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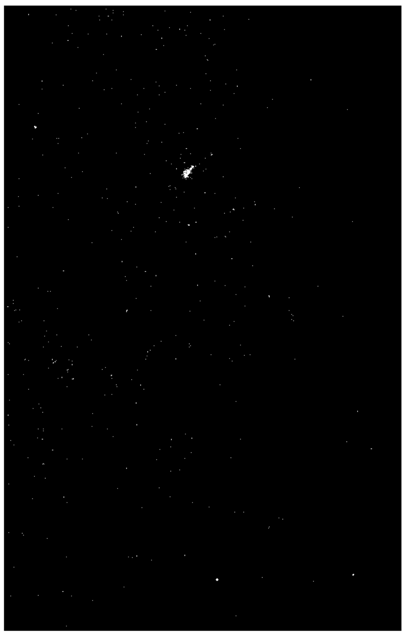

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THE INCREASING RISK AND EXPENSE OF DEEP OCEAN SUBMERSIBLE OPERATION HAS STIMULATED INTEREST IN CONTROLLING UNMANNED, UNTETHERED, REMOTELY CONTROLLED TELEOPERATORS THROUGH ACOUSTIC LINKS. THE LOW BANDWIDTH ACOUSTIC CHANNEL POSES PROBLEMS IN VIDEO COMMUNICATION WHICH NORMALLY REQUIRES A WIDE BANDWIDTH. TRANSMISSION RATE IN VIDEO COMMUNICATION DEPENDS ON THREE FACTORS: FRAME RATE, RESOLUTION, AND GRAY SCALE. IF THE OPERATOR OF THE SUBMERSIBLE'S MANIPULATOR MUST USE A DEGRADED PICTURE FOR VIEWING, IT MAY BE USEFUL TO BE ABLE TO TRADEOFF BETWEEN FRAME RATE, RESOLUTION, AND GRAY SCALE AS THE

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REQUIREMENTS OF THE TASK CHANGE.

THE PURPOSE OF THIS INVESTIGATION WAS TO DETERMINE IF SUCH A SYSTEM WOULD ACTUALLY IMPROVE OPERATOR PERFORMANCE COMPARED TO A SYSTEM IN WHICH THE COMBINATION WAS SET. EXPERIMENTS WERE RUN IN WHICH FOUR SUBJECTS PERFORMED MANIPULATIVE TASKS WITH A MASTER-SLAVE MANIPULATOR UNDER A VARIETY OF TASK REQUIREMENTS, BIT RATES, AND VIDEO CONTROL MODES.

THE RESULTS SHOWED THAT CONTROL OF THE FRAME RATE, RESOLUTION, AND GRAY SCALE COMBINATION WAS A STATISTICALLY SIGNIFICANT FACTOR IN IMPROVING OPERATOR PERFORMANCE.

OPERATOR-ADJUSTABLE FRAME RATE, RESOLUTION, AND GRAY SCALE TRADEOFF IN FIXED-BANDWIDTH REMOTE MANIPULATOR CONTROL

by

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ABSTRACT

The increasing risk and expense of deep ocean submersible operation has stimulated interest in controlling unmanned, untethered, remotely controlled teleoperators through acoustic links. The low bandwidth acoustic channel poses problems in video communication which normally requires a wide bandwidth. Transmission rate in video communication depends on three factors: frame rate, resolution, and gray scale. If the operator of the submersible's manipulator must use a degraded picture for viewing, it may be useful to be able to tradeoff between frame rate, resolution, and gray scale as the requirements of the task change.

The purpose of this investigation was to determine if such a system would actually improve operator performance compared to a system in which the combination was set. Experiments were run in which four subjects performed manipulative tasks with a master-slave manipulator under a variety of task requirements, bit rates, and video control modes.

The results showed that control of the frame rate, resolution, and gray scale combination was a statistically significant factor in improving operator performance.

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Chapter 1

Introduction

As undersea work has moved to increasingly greater depths, much attention has been directed toward the design and use of teleoperators. Undersea teleoperators have been defined as "general purpose submersible work vehicles controlled remotely by human operators and with video and/or other sensors, power and propulsive actuators for mobility, with mechanical hands and arms for manipulation and possibly a computer for a limited degree of control autonomy." (Sheridan and Verplank, 1978)

Submersibles have been around for a suprisingly long time, dating back to approximately 350 B.C. when, according to legend, Alexander the Great descended into the sea in a large glass barrel to observe the undersea plants and animals. The life support system consisted of the air trapped inside the shell, which would have limited the safe diving period to only a few minutes, even though the legend claims Alexander remained submerged for three days. Through the years, considerable progress has been realized in improving the performance of manned vehicles, both in terms of operator comfort and safety and in the accomplishment of complex tasks. One major improvement has been the move toward the remotely controlled vehicle or teleoperator described above. Remote control of such a submersible is desirable for a number of reasons.

The first and foremost reason is the increase in operator safety. When diving to a great depth, submersibles are subjected to tremendous pressures, of the order of eight tons per square inch at a depth of 35,800 feet. Without the protection of pressure hulls, the human body would be unable to survive at any depth greater than 3,000 feet, even for a short period of time. Therefore, the risk of a break in the protective shell is a real danger in manned underwater work. In addition, vehicles may be forced to operate in strong ocean currents, which may reach 3 knots or more. With the growing number of offshore oil wells and the need to maintain them, a number of other dangers arise. In an attempt to shut down a blowout at the *Ixtoc-1 platform* in the Gulf of Campechi off the coast of Mexico in the summer of 1979, a remotely controlled submersible "came too near the high-velocity vortex stream from the well and was blown violently to the surface."(Royce and Robertson, 1978) If a manned vehicle had been used, the results would have been tragic.

A second factor in favor of remote control of submersibles is cost. Unmanned vehicles are less expensive to build because it is not necessary to include sophisticated life support systems or safety features that are otherwise required. The few remaining pressure sensitive instruments and equipment may be protected with simpler, less expensive packages than the large pressure hull used in manned vehicles. This results in smaller, lighter, and less complicated submersibles.

Since unmanned submersibles are generally less bulky and lighter than their manned counterparts, transportation to the worksite is much faster and easier. During the Campeche blowout, both a manned and an unmanned submersible were sent for. The remotely controlled TREAC submersible was loaded onto a plane and arrived hours later while the three-man submersible Pioneer I required a three day voyage by sea. It is clear that if there had been a life or death situation, the manned submersible would have been useless.

