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RPV Application of a Globally Adaptive Rate Controlled Compressor

Prepared for

U.S. Army Aviation Research and Development Command,
RPV Development Office, St. Louis, Missouri

by

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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PREFACE

The work described in this report was performed by the Information Systems Division of the Jet Propulsion Laboratory.

ABSTRACT

This paper introduces a globally adaptive image compression structure for use in a tactical RPV environment. The structure described would provide an operator with the flexibility to dynamically maximize the usefulness of a limited and changing data rate. The concepts would potentially simplify system design while at the same time improving overall system performance.

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RPV APPLICATION OF A GLOBALLY ADAPTIVE RATE·CONTROLLED COMPRESSOR

I. INTRODUCTION

The purpose of this report is to briefly introduce a globally adaptive rate controlled image compression structure which is ideally suited to the tactical environment of a Remotely Piloted Vehicle (RPV). Such a structure could provide an operator with the flexibility to dynamically maximize the usefulness of a limited and changing bit rate. This structure was previously developed as a fundamental part of image compression algorithm RM2†.[1], [2] Required modifications to standard algorithms are noted.

RPV Environment, Simplified

The assumed tactical problem is one in which an operator-controlled RPV equipped with an imaging device flies over terrain looking for various targets. An operator views imaging information transmitted back and first seeks to detect and recognize targets of interest. Once accomplished, the operator may initiate automated tracking and/or various actions against the targets.

A sophisticated adversary will seek to jam both the command uplink and imaging downlink of the RPV communication system. We will assume that a necessarily digital spread spectrum anti-jam (AJ) downlink is used to counter such jamming threats. For our purposes here we will also assume that the AJ protection is sufficient to provide an error-free uplink. A simplified picture of the operational environment that results is shown in Fig. 1.

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† Performance curves for an adaptive cosine algorithm were mislabeled in Ref. 2 as adaptive Fourier.

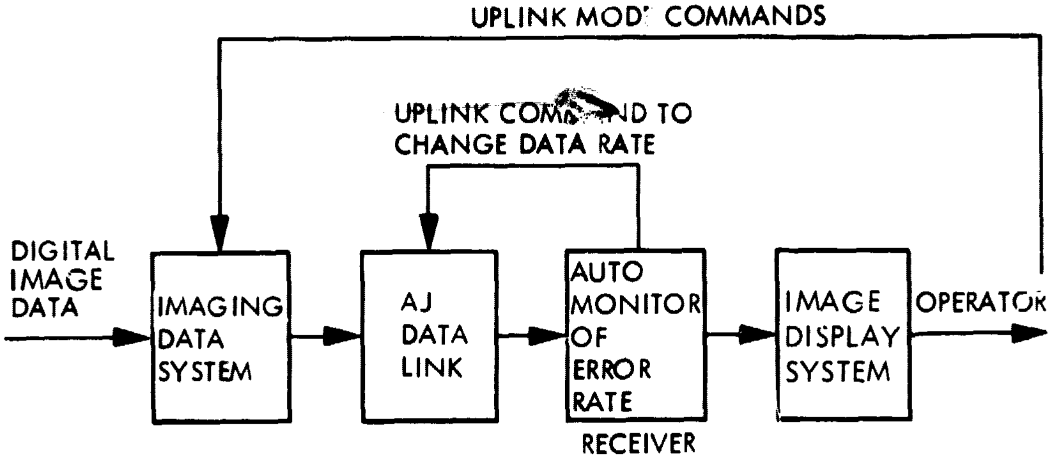

Fig. 1. Simplified Block Diagram.

As shown in Fig. 1 the error rate at the ground station receiver is automatically monitored. When the error rate exceeds some threshold, an uplink command is given to reduce the available data rate (to gain more AJ protection) until the received error rate is acceptable (this could be an automated or operator controlled function). Similarly if the jamming situation improves the available data rate is increased.

Thus the operator is faced with accomplishing his task of detection, recognition, etc., under limited and changing data rate conditions. He must dynamically communicate commands to the imaging data system to select modes which maximize the usefulness of the limited data rate.

II. RM2 SYSTEM STRUCTURE

This section provides a tutorial view of the RM2 algorithm internal structure and a description of the flexibility it provides in utilizing a limited number of bits more effectively in a given image frame. A later section will be concerned with extending this flexibility to sequences of images within an RPV tactical environment.

