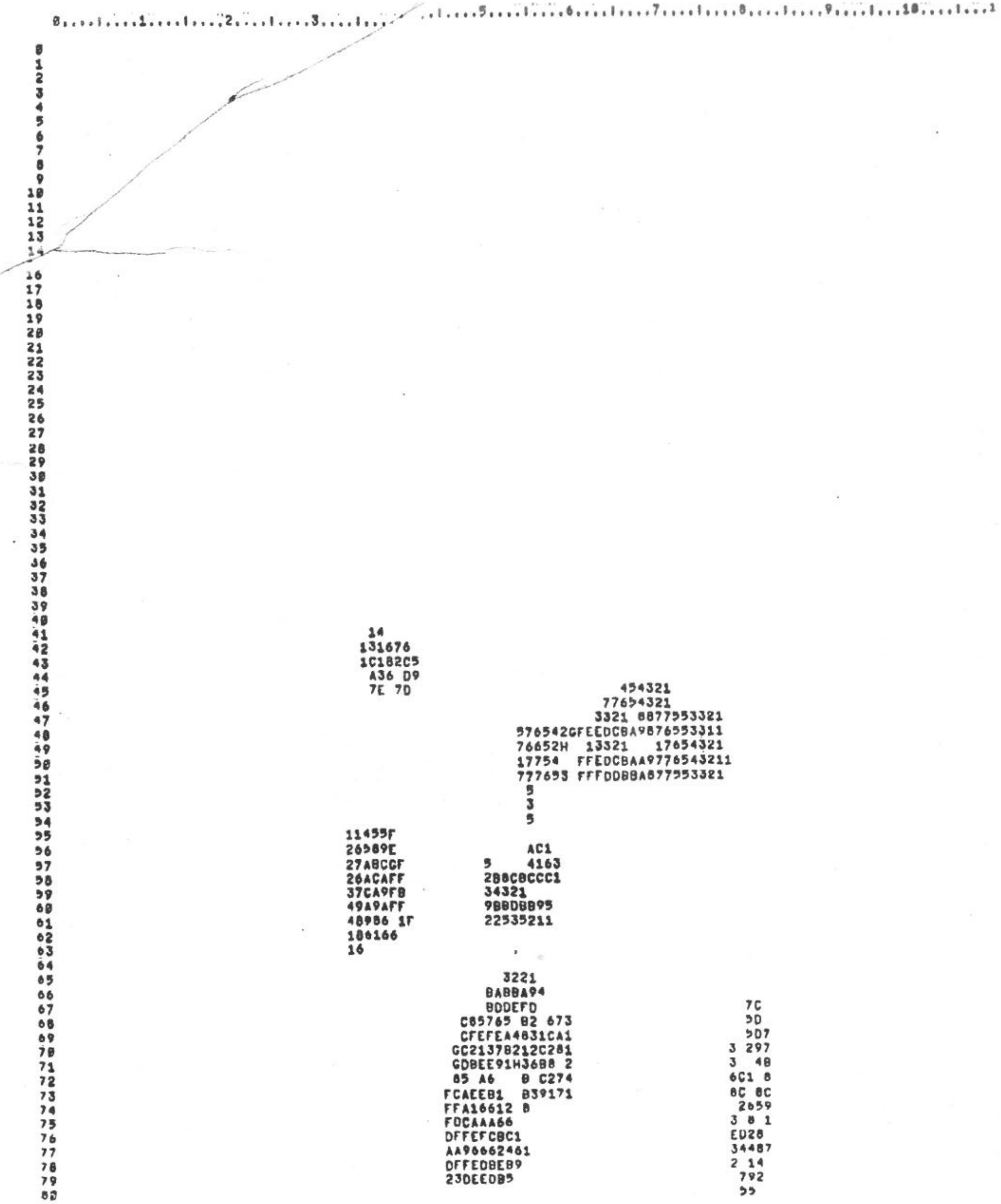
CPU-ZEIT FUER DRUCKEN DER SODP-BEREICHE   8,59 S
```

Fig. 9b



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CPU-ZEIT FUER DRUCKEN DER FODP-BEREICHE   6,73 S
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