Once on site, a teleoperator is also less expensive to run. With manned operations, a great deal of time and money is spent raising and lowering the vehicle due to the limited operating period of the life support system. When working at depths of 20,000 feet, an ascension/descension rate of 40 feet per minute means over 15 hours are spent in transit for each mission. A remotely controlled vehicle may be left at depth until its task is completed, saving time and money and allowing continuous monitoring of the situation. Since unmanned vehicles are smaller and lighter than their manned counterparts, launching and retreiving the submersible requires less massive handling equipment and can be used in more severe weather conditions.

The next phase in the development of submersibles may be the elimination of all physical connections between the surface and the remotely operated vehicle. At present, most teleoperated vehicles require a cable for transmitting information to and receiving control signals and power from the support ship. This is often an expensive, reinforced coaxial type of cable through which electrical power and signals are sent. It must be strong in order to withstand the tensile stresses produced by the submersible at the end and by drag on the rest of the cable. The bulkier cable causes special problems of storage and tending on the support ship deck, but it has the advantage of allowing indefinite mission time since all power is supplied from above and permits fairly high information transmission rates. Another type of cable being tested is the optical fiber. This fiber is formed from glass by rapidly heating a localized section of a glass ingot and drawing the molten glass out to form a very thin fiber. The fiber is then used to transmit information by sending pulses of light through the fiber. Optical fibers permit very high bandwidth communication between the surface and submersible and since the cables are so thin, drag and handling problems are negligible. However, mission time must be limited since optical fibers are not useful for transmitting power. It is possible to have surface-supplied power and high-bandwidth transmission lines by combining coaxial and fiber optic cables, but the low drag and handling ease advantages are lost. All cables have the serious disadvantages of entanglement and limited freedom of movement. When working near offshore oil well platforms, for example, submersible operators must take special care that tethers do not become entwined with platform legs or other cables. Some submersibles are even designed to disengage from the tether and float to the surface if the cable becomes ensnared, a rather unsatisfactory way to end a mission and possibly lose an expensive cable in addition. Dependance on the tether also means the submersible does not have complete freedom of movement underwater. This limitation occurs in two ways. First, the cable is of finite length so that the submersible is restricted to a depth equal to the tether length. Motion in the horizontal directions may also be limited if the support ship movement is restricted, as in the Ixtoc blowout. Burning oil on the surface prevented the support ship from moving above the damaged wellhead, making it difficult to reach with the submersible.(Royce and Robertson, 1979) Another example from the Ixtoc incident illustrates the second way in which tethers limit mobility. When the platform was dragged away, hundreds of feet of drilling pipe were left scattered about the wellhead. Because it was dragging along a cable, the submersible had to spend many hours searching for a path to the wellhead that could be negotiated with the tether.(Royce and Robertson, 1979) Another limitation placed on some submersibles by the cable is in yaw, or rotation about the vertical axis, since many cables can only withstand a certain amount of twist. With all these problems, it is clear that a tetherless, remotely operated vehicle would be very useful. If this is to be realized, a method for communicating underwater without physical connections must be developed.

Wireless communication is most often accomplished with electromagnetic waves, such as radio waves, microwaves, etc. However, these are not suitable for underwater communication due to their high attenuation in seawater. For example, the lowest frequency radio wave in commercial use, 30 kHz, is attenuated by one decibel in 30 cm. (In other words, the wave intensity is cut in half every 90 cm.) Due to scattering and diffusion, light beams are practically opaque at any distance greater than 200 m. Sound waves are also attenuated in water (approximately 1 db per km at 1 kHz), but not to the extent of those above so that an acoustic link is one possibility.

In general terms, an acoustic communication system consists of hydrophones on the submersible and surface ship which transmit and receive sound waves. The messages to be sent are encoded into the acoustic signal in a manner determined by the particular system. Since no cables are necessary for communication, the only limiting factor on the submersibles mobility is the amount of energy it can store per dive.

The major problem with an acoustic link is the low frequency bandwidth of the channel. Due to the attenuation of sound in water, frequencies useful for transmission are limited to below approximately 150 kHz.(Anderson, 1970) A low bandwidth means that a relatively small amount of information can be sent over the channel per unit time. The specific relationship between bandwidth and information transmission rate will be described after a quantitative measure of information is developed. (see Appendix A)

Chapter 2

Information Theory

In order to discuss possible solutions to the problem of low bandwidth communication, it will be necessary to introduce some basic information theory. An information system may be described as consisting of an information source, transmitter, noise source, receiver, and destination as in Fig. 1.

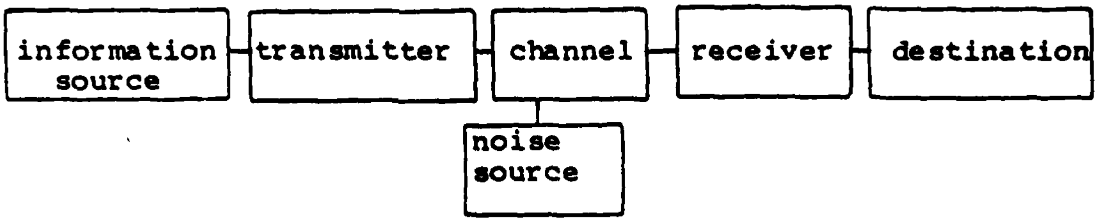


Figure 1. Information System

A message from the information source is encoded by the transmitter into a signal and sent through the channel to the receiver. In the case of an acoustic link underwater viewing system, the information source is the visual scene, including the size, color, shape, and location of objects. These attributes are almost always a function of time as the submersible moves objects around in the work area.

The transmitter is the camera system hardware and software necessary to translate the picture into the acoustic signal to be sent through the channel, the water.

It is at this stage that the message is mapped, through some transformation, into the signal set. This is a 1:1 mapping in which every possible message has one and only one corresponding signal, but there may be a reduction in the number of dimensions in the coordinate system. In the case of acoustic video transmission systems, the three-dimensional visual scene is transformed into a one-dimensional acoustic signal for transmission (neglecting time as a dimension).

The noise in the ocean can come from any number of sources from marine animals to the submersible motors although the major source of noise in the range of acoustic frequencies comes from surface waves and sea spray. The acoustic signal can itself become noise through reverberation in shallow waters.

Hydrophones on the surface ship receive the acoustic signal which is converted into a picture for the destination, the operator. The communication system may be extended by considering the human operator as an information system in series with the one above, with the input to the operator being the picture on the television screen and his output signal being the forces applied to the master manipulator arm.