Bits/Pixel vs. Quality

In simple terms RM2 can compress images to any requested bits per picture element (bits/pixel). A higher requested bits/pixel results in a better decompressed approximation to the original image. This basic relationship is shown in Fig. 2.

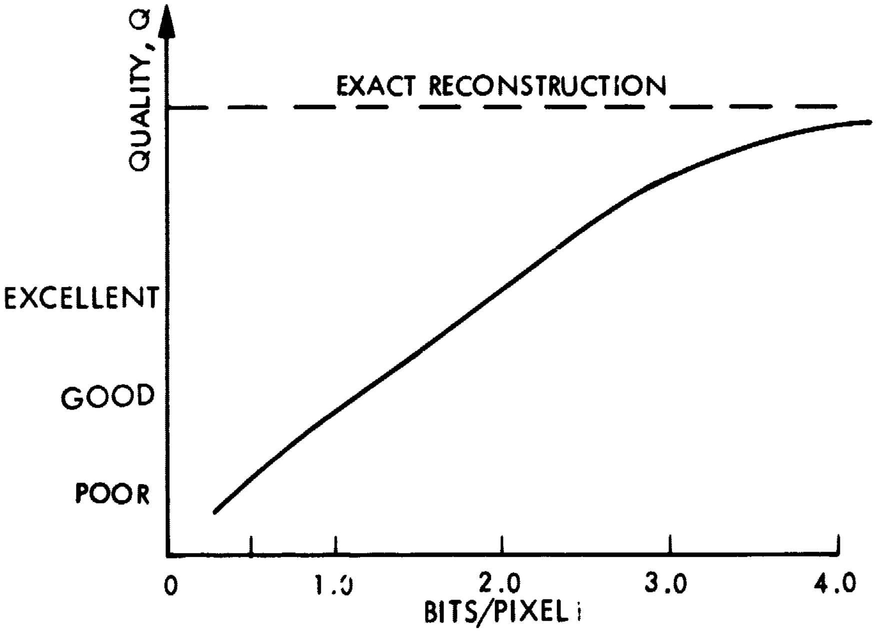

Fig. 2. Monotonic Relationship Between Bits/Pixel and Image Quality

Internal Bit Allocations

RM2 treats an image as an array of subpictures (e.g., 32 x 32 pixels) and first surveys these subpictures to determine their "data activity" A_1, A_2, ... A_N as shown in Fig. 3. These measures of activity directly relate to the relative need of each subpicture for the limited number of bits available for the complete image. An internal algorithm[1] will allocate the total number of bits available for an image frame, B, to the subpictures in a way that reflects this need. The more active subpictures receive more bits that the less active subpictures. As in Fig. 2 more bits applied to a given subpicture imply better quality. Let b_i, i = 1, 2, ..., N be the bits assigned to the $i^{\underline{th}}$ subpicture, then

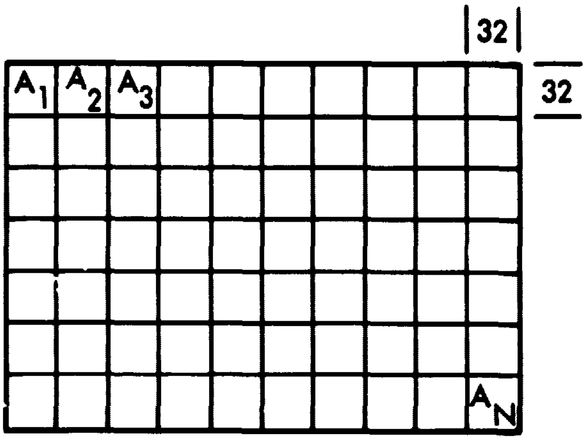

Fig. 3. Array of Data Activities.

$$B = \sum b_i \tag{1}$$

Rate distribution parameter. The rate allocation algorithm described in Ref. 1 includes a parameter which controls the amount of nonuniformity of rate distribution. At its lowest setting, this parameter causes the same bits/pixel to be allocated everywhere, regardless of any differences in the activities. As this parameter is increased the range of bits/pixel allocations also increases (provided the activities aren't all the same). The consequence of this effect is that very low parameter settings put a "quality emphasis" on inactive subpictures relative to active ones whereas a very high setting emphasizes active subpictures.