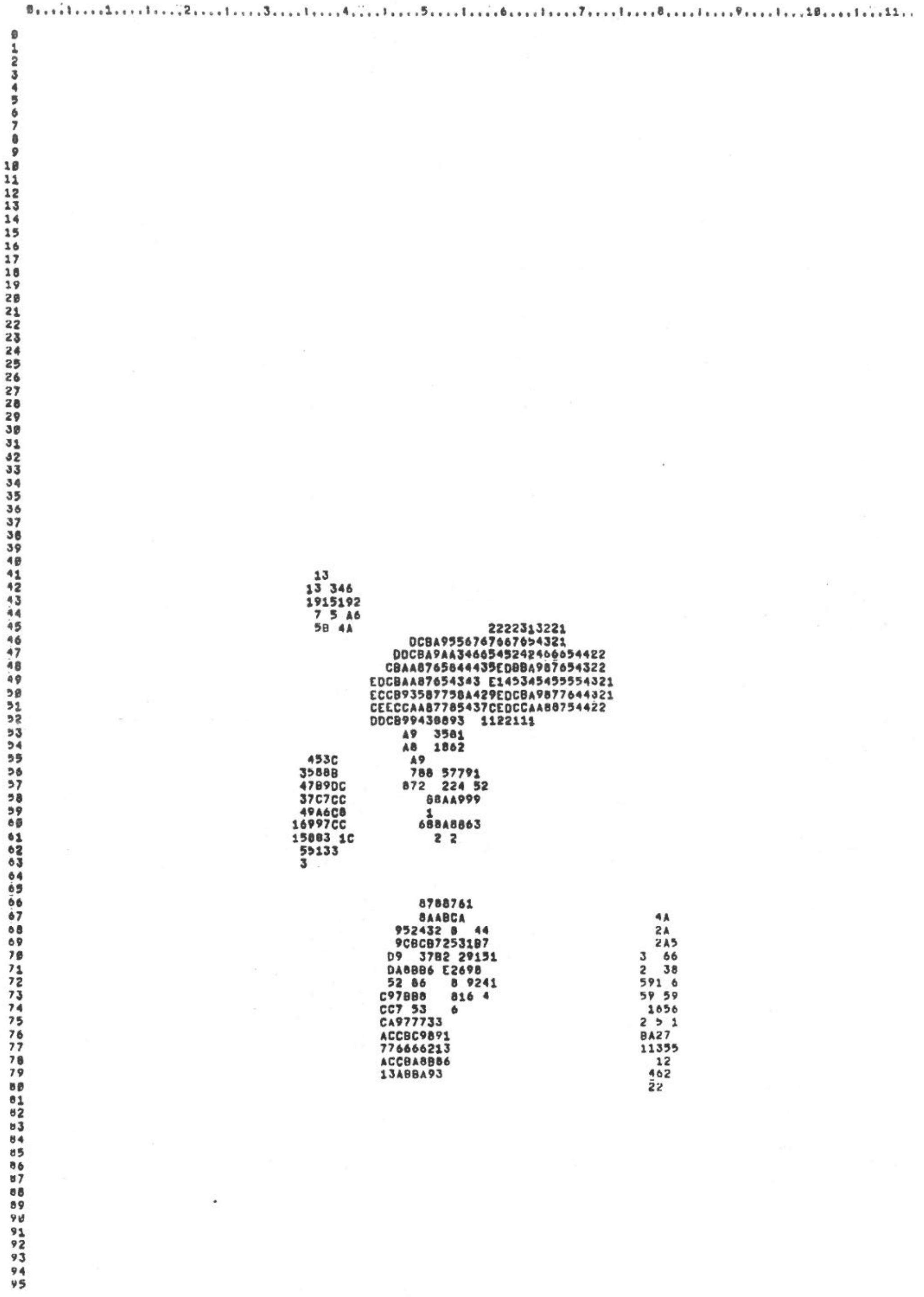
Fig. 9a



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CPU-ZEIT FUER DRUCKEN DER FOOP-BEREICHE   7,86 S
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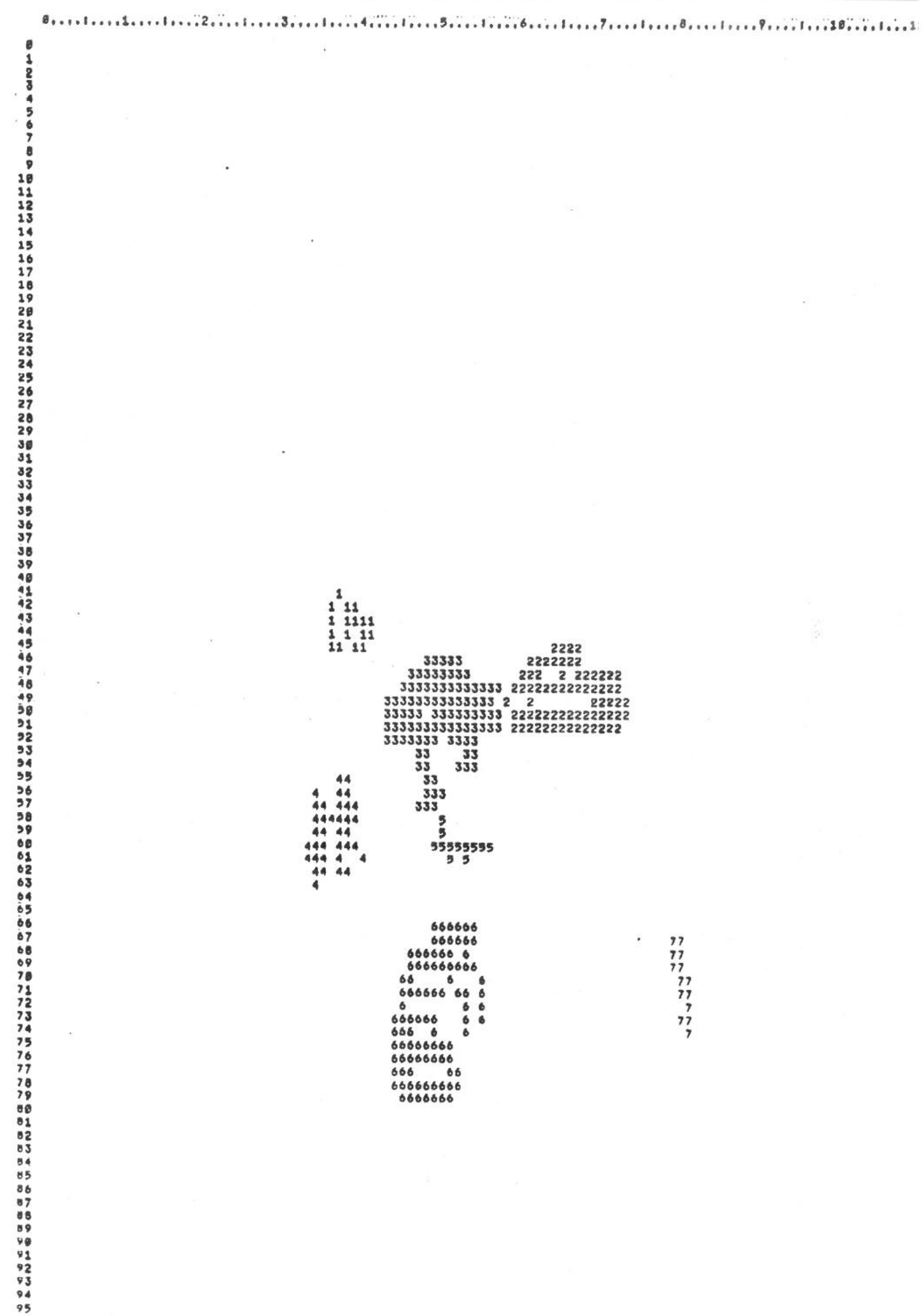