Information may be defined as any evidence that reduces uncertainty about a situation. However, before information systems can be compared, it is necessary to develop a quantitative measure for the abstract notion of information. A number of desirable features for the unit of measure may be specified. First, the information measure should be a function of p(i), the probability of a message i being selected out of a given set of n possible messages. For example, if a block can only be in one position, the information transmitted by confirming the position would be zero, while the greater the number of possible positions, the greater the information transmitted. It would also be desirable for the measure to be continuous in p(i) and if all messages are equally probable, $p(i)=1/n$, for $i=1,2,\ldots,n$, the information should be a monotonic increasing function of n. In less mathematical terms, a message indicating a block is in one of four possible positions provides twice as much information as a message giving one of two possible positions. Finally, if a choice consists of two successive choices, the total information should be the weighted sum of the individual information values. It can be shown (Shannon, 1949) that the only definition satisfying these requirements is

$$H(i) = -K\, p(i) \log p(i)$$

Since $K \log_s M = K \log_s r \log_r M = K \log_r M$, the choice of the constant coefficient is equivalent to the selection of a logarithmic base. A convenient base for a discrete, binary system is two, i.e.,

$$H(i) = p(i) \log_2 p(i)$$

for which the units of measure have been termed bits. The information content of a source is often called its entropy because of the similar form in the definitions of information above and entropy in thermodynamics. Entropy is often described as the relative degree of randomness in a physical system. Information content of a message set is similarly described as the degree of uncertainty as to which message will be sent.

The capacity of a channel is the number of bits that can be sent through it per unit time. If all possible messages are equally probable, or $p(i) = 1/n$, the rate of information transmission will be a maximum and equal the capacity of the channel. When the probabilities are not so evenly distributed and the same encoding scheme is used, the efficiency of the system may be less than maximum and is said to have some degree of redundancy. This redundancy may be reduced to an arbitrarily small amount by properly encoding the message into the transmitted signal using knowledge of the statistical properties of the information source. One method for accomplishing this is to encode the most often used messages with the shortest symbols. For example, in telegraphy, where a message is encoded by a series of dots and dashes, the most common letter in the English language, e, is represented by a single dot. Less frequently used letters, such as q, x, and z are represented by longer sequences of dots and dashes. In this way, messages, on the average, require less time to transmit. A more general method for generating an optimal code uses a binary system to represent messages. The Shannon-Fano method first arranges the set of possible messages in order of increasing probability. The messages are then split into two equal halves and the group with the higher probability is labeled with a one in the first location of its code. The half with lower probability contains a zero for that bit. Each group is then divided again and the second digit in the code is assigned a one or zero depending on whether the subgroup is of higher or lower probability. This is continued until each message is assigned a unique code. Special rules are used if it is not possible to evenly divide a group and are described in Shannon.

Chapter 3

Video Transmission

The bits per second necessary to transmit a video signal with no signal processing is determined by three quantities; frame rate, resolution, and gray scale. The frame rate is the number of independent images that are displayed per unit time. A distinction should be made here between frame rate and delay. Under slow frame rate, when a new picture appears on the screen, it represents the actual scene at that instance. With a delay, T, the frames may appear at a high or slow rate, but when a new one appears on the screen, it is a representation of the physical scene T seconds ago. It is possible to have a slow frame rate and a delay, especially with an acoustic link, but the difference between the two should be kept in mind. Resolution is the number of independent picture elements (pixels or pels) or dots that make up the scene. This quantity is often expressed as the number of lines in a frame since, in a square frame, the number of pixels per line is usually the same as the number of lines. Gray scale is the number of levels into which the continuous intensity spectrum is quantized. The number of binary digits necessary to specify the intensity level is equal to the base two log of the number of possible levels.

For example, a normal television transmission contains 512 X 512 pixels, each with 64 levels of gray (6 bits), and transmitted at a rate of 30 frames per second. The total bit rate necessary is then found by the following equation:

$$B = F * R * R * G$$

where F is the frame rate (30 sec^{-1}),

R is the resolution (512 pixels/line),

G is the gray scale (6 bits/pixel),

and B is the total bit rate (bits/sec).

Substituting the values for frame rate, resolution, and gray scale from above, it is seen that a bit rate of approximately 47,000,000 bits per second is required. Since this value is much greater than that possible with an acoustic link, some alternative method must be investigated.

With the information theory background in mind, a method may be proposed to reduce the necessary information transmission rate for a video system. Either from prior knowledge of the visual scene or a distribution estimated from samples, an encoding system may be devised to eliminate redundancy and increase the system efficiency. This would insure that the acoustic communication link was being used at as near to maximum efficiency as desired.

Many methods have been devised to accomplish this and it will be helpful to discuss a few of them here. It has long been known that much of the redundancy in video transmission results from the high frame rate at which pictures are sent. In normal television broadcasting, a new frame is transmitted every 1/30th of a second to give the viewer the impression of continuous motion. However, the scene being sent changes very little from frame to frame. When the probability of a particular value for a bit of information is dependant on the previous bits, it is termed a sequential constraint. This constraint is particularly strong in video transmissions, where it has been estimated that only 4% of the pixels that make up an average scene change from one frame to the next.(Dickson, 1973) The transmission of the remaining 96% of the pixels is.therefore redundant and cuts down on the system efficiency.

One of the early techniques for video bandwidth compression called conditional replenishment, takes advantage of this redundancy by transmitting only those pixels that have changed from the previous frame.(Mounts, 1969) The receiver then displays the new pixels and repeats the ones that have not changed. This is much the same way that cartoons are created with the unchanging background drawn first and the moving characters overlayed to give the impression of motion. Of course, this means that the transmitter must also send locational information about the intensities that have changed, but significant bandwidth savings are still possible. A second complication is the necessity of maintaining buffer memory at the transmitter in order to compare the current frame to the previous one and also at the receiver so that unchanged pixels can be redisplayed. A variation on this technique uses the idea that pixels change most rapidly near moving objects.(Haskell and Schmidt, 1975) The frame is divided into moving and stationary areas. The non-moving blocks are then transmitted immediately at a reduced resolution and full resolution is built up over a period of time. The receiver may also display full resolution of the moving objects by interpolating between the pixels that are transmitted to determine the intensities of the ones that are not. This appears quite natural to the operator since it has been found that humans are unable to detect small errors in pixel intensity in moving areas.(Pease and Limb 1971) The human transmission system is unable to process the extra amount of information transmitted at such a high rate. Another reason why high resolution is wasted on rapidly moving objects is due to integration by the camera. The intensity at a point is determined by the amount of light falling on the sensitive element between one frame and the next. If an object is moving fast enough, it can cross a number of pixels in that time period, tending to blur the picture so that a high resolution is not necessarily helpful. High resolution may also be irrelevant through the process of 'chunking' by which people, generally compulsive encoders, categorize or 'chunk' information into easily remembered blocks.(Sheridan and Ferrell, 1974) For example, the shape of the manipulator arm may be stored as a unit. Thus only a small portion of the arm need be transmitted through the channel and the remaining part filled in by the operator in his or her mind.