Edit header. Define an edit header

$$E = e_1 e_2 \ldots e_N \tag{2}$$

where e_i is a one bit indicator of the editing status for the i^{th} subpicture in the image. If $e_i = 1$ then the i^{th} subpicture is treated normally, whereas if $e_i = 0$ then the i^{th} subpicture will be "edited" and the allocation b_i is only one bit (the header bit). If e_i is zero, then the ground decompressor would reproduce subpicture i as all zero. The bits that would have been used on edited subpictures are instead allocated (still according to relative activity), to the non-edited subpictures. This means that different frame sizes can be specified by selecting a different header, as for example in Fig. 4.

Enchanced Q for Selected Areas

Suppose it is desirable to emphasize the quality in a selected area while still limited to a fixed bits/image. This can be accomplished quite

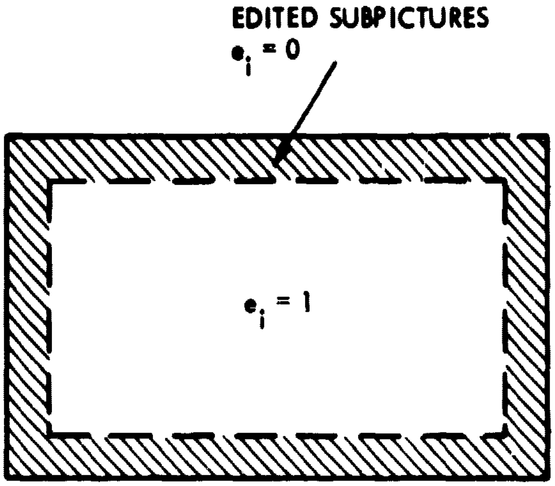

Fig. 4. Changing Frame Size by Editing Subpictures.

simply by artificially increasing the activity measurements for the selected subpictures. The algorithm that allocates bits would cause more bits (and hence quality) to flow to these subpictures at the expense of the subpictures that did not get an artificial increase to their activity.

Foveal spot. The most obvious application of selective quality enhancement is the concept of a foveal spot where an operator selects the central part of an image for emphasis as in Fig. 5.

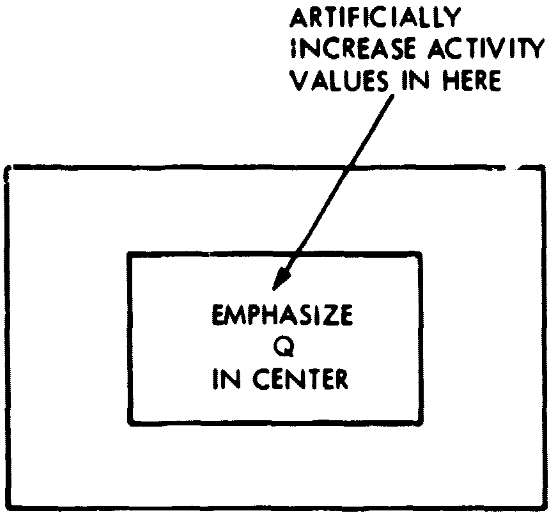

Fig. 5. Foveal Spot.

The size of the foveal spot is of no consequence, other than its boundaries should correspond to the subpicture boundaries. The tradeoff between quality inside or outside the foveal spot is easily varied by providing a single parameter, say β, which simply multiplies the normal activity measures before bit allocations are made.

Cursor foveal spot. It might be desirable to allow the operator to move the foveal spot to areas which are of specific interest. That is, the operator may want excellent quality in some specific region. This might mean moving the central foveal spot to an operator controlled cursor or introducing an altogether separate region of emphasis. In either case, the implementation is no different: multiply the activities of the selected region by some parameter β'.

Target screener. While not immediately available in hardware form, pattern recognition techniques would provide in the not too distant future the ability to automatically select areas which, "with high probability," contain targets of special interest. This is much like the foveal spot except the spots are automatically selected instead of selected by the operator.

However, the same concept holds. Given a limited number of bits available in a frame time it is clearly desirable to place them where they do the most good. This leads to the most general situation depicted in Fig. 6.