Fig. 10a



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CPU-ZEIT FUER DRUCKEN DER SOOP-BEREICHE   9,24 S
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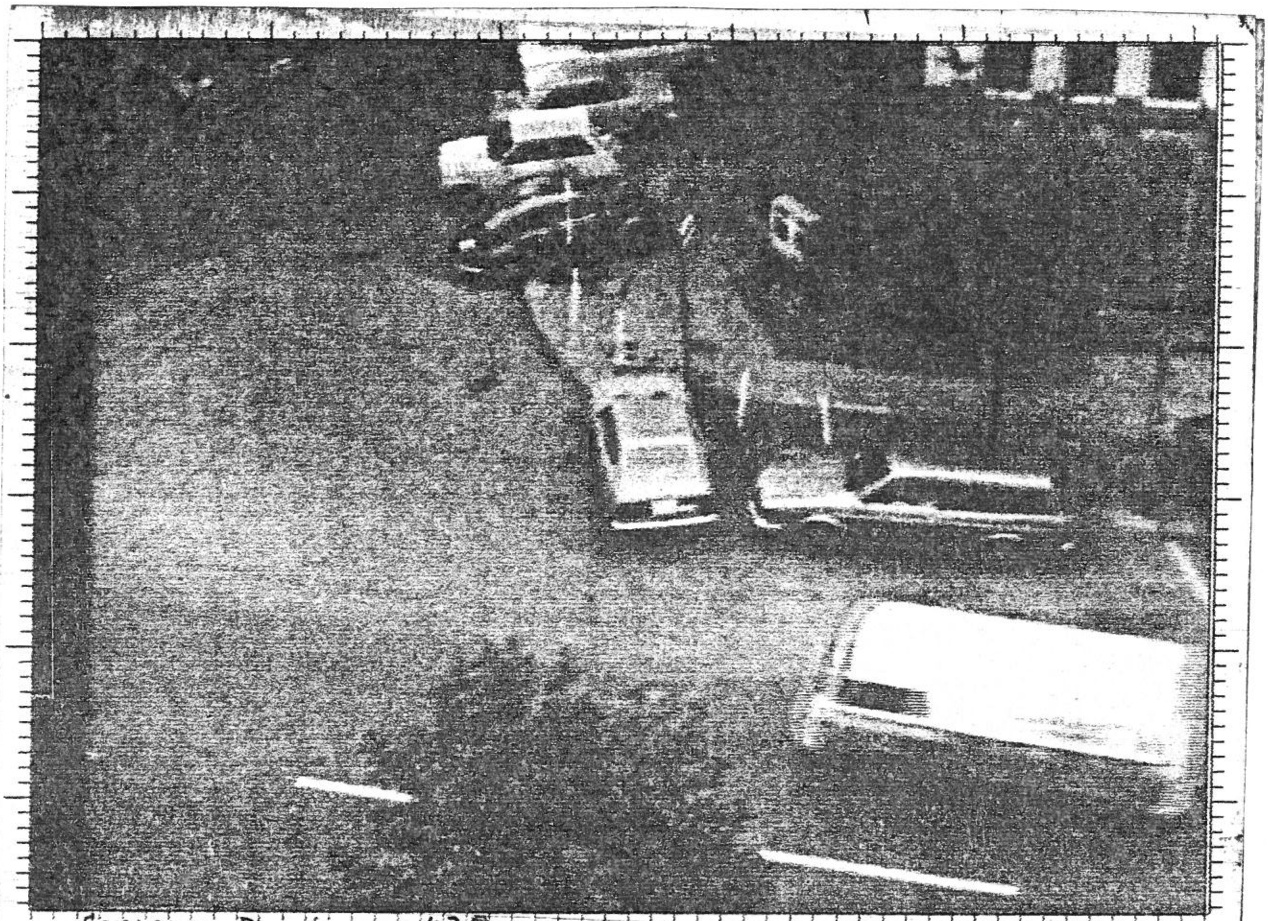
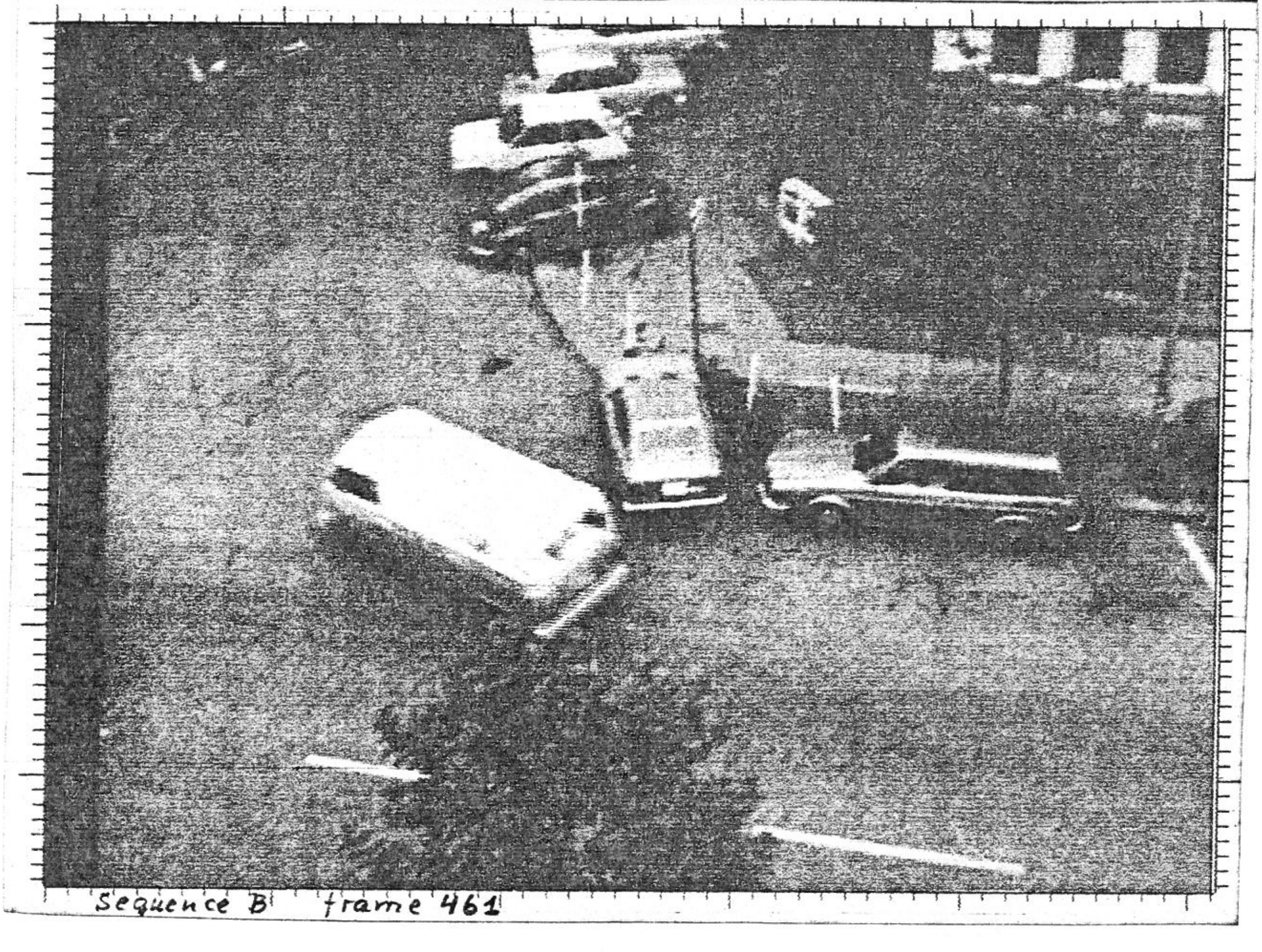