A second source of redundancy in video transmission occurs within individual frames. Figure 2 shows a plot of the space-dimenision autocorrelation along the horizontal and vertical directions for two typical video pictures. Picture A was a medium distance portrait while picture B was a crowd scene, resulting in a lower autocorrelation for the second picture, but both frames show considerable redundancy.
This intraframe redundancy may be exploited to reduce transmission rates with the proper encoding system. If the pixels above, below, to the left and to the right are all of the same intensity, the probability that the center pixel is of the same intensity is very high. In fact, this is often used as a way of detecting and eliminating noise in a picture. In this technique, the transmitter only sends those pixels that are significantly different from the predicted value. If the receiver uses the same predictive scheme as the transmitter, the pixel intensities that are not sent can be determined and displayed. Again, this requires the transmission of locational information and buffers at the transmitter and receiver, but transmission rate requirements may still be considerably reduced. A similar type of prediction has been used to detect the

motion of objects and predict when pixels are likely to change, allowing better frame to frame encoding. Since the type of encoding that will optimize the information transmission depends on the statistics of the visual scene, it is expected that the best system will vary if the statistics are non-stationary. For this reason, considerable work has been done on developing a coding

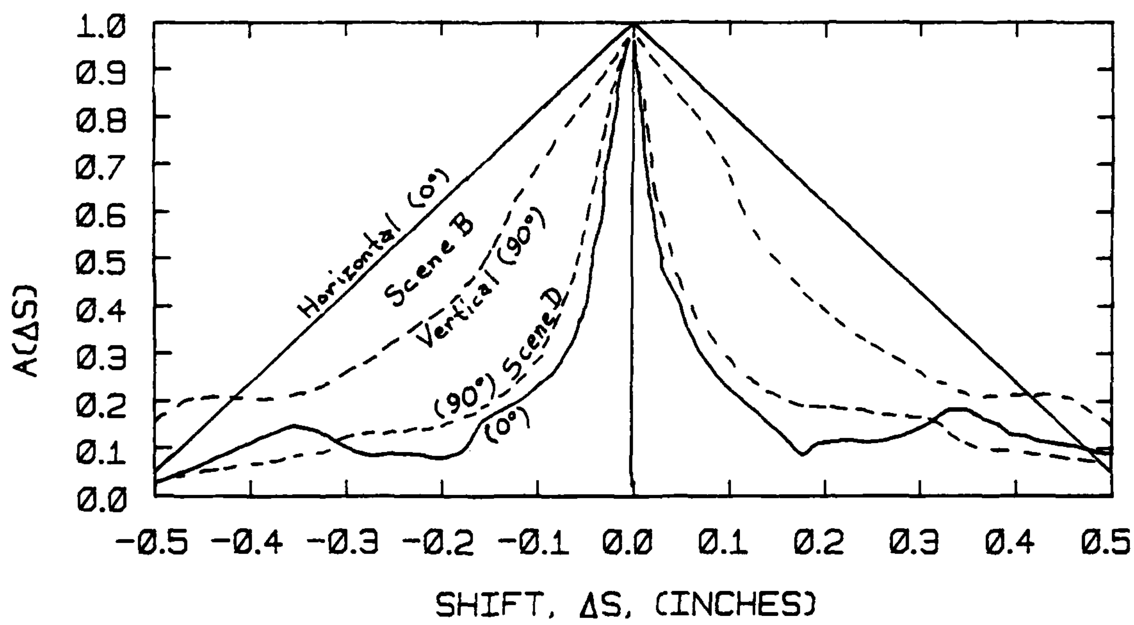


FIGURE 2. Autocorrelation of Two Video Scenes (Reference 1.)
(Note: Linearity of horizontal autocorrelation for Scene B is coincidental)

system that will adapt to changes in the picture statistics for use in video telephone systems.(Haskell and Schmidt, 1975) These techniques monitor the amount of data building up in the transmitter and receiver buffers as an indication of the amount of movement in the picture and how well the current code is doing in reducing the number of bits necessary to specify the picture. When the buffer reaches a certain level, a new coding system is used, trading off between gray scale quantization levels, resolution, and replenishment rate to reduce the transmission rate. If the buffer fills to its maximum capacity, no more information is loaded until it falls below some level. However, the digital processing necessary to accomplish these savings requires time, both for sampling and calculating probabilities if these are not known beforehand and for generating the appropriate code.

Chapter 4

Controlled F-R-G

The method to be investigated here is suggested as a compromise between the systems above and no encoding at all. Two viewpoints may be used to justify this system; the intuitive, practical, approach or information theory. First, the practical approach is covered.

One possible method, in which an 'optimal' F-R-G combination is found and installed, ignores the possibility that the 'optimal' combination may be task dependant. The best choice may differ from task to task and even within a single task. For example, locating a large pipeline would not require a fine resolution or much gray scale, but would need a high frame rate as the camera is panned across a large area. On the other hand, inserting a small hydraulic hose into a socket would be easiest with high resolution and relatively low gray scale and frame rate, while selecting the blue valve from a bank of color coded valves would require high gray scale and less of the other two factors. If a number of these subtasks are grouped into a single, more complicated task, the 'optimal' combination could change almost continually.

An improvement in this method would therefore be to allow the operator to choose the F-R-G combination desired as the task progressed. If the operator found that the scene was changing too rapidly to keep up with, he could trade off resolution and gray scale for a faster frame rate. If a detailed, high quality picture of an object was desired, such as in a precise positioning task, the resolution and gray scale could be increased and frame rate necessarily slowed to maintain a constant available bit rate.