In the figure we show the following:

a) A selected edited region which reduces frame size.

b) A selected foveal spot region.

c) Subimage regions which an automated pattern recognition algorithm has determined as likely to contain targets of specific interest. Two possible classes are shown.

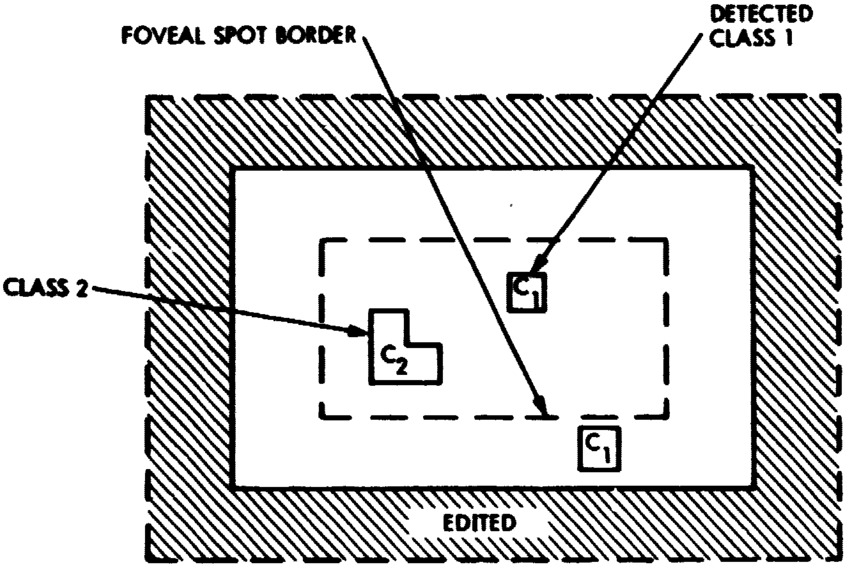

Fig. 6. General Flexibility.

In actual situations, a data rate limitation forces a tradeoff between frame rate, frame size and the bits available per frame time. As discussed earlier:

1) the specified edited regions would receive no bits (except for the header bits);
2) activity measurements would be made in non-edited areas;
3) activities inside the foveal spot would be increased by some factor, β;
4) areas identified as target class 1 would get an added boost say γ_1, and class 2 area activities would be boosted by γ_2. The values of γ_1, γ_2 no doubt reflect the importance of target classes 1 and 2 but would be experimentally determined;[†]
5) bits are allocated to subimages according to the relative activity measures;
6) actual compression coding of the image is performed.

[†] Observe that the target screening need not be applied only to non-edited regions. If a "target" was determined to be likely in an edited area the edit command could easily be overridden in that specific area.

In a real system, various edit headers, foveal spot definitions and activity emphasis parameters could be stored in ROMS and selected by appropriate system commands.

The combination of a target screener, once practical, with a compression algorithm which is structured like RM2 should result in significant reductions in the required data rate needed to accomplish various mission objectives. A flow chart of these simple steps is shown in Fig. 7.

Modifications to Standard Algorithms

If we delete the ability to distribute a given number of bits according to a "data activity" measure then the more familiar standard two-dimensional algorithms can be simply modified to accomplish most of the features described in previous paragraphs. The required attributes are as follows:

a) The algorithm should be structured to operate on subpictures (this is usually inherent anyhow).

b) Rather than be limited to one or two compression options, the algorithm should provide the ability to choose closely spaced bits/pixel options <u>for each subpicture</u> which are monotonically related to the quality of reproduction of a given subpicture.† Each coded subpicture would be prefixed by a header which identified the selected option. The range of options should be broad (e.g., 0.5 bits/pixel to 2.5 bits/pixel).

These are not difficult requirements and would permit most of the rate distribution capabilities just discussed: editing, arbitrary foveal spot emphasis (cursor or center), and target screener emphasis. The same rate allocation algorithms could be used by assuming activities were all unity.

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†See Ref. 1 for simple RM2 control loops to handle cases where the allocated number of bits does not equal a prescribed option. Basically, any discrepancy is reallocated to subsequent pictures or subpictures.