Fig. 10.



Sequence B frame 435

Fig. 11a



Sequence B frame 461

Fig. 11b

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1 6883
1277841
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DRUCKEN DER FODP-BEREICHE   6,91 S
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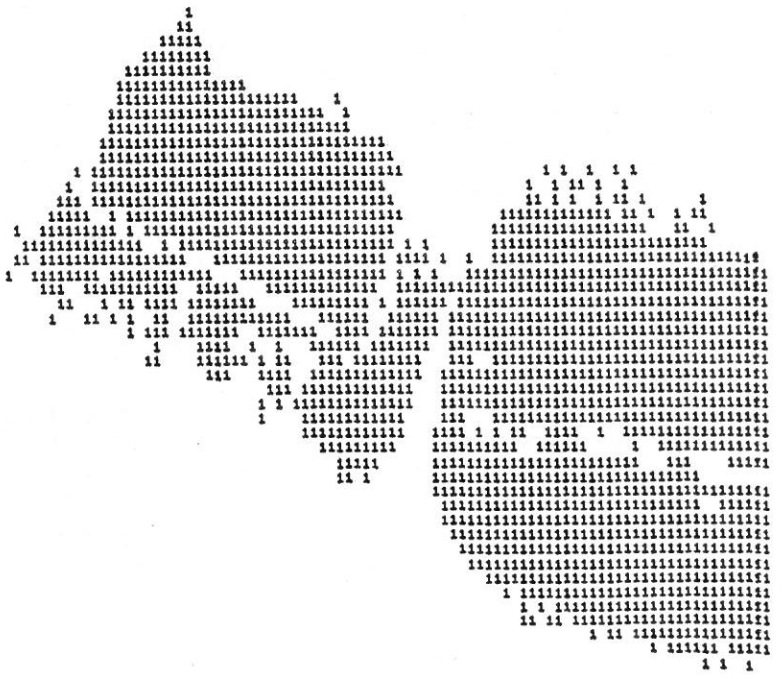
Fig. 12a



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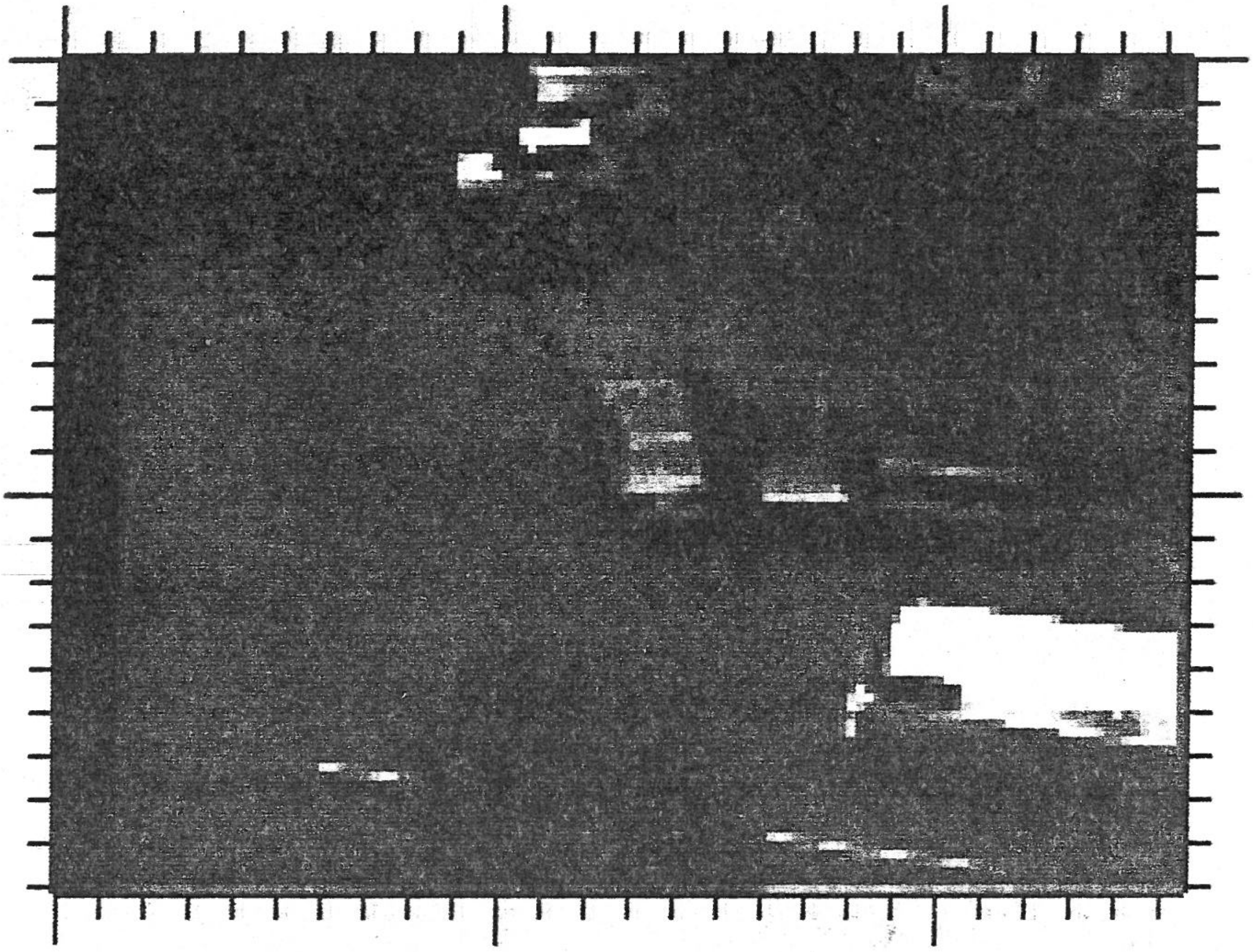
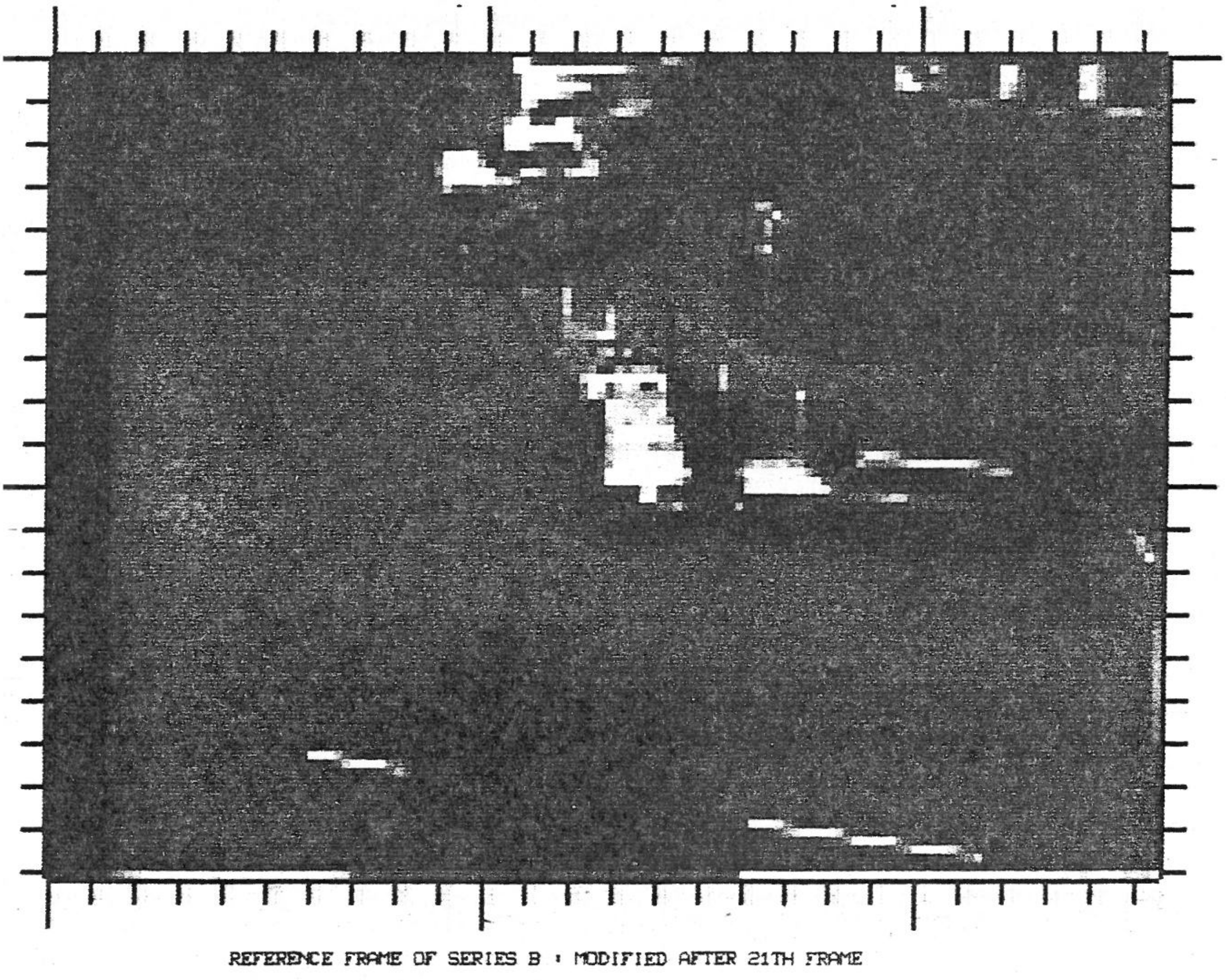
DRUCKEN DER SODP-BEREICHE   9,38 S
```