From the information theory point of view, this technique can be seen as an improvement over the first method by reducing the redundancy of the picture when it is not helpful and increasing it when it is useful. For example, for a visual scene in which there is not much movement (as in the valve selection example above), the repetition of the scene at a high frame rate does not present much new information since the probability of a change in the picture is low while an increase in the gray scale or resolution may introduce valuable information. This system could be accomplished easily and quickly without relying on complicated encoding processers. The matching of a communication link to the information source is sometimes compared to the matching of a transmission to the power requirements in an automobile power train. This analogy may be extended to the present case by equating the proposed system with a manual transmission and the buffering system discussed above with an automatic transmissiion. The manual transmission is less costly, more reliable, and more responsive to the operator's wishes in rapidly changing situations. The same may be true of an operator controlled F-R-G system. By using the human operator's ability to rapidly and accurately estimate probabilities instead of the computer's exhaustive sampling and computing, an encoding scheme may be chosen from a limited selection. In this supervisory control mode, while not consciously calculating any probabilities, the operator uses his or her past experiences and knowledge about the situation to predict probable changes in the scene and determine the best F-R-G combination. This would in fact be an adaptive encoding scheme using the human operator to select the mode of operation in place of the buffer monitoring system discussed earlier. Unfortunately, this will require a certain amount of the operator's time and concentration. Just as any other communication channel, the human operator has a limited capacity for processing and transmitting information. The operator would be required to monitor his or her own performance and decide when another F-R-G combination would produce better results. Humans tend to be conservative in their estimates of probabilities, weighting evidence less than it deserves, so that the operator may not be able to optimally select the best combination. Also, since the operator must indicate the preferred F-R-G combination with some physical action, there may be some interference with the primary task of controlling the manipulator. The goal of this investigation is to determine if the improved flexibility of the information transmission offsets this distraction and, if so, under what conditions.

Chapter 5

Experimental Design

Discussion of this experiment has been divided into three main parts; factors to be studied, experimental procedure, and data analysis.

F-R-G Control - The major factor to be studied in this experiment was the effect of allowing the operator to dynamically control the frame rate, resolution, and gray scale (F-R-G) combination of the television picture under the constraint that total bit rate is fixed. This factor was measured by running the tasks twice, once with a set combination and once allowing the operator to choose among the possibilities listed on page 44 (Appendix B).

Tasks - It is also important to know what kinds of tasks are affected by the new method. If only a single task is used, there may be some doubt as to whether improvement in the operator performance is valid for tasks other than the one used. While it is of course impossible to cover every imaginable task a teleoperator may be called upon to perform, the experiment demands that at least two rather different tasks be tested. One parameter by which tasks may be categorized is the response variable to be measured. In this experiment, the first task measured time to completion for a fixed task and the second measured the amount accomplished in a fixed time.

The first task chosen was taking a nut off a task hub (TON). This is a fairly common task for manipulative work that involves considerable dexterity. It is an example of a task in which the operator must work as quickly as possible and errors are not directly counted. This task is often used in experimental work and using it here will allow comparison of results with previous work. It is a task in which the visual scene changes little during the work. The second task chosen was moving pegs from one hole to another (PEG). This is also a common experimental task in which the operator is asked to move pegs from one side of a board to the other and is scored on how many pegs are successfully moved by the end of a given time period. Dropped pegs are not recoverable and only a certain number of pegs are provided so that errors are important to the final score. This type of task is representative of a large number of real-life tasks in which time is not the overwhelming factor. Examples are: picking up dropped items from the ocean bottom, handling dangerous materials, etc. In this task, the type of visual information varies from time to time. To locate the peg, a high frame rate may be desired, while a high resolution may be necessary to position the peg near the hole. It would probably not be advisable to completely eliminate time as a factor in the tasks because the operator could achieve a perfect score even at the slowest frame rates by taking a long time to complete the task. Also, all realistic tasks have some time limit.

Bit Rate - The final factor to be considered is the bit rate. It may be that the effect of enabling control of the F-R-G combination is greater at one bit rate than at another. It was therefore decided to run the experiment at two different bit rates. The first rate chosen was 10,000 bits/second to correspond to the current lower limit for an acoustic link between the surface and a submersible. For the range of variables possible with the available equipment, going to a bit rate less than around 7,500 bits per second would not allow a sufficient selection of possible combinations and it was felt that this value was too close to the first bit rate to produce a significant difference in performance. A transmission rate of approximately 20,000 bits per second was chosen as the second level because it represented the other end of the acoustic link range and was still sufficiently greater than the first rate to enable detection of any effect on performance or interaction with other variables.

Equipment - The physical setup of the experiment was fairly standard. The MMSL master-slave manipulator was used with a heavy black curtain between the operator and slave end of the manipulator to block direct vision. The work area was viewed on a television monitor placed in front of the operator through a camera just on the other side of the curtain. The information from the camera was fed into the matching interface and then into the special electronic box, SPOX, where the frame rate, resolution and gray scale were altered. A more detailed description of the camera, interface, and SPOX may be found in Appendix B. The F-R-G combination was controlled by the operator with three keys of a CRT terminal at his or her left. When an increase in frame rate, resolution, or gray scale was indicated, the reductions in the other two factors required to maintain a bit rate below the maximum level were determined by the computer software and the proper codes sent to SPOX (see Appendix C). The current F-R-G was displayed at the terminal along with the running time. The video from SPOX was displayed on a Tektronix monitor before being relayed to the operator's television screen through a Panasonic television camera.

For the first task, taking a nut off, the task hub was placed directly in front of the slave manipulator with the stud and nut pointing at an angle of 45° towards the camera which was four feet away. The area around the nut and hub was viewed with a 50mm lens in order to obtain a close-up since the objects were small. For the PEG task, a 25mm lens was used so that the entire work area could be seen at one time. The task apparatus consisted of five pegs of various colors placed in a board perpendicular to the line of sight and raised to an angle of approximately 10 degrees. The boards and pegs are best described with the following figure:

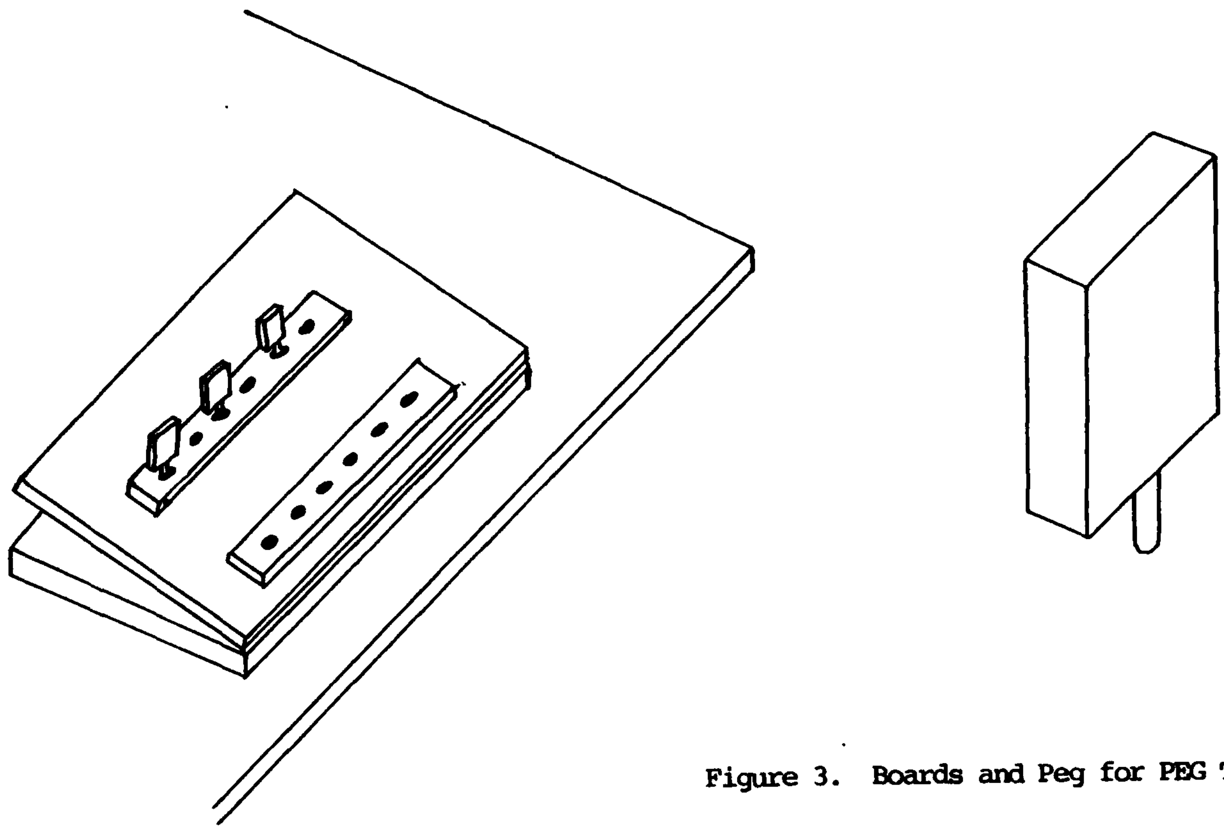


Figure 3. Boards and Peg for PEG Task

The procedure for the TON task was fairly simple. The subject entered his or her identification and the number of the run on the terminal. The task began when a picture appeared on the monitor and the computer timed the run until the operator typed a digit indicating the nut was off. A hardcopy report for the run was then produced indicating the run time, date, subject, time spent at each F-R-G combination, etc.(See Appendix C for examples of the data reports) During the run the operator either worked with a preset F-R-G combination or controled the combination with the three terminal keys. The bit rate depended on the option chosen at the start of the run.

The procedure for the PEG task was similar to the TON task except the task was stopped by the computer after a set time by cutting out the picture on the monitor and ringing a bell on the terminal. The operator then entered the number of pegs successfully moved and a report was again produced. If the subject was able to move all five pegs from one of the boards before time ran out, the task was continued by moving them back to the first board.

<u>Training</u> - Training required much time in this experiment. Previous experiments by Ranadive (see reference) have shown that subjects' performance levels off after approximately 9 hours of training. Even more time was anticipated to be required with this system since the operator must also learn to use the F-R-G control. Figures 4 through 7 show the