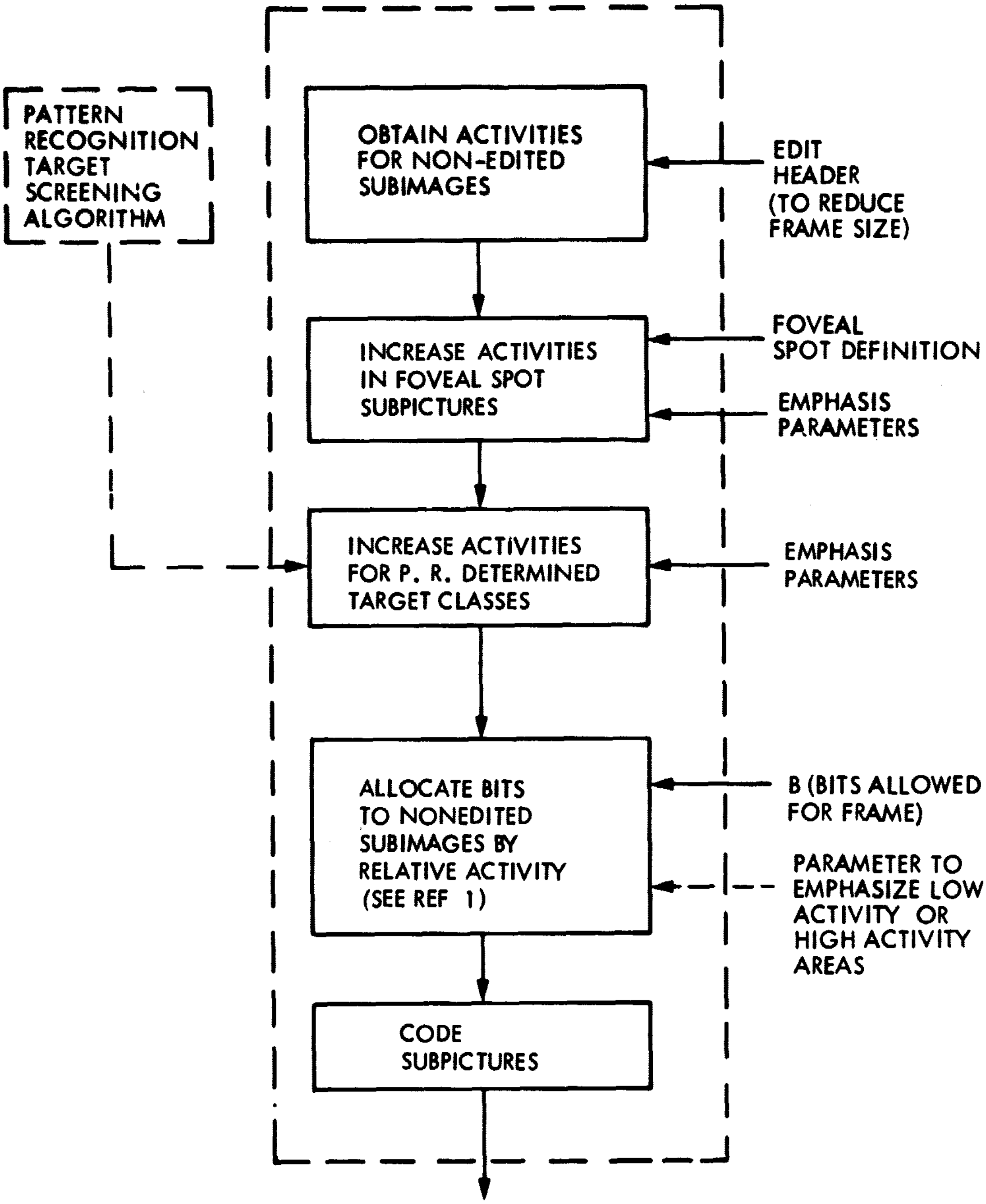

Fig. 7. Generalized Bit Allocation Flow Chart.

Computation. The conversion of standard algorithms to the desired rate control structure would have a minor impact on overall computation requirements. Adequate activity measures can be obtained using only a few adds and subtracts per pixel. Further, the per pixel computations needed to determine subpicture bit allocations are negligible.

Adding activity measures. Actually, it is a simple matter to obtain activity estimates quite similar to those derived in RM2. An estimate of data variance, or entropy would suffice. Any of these, properly normalized, would permit a direct use of the RM2 or similar rate allocation and control algorithms. All of the preceding discussions would hold. The only difference would be the manner in which a given subpicture is represented at a specified bits/pixel.