Fig. 12b



REFERENCE FRAME OF SERIES B : INITIAL FRAME

Fig. 13a



REFERENCE FRAME OF SERIES B : MODIFIED AFTER 21TH FRAME

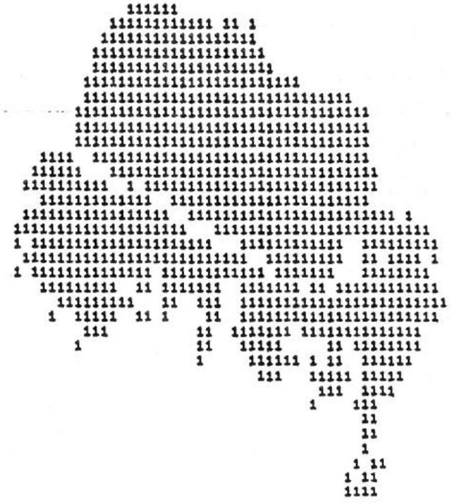
Fig. 13b

```
.1....!....2....!....3....!....4....!....5....!....6....!....7....!....8....!....9....!....10....!....11....!....12....!..
                         3 68873
                         1277A852

                          11
              111222     1 42
            11112233332221545
          11122233344449554551
          11122233344455566667
          111223334455566677772
         11122333445556677778888761
         11123334445566777888999AAAAAA9A
       11122333445556677788999AAABBBBCCB97
       1111233444556677788899AAABBBCCCCDDCC
       1122333445556677788999AABBBBCCDDDDDDD
   1112   2333444556677788899AAABBBCCCDDDEDDE
  1113222   14545565677888999AABBBCCCDDDEEEE
 1112333313   3 5565667789999AABBBCCDDDDEEFEEF
   22333444553113577787889AAAABBBCCDDDEEEEEE
 12133341455566637   18798999BBBCCCCDDDEEFFF1 G
2313235445666777775637 9AAA9BABBCDCDEEEFFFFGGGHH
2 3234456676787888AC86577 CBCACCCCDDDEEEFG1GF1HFHG
 1126385486778A66H6BCAC8981   CDCDDCDEEEEF1 FG1HFI
  22273465877A96 A67C8BB76AA9511EEDEECDE111GHHHIHH
   1523447573 A755E879BB7 1CC9CB18BFEFG111FFGGHHIHI
     122434753   31C  7CA62DDDEDCEF71ACG1HGFHHFGHJI
       43464   6516    1A  BEDDECDDCED11ABFHJHHJHHI
        333    6      8E7 6EECEFB 1GFEEFFGABCDJJHIH
                      19   16CDD  8  FD 1FHFGCBBCF
                      87    DEDEDC8E GG  DFGFFIB9
                             DDD   DDEF1AHIHHGGF
                                     BFG DHHIIII
                                      EBFGHIIHI
                                          HIHI
                                         GHGG
                                          1C
                                           17
                                        1 11
                                        1111

DRUCKEN DER SODP-BEREICHE   0,48 S
```