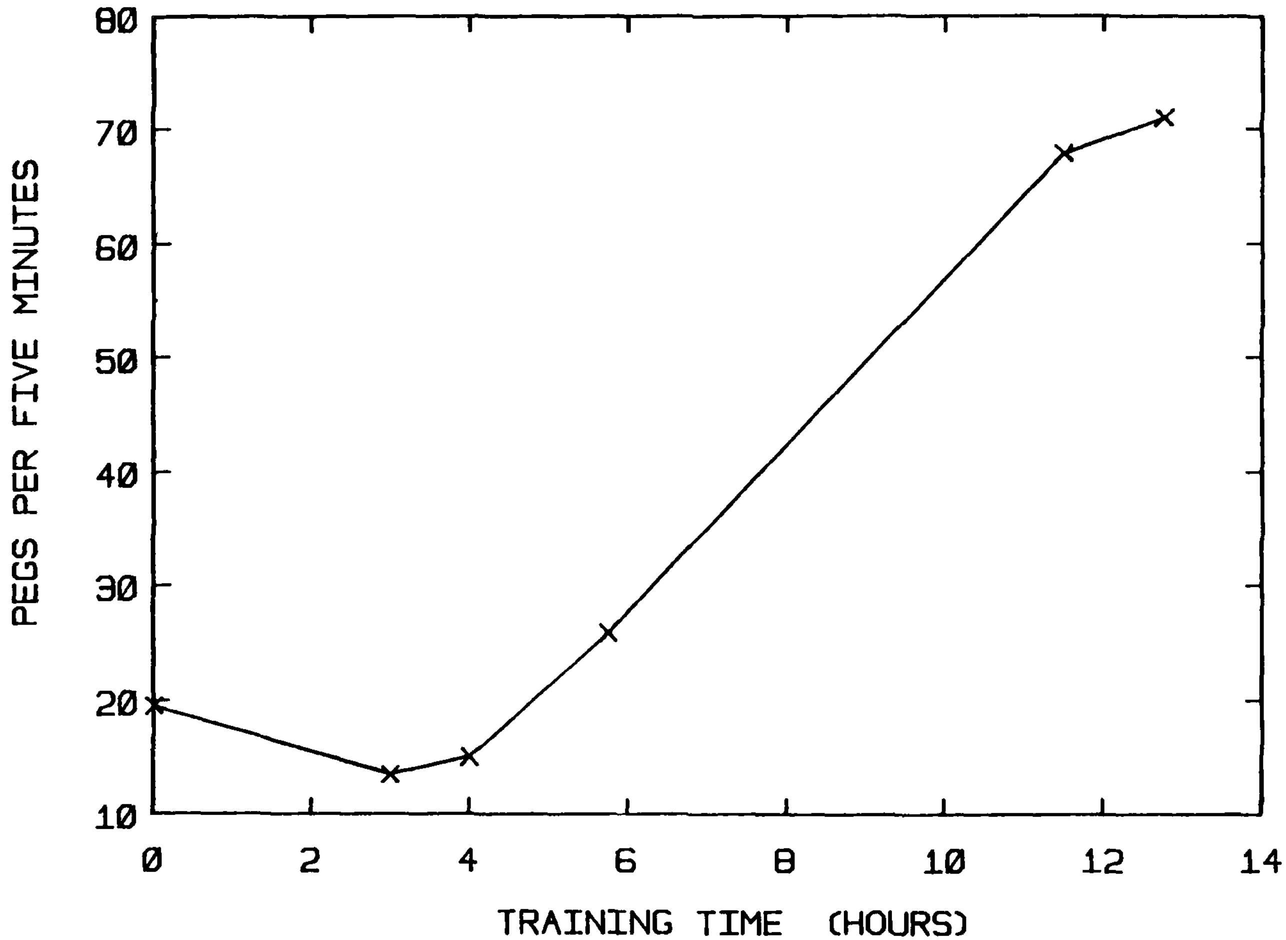


Figure 4a. Learning Curve for Subject 1 PEG Task

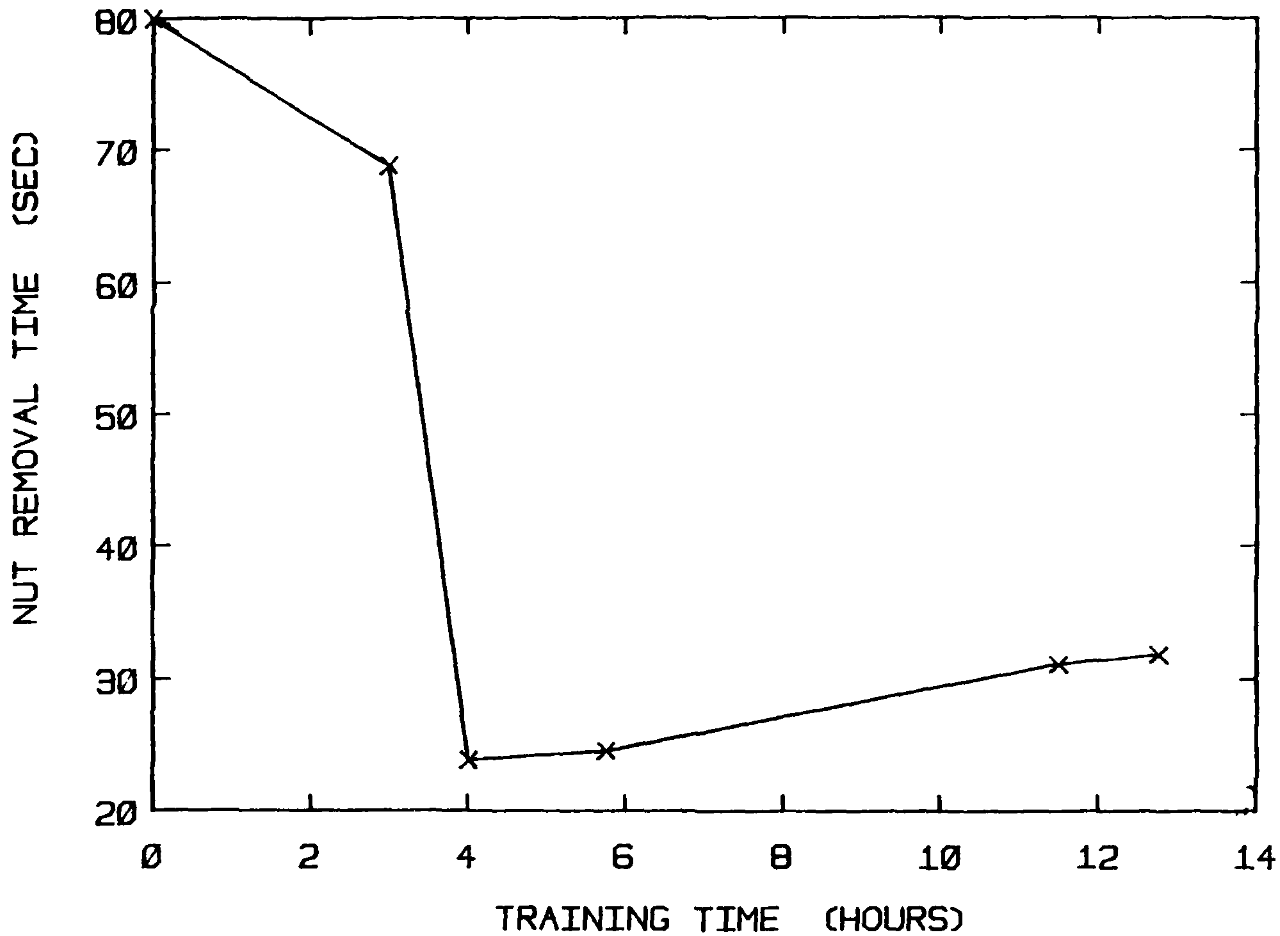


Figure 4b. Learning Curve for Subject 1 TON Task