III. DATA SYSTEM COMMAND AND CONTROL

The preceding discussion should indicate that a globally adaptive rate controlled structure can provide extensive flexibility to make the most of a limited number of bits available for a static image frame. Here we extend discussions to the dynamic situation in which an operator is making real-time decisions on how he will make most effective use of a limited and changing data rate.

Parameters

Frame rate, 30/k. Assume that all possible frame delays, k/30, lying between $k_{min}/30$ and $k_{max}/30$ are options. (This indirectly specifies frame rates $f_k = 30/k$.)

$$\frac{k_{min}}{30}, \frac{k_{min}+1}{30}, \ldots\ldots \frac{k}{30}, \ldots \frac{k_{max}}{30} \qquad (3)$$

Frame size, FS. A collection of frame sizes labeled $FS = FS_i$ where FS_i equals the number of pixels in frame size i (assumed to be a multiple of the subpicture size). Assume also that the FS_i are monotonically ordered so that

$$FS_0 < FS_1 < FS_2 < \dots < FS_{i_{max}} \tag{4}$$

Increasing or decreasing frame size will mean stepping through the FS_i in this order.

Foveal spot, FV. These are similarly defined as FV_j where

$$FV_0 < FV_1 < FV_2 < \dots < FV_{j_{max}} \tag{5}$$

Bits/pixel, b. For later use we specify parameters

$$b_{max} \text{ and } b_{min} \tag{6}$$

as the maximum and minimum desired average bits/pixel, b, in a frame. b_{max} might correspond to the compression rate at which no noticeable degradation is possible and b_{min} to a minimum acceptable quality under severe conditions.

Data rate. Let $D = D_d$ be the possible data rates available where

$$D_0 < D_1 < D_2 < \dots \quad D_{d_{max}} \tag{7}$$

While an operator could choose D, it is more reasonable to assume that D is automatically determined by monitoring the bit error rate at the ground receiver. Increasing or decreasing D will mean stepping through the D_d specified in (7).

Basic Constraints

Quite trivially we have the equation

$$D = \left(\frac{30}{k}\right) (FS) (b) \tag{8}$$

Since bits/pixel, b can be arbitrarily assigned when using RM2 or some other properly structured algorithm, the parameters k and FS are acceptable options provided b lies in the allowable range. That is

$$b_{min} \leqslant b \leqslant b_{max} \tag{9}$$

The only constraint on foveal spot size FV is that it be less than or equal to the corresponding choice for frame size FS.

$$FV \leqslant FS \tag{10}$$

We will henceforth assume that any foveal spot command for which (10) is not true will automatically be converted to FV = FS (which is equivalent to "no foveal spot").

Changing System States, Concept

This section addresses the problem of allowing an operator to efficiently move between the potential system states specified by k, FS and b. The concept is introduced in Fig. 8. For the moment we will assume that data rate D is fixed.

In the figure an operator has three levers or slide switches at his command, one for frame rate, one for frame size and one for quality. The relative position of the levers corresponds to an operator's current relative importance