Fig. 14a



```
0....!....1....!....2....!....3....
0
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2
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48                                                           111111
49                                                         111111111111 11 1
50                                                        1111111111111111111
51                                                       111111111111111111111
52                                                       1111111111111111111111
53                                                      11111111111111111111111111
54                                                      11111111111111111111111111111111
55                                                     111111111111111111111111111111111111
56                                                     111111111111111111111111111111111111
57                                                     111111111111111111111111111111111111
58                                                1111   1111111111111111111111111111111111
59                                               111111    111111111111111111111111111111111
60                                              1111111111   1 11111111111111111111111111111
61                                                11111111111111  1111111111111111111111111
62                                              111111111111111111  1111111111111111111111111 1
63                                               111111111111111111111    11111111111111111111111111
64                                               1 1111111111111111111111    1111111111111  111111111
65                                                111111111111111111111111111   111111111   11 1111 1
66                                               1 111111111111111 1111111111111 1111111    11111111
67                                                  111111111   11 1111111   1111111 11 111111111111
68                                                    111111111    11   111  1111111111111111111111111
69                                                   1  11111   11 1     11  111111111111111111111111
70                                                       111            11  1111111 11111111111111
71                                                      1               11   11111     11 11111111
72                                                                      1     111111 1 11  111111
73                                                                             111   11111 11111
74                                                                                    111  1111
75                                                                                   1    111
76                                                                                         11
77                                                                                         11
78                                                                                         1
79                                                                                        1 11
80                                                                                       1 11
81                                                                                       1111
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95

CPU-ZEIT FUER DRUCKEN DER SODP-BEREICHE    0,79 S
```

Fig. 14b

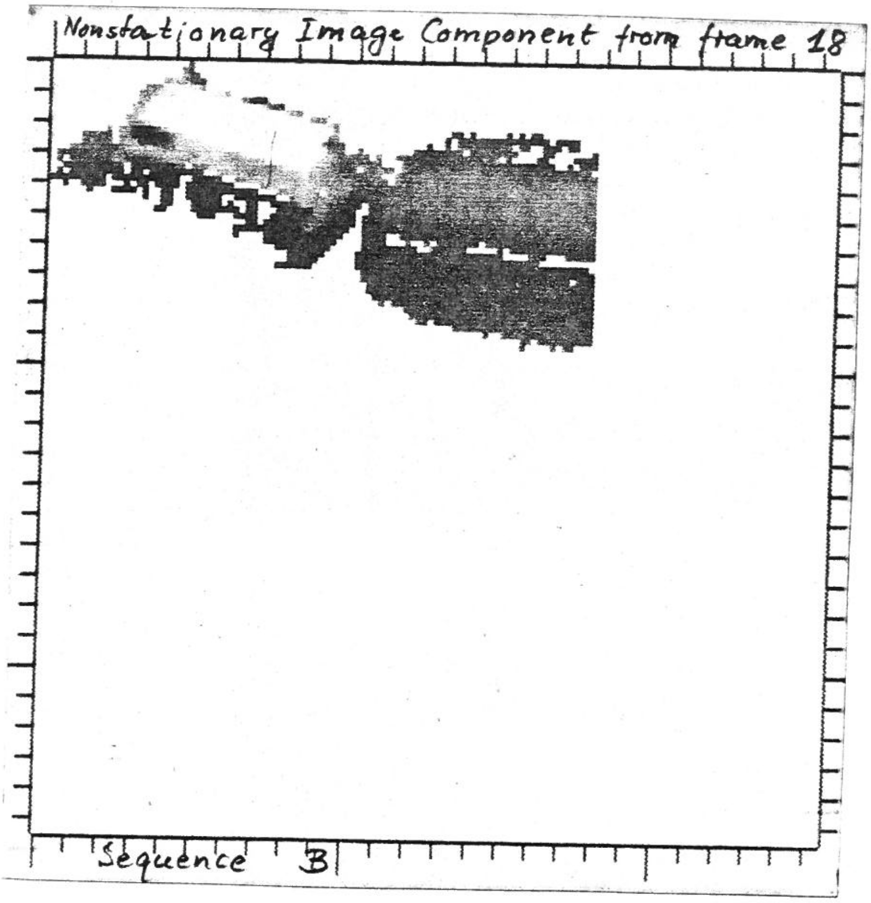

Fig. 15a

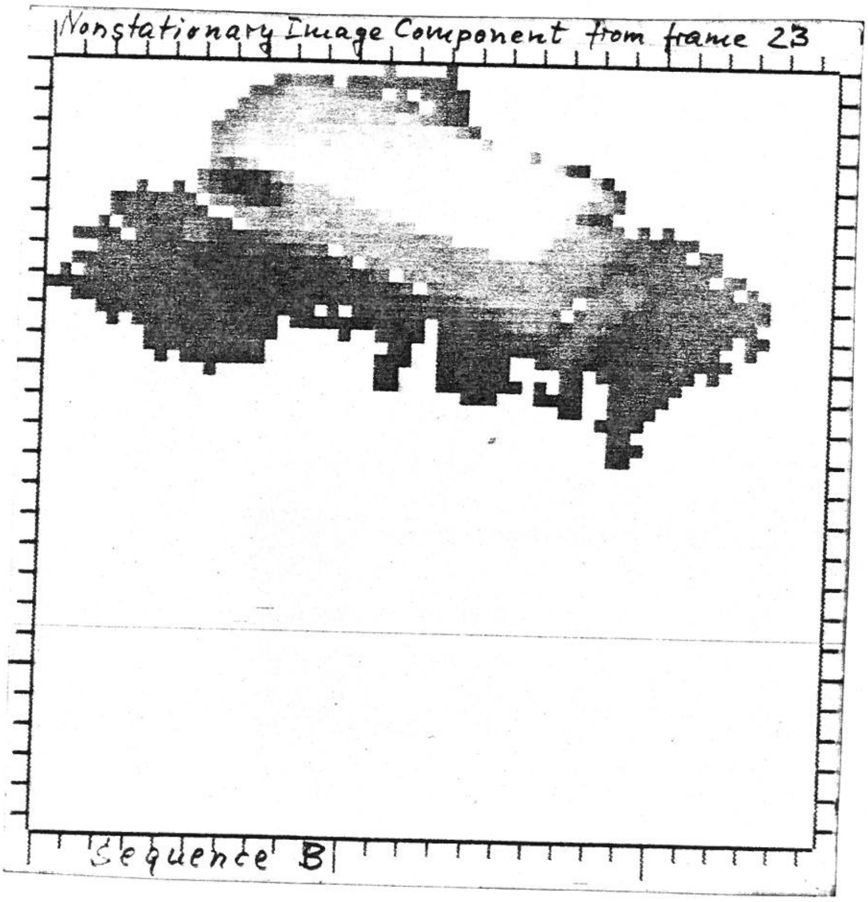

Fig. 15b

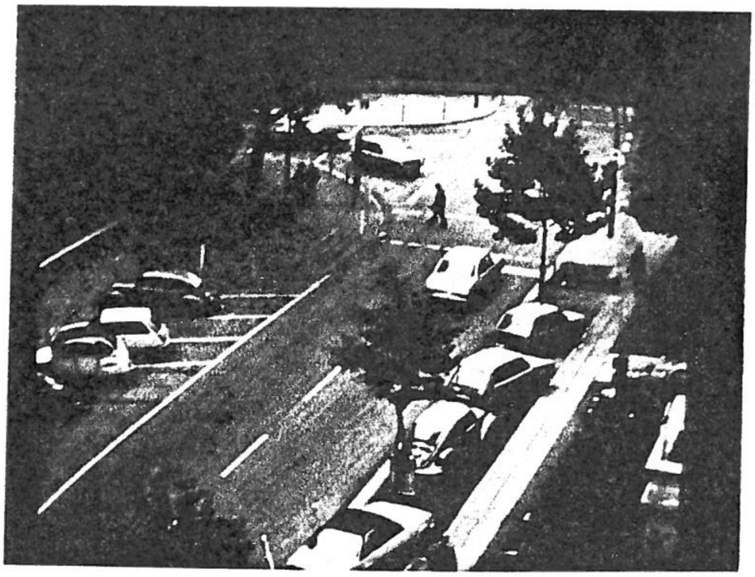

Fig. 16a

frame 10

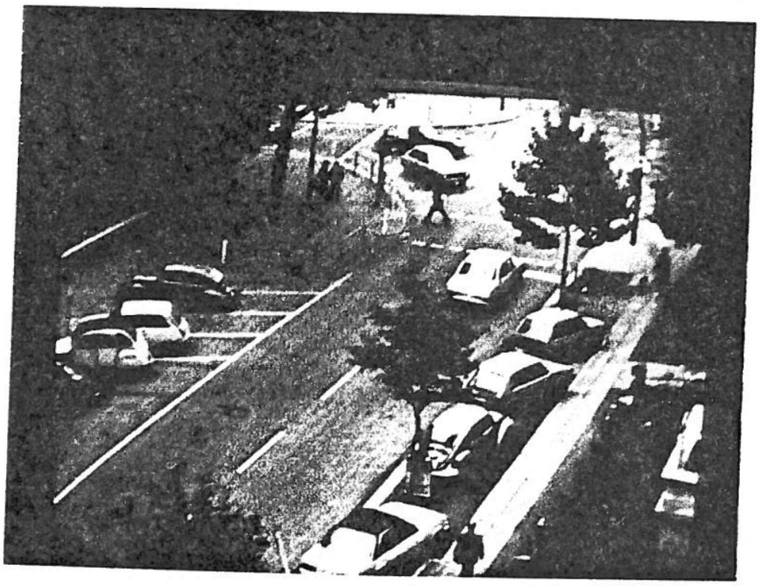

Fig. 16b

frame 26

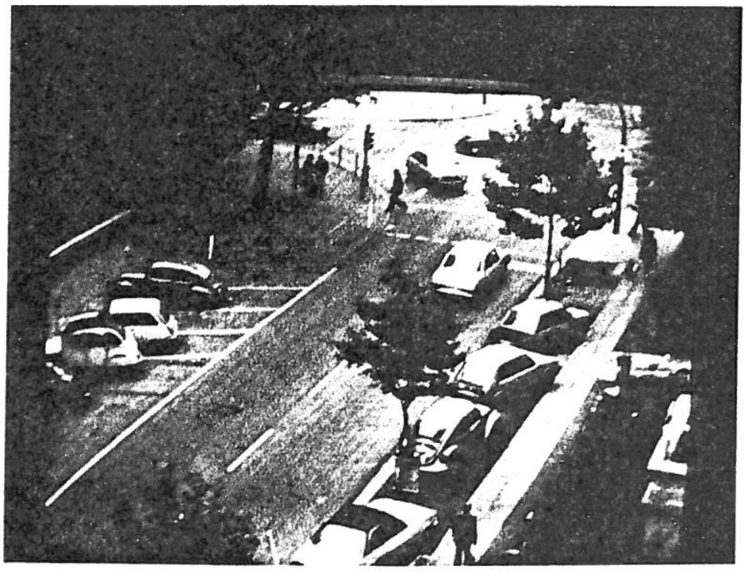

Fig. 16c

frame 40