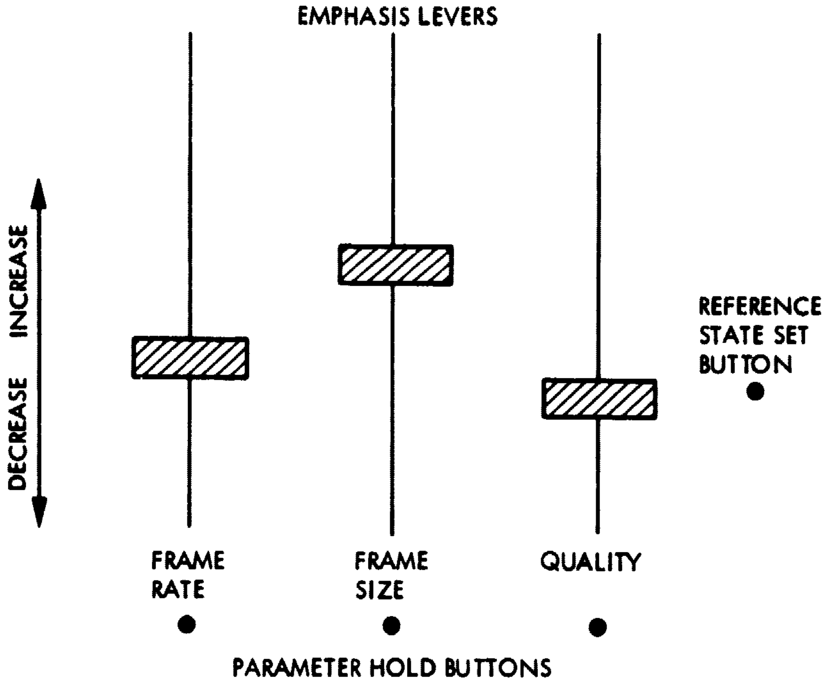

Fig. 8. Lever Control of System States.

that he places on the 3 variables k, FS and b.† When the 3 levers are all in the same horizontal position then the system will be in some preselected <u>reference state</u> defined by

$$S^*(D) = (k^*, FS^*, b^*) \tag{11}$$

where $S^*(D)$ satisfies (8) at data rate D. This reference state might have been determined from a prior run on a target at rate D or simply established as a good choice during training. In any case it can be reset at any time to a current state by pressing a "state set" button as shown.

If he moves one of the levers away from the equal emphasis position (all switches in the same horizontal position), more (up) or less (down) emphasis

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† Remember k = 30/(frame rate) and b = bits/pixel is monotonically related to image quality.

is placed on the corresponding parameter. For example, as he raises the quality lever, the bits/sample would increase at the expense of the other parameters frame rate (30/k) and frame size (FS) which would have to decrease to satisfy the constraint equation (8). If a limiting value for a parameter is reached (i.e., max or min) no more changes to system states would occur. Such boundary conditions could be signaled to an operator. An operator can always return to the reference state by equalizing the lever positions.

Fixing single parameter. If an operator wants to fix a particular parameter and trade off the remaining two he simply presses the appropriate "Parameter hold button" as shown in Fig. 8. This would fix the selected parameter at its current value. Subsequent adjustments to the remaining two lever positions would effectively trade off the relative importance of the remaining two parameters, while still satisfying (8).

Automated adjustments to b. Instead of fixing the bits/pixel parameter b as above, an "activity track" mode could be implemented. In earlier discussions we described the internal operation of RM2 (or modified standard algorithms) as one which uses subpicture activity measurements as a measure of the relative need of each area for a limited number of bits, with the more active areas requiring more bits than less active ones. Such measurements can be used to roughly maintain a given average quality as terrain changes. When an "activity track" mode is activated, b would be adjusted up or down in subsequent frames depending on the values of average image activity compared to the corresponding value at activation.

Automated edit. When there is a gradual sweep of ground terrain, much of each image may be redundant. Improved quality in the non-redundant image areas can be obtained by editing those image areas where frame overlap occurs. The internal rate control structure described earlier allows for a simple implementation of the editing functions. The information necessary for automated decisions of which areas are affected should be available from camera gimbal controls, RPV position and motion information. This could have a significant impact on capability during panoramic scans. The lever controls of frame rate, frame size and quality (bits/pixel) described in Fig. 8 would still operate in the same manner. Quality would increase at a given frame rate and frame size because bits which would have been allocated to edited redundant regions would instead be allocated to "new data" areas only. The operator might then elect to increase frame rate or frame size.

Data rate changes. As noted earlier, data rate D can be expected to change as a function of variations in the jamming environment. Such changes could be in factors of two. Ideally the system should switch from a set of parameters which the operator has optimized for the particular tactical situation and rate D, to one which is similarly optimized for the new rate D'. In a real system, the closer the new set of parameters is to the ideal, the less the operator has to fiddle with knobs, etc. The concept described in Fig. 8 is a reasonable approximation to these goals.

Each data rate D has a corresponding reference state $S^*(D)$, where $S^*(D)$ has been previously determined as a "good" choice. $S^*(D)$ might be determined as simply a state which is typically good for data rate D. More dynamically, $S^*(D)$ could be selected by the current operator as his best choice for the given situation (perhaps as determined by an earlier run at rate D).

If the operator's levers are held in an equal emphasis position (all in the same position) then the system would switch between reference states as D varied. However, when an operator moves away from $S^*(D)$ to some new state by moving the levers he is establishing a new relative emphasis between the parameters k, FS and b. If D is changed to D' this same relative emphasis is instead applied to move the state away from reference state $S^*(D)$. That is, the system responds as if the system had been in reference state $S^*(D')$ and the operator had then moved the levers.

Joy stick. It may be simpler for the operator if the three emphasis levers are combined into a single joy stick implementation.

Parameter Emphasis

This section provides some additional detail on potential approaches to the implementation of state adjustments by parameter emphasis.

Let δ_F, δ_{FS} and δ_b be operator assigned priorities for frame rate (30/k), frame size (FS) and b ≡ bits/pixel (quality) respectively, satisfying

$$\delta_F \, \delta_{FS} \, \delta_b = 1 \tag{12}$$

Let k^*, FS^* and b^* be parameter values corresponding to reference state $S^*(D)$. Then new values satisfying (8) can be determined from

$$D = (\delta_F \cdot \frac{30}{k^*}) (\delta_{FS} \, FS^*) (\delta_b \, b^*) \tag{13}$$

as

$$k' = \frac{k^*}{\delta_F}, \quad FS' = \delta_{FS} \, FS^*, \quad b' = \delta_b \, b^* \tag{14}$$

Some additional tests are necessary to ensure from 3, 4 and 9 that

a) k', FS' and b' lie within the allowable boundary values (i.e., the maximum and minimum range), and

b) The chosen values are actually available options.

The boundary conditions on k, FS and b simply mean that the δ are also bounded. For example

$$\frac{k^*}{k_{max}} < \delta_F < \frac{k^*}{k_{min}} \qquad (15)$$

Further motion of a given emphasis lever beyond a boundary value would have no effect. That is, the corresponding parameter is fixed at the boundary value. Reaching a boundary value can be easily signaled to an operator (e.g., buzzer).

If the values of k' and FS' as computed in (14) do not match up with the allowed values in (3) and (4) they are set to the nearest allowed values. b' is adjusted to satisfy (8). It is not necessary that the available options for b match up precisely with the computed b'. A simple control loop described in Ref. 1 will handle this mismatch provided the available options are in steps of 10% or so.

IV. CHANNEL CONSIDERATIONS

Error sensitivity problems with transmitted data have generally meant reducing transmission rate (increase S/N) to reduce the error rate to an acceptable level. A given compression technique will tend to become more sensitive as that technique is modified to become more adaptive. Individual errors have a more dramatic impact on reconstruction. Errors in identifiers of algorithm changes (such as headers) can propagate their effect over long sequences.

A practical solution to this problem was developed for space applications in Refs. 1, 3 and 4. Briefly, the solution is to concatenate a (large symbol) interleaved Reed-Solomon code with a convolutionally coded, Viterbi decoded inner channel, yielding virtually error free data at the same S/N that an uncoded link would have a $P_e \approx 1/33$. In addition interleaved Reed-Solomon coding by itself can provide significant burst error protection. Boyd, Cain and Clarke (5) clearly suggest that high rate implementations of the desired RS coders and decoders is feasible with today's technology. The RS/Viterbi combination would appear to be directly applicable to the various AJ spread spectrum techniques likely to be elements of an RPV communication system.

V. DISCUSSION

The globally adaptive rate controlled compressor structure clearly opens up the practical possibility of providing an operator with extensive flexibility to dynamically maximize the usefulness of a limited and changing bit rate. Preliminary descriptions of possible approaches were presented above. Potentially, such techniques should result in significant improvements in overall system performance within severe tactical environments.

Standard approaches to system design would require selecting a few parameter options years before they are used. This essentially means trying to pick a set of options which would "on-the-average" perform best over all possible tactical environments, operators, sensors, data rates, etc. The choices would necessarily be only intelligent guesses since testing all the possibilities beforehand is a practi [illegible] sibility. This perhaps "most difficult" aspect of system design is alleviated by the approaches described above since "all" the possible options are always available to an individual operator.

The compressor rate control structure and the operator control approaches presented here exhibit some degree of autonomous operation. That is, a limited number of bits can be adaptively distributed spatially and temporally to improve the return of desired information. Further degrees of autonomous operation which further reduce operator intervention should be possible.

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