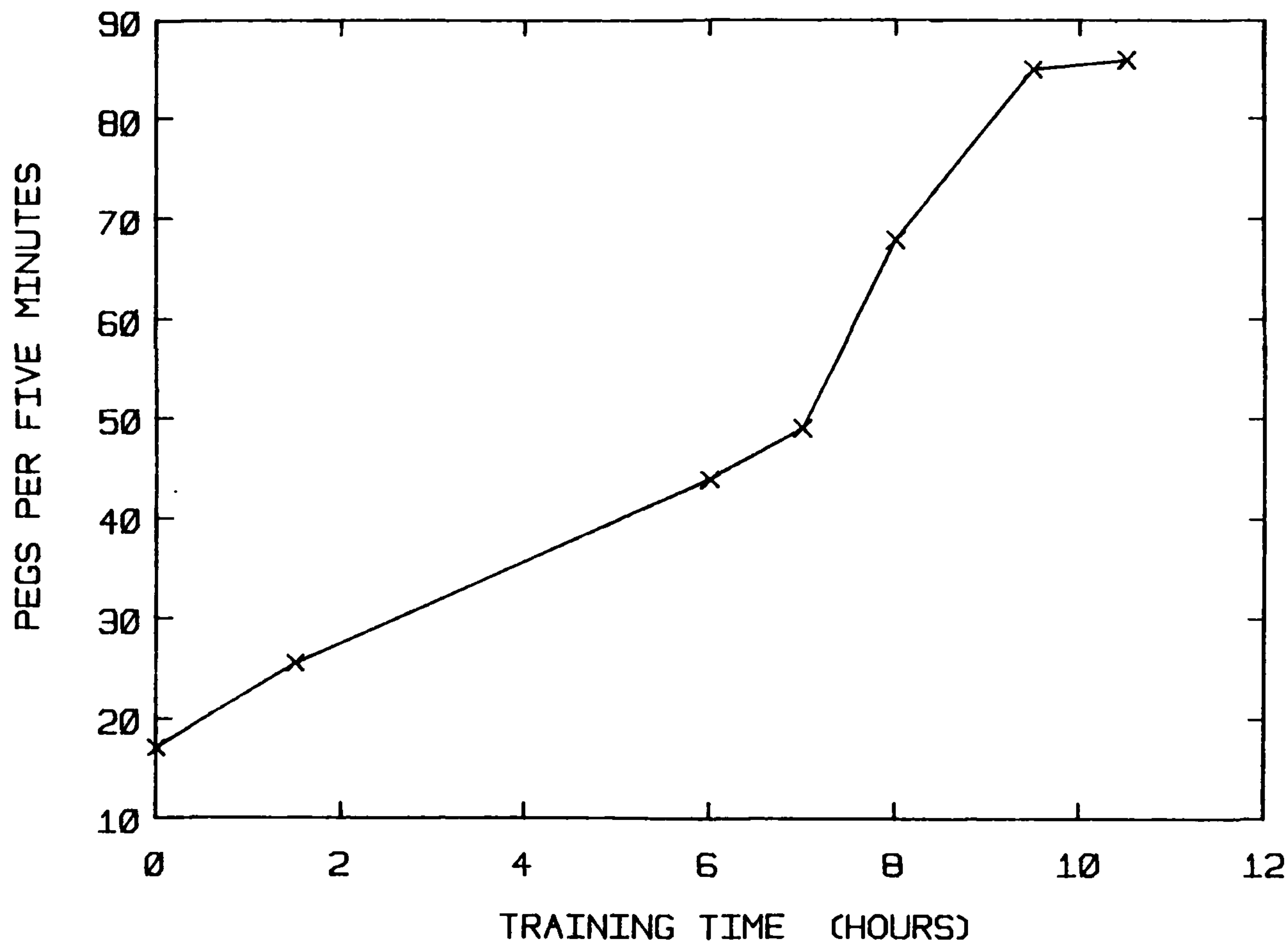


Figure 5a. Learning Curve for Subject 2 PEG Task

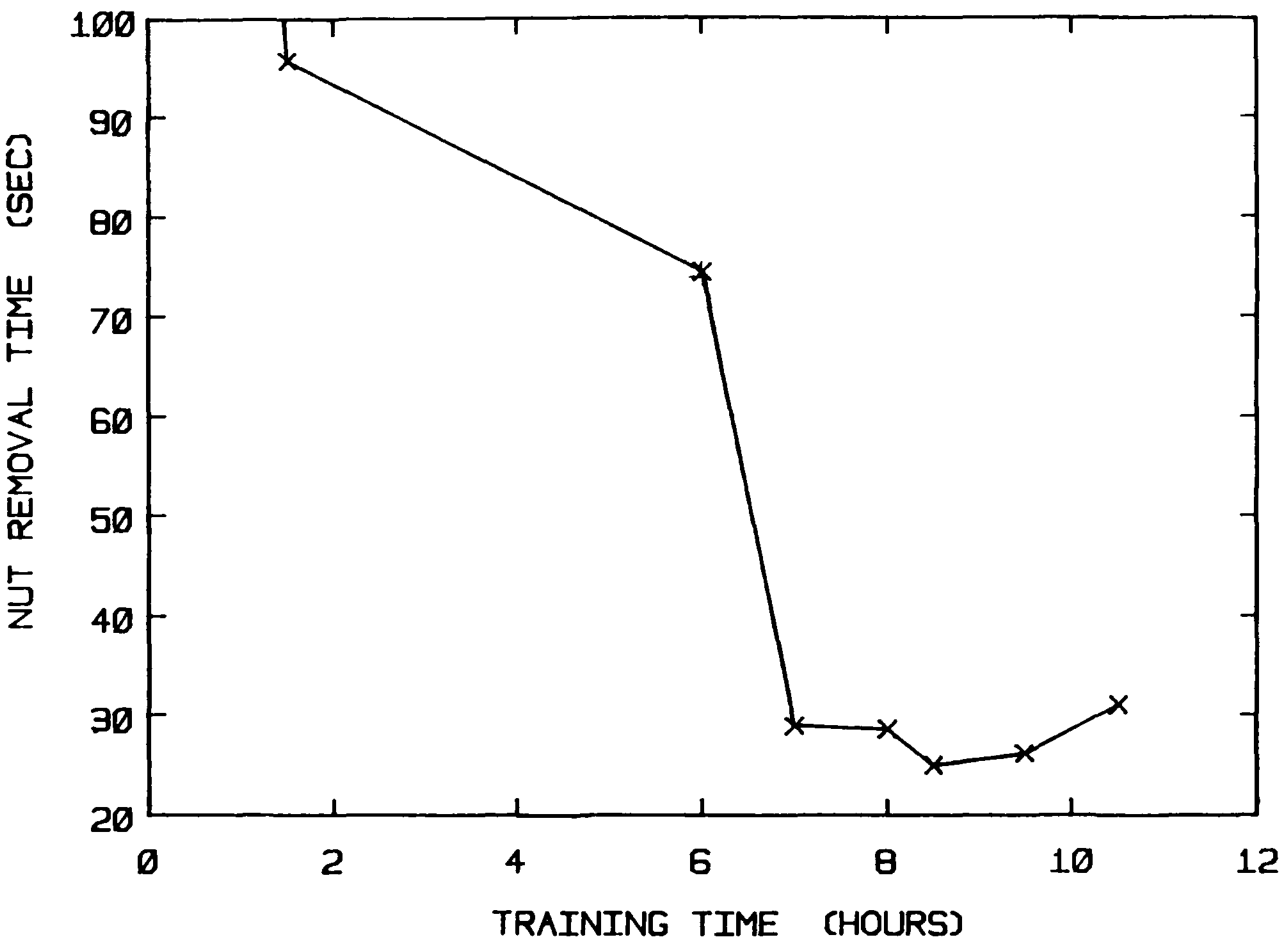


Figure 5b. Learning Curve for Subject 2 TON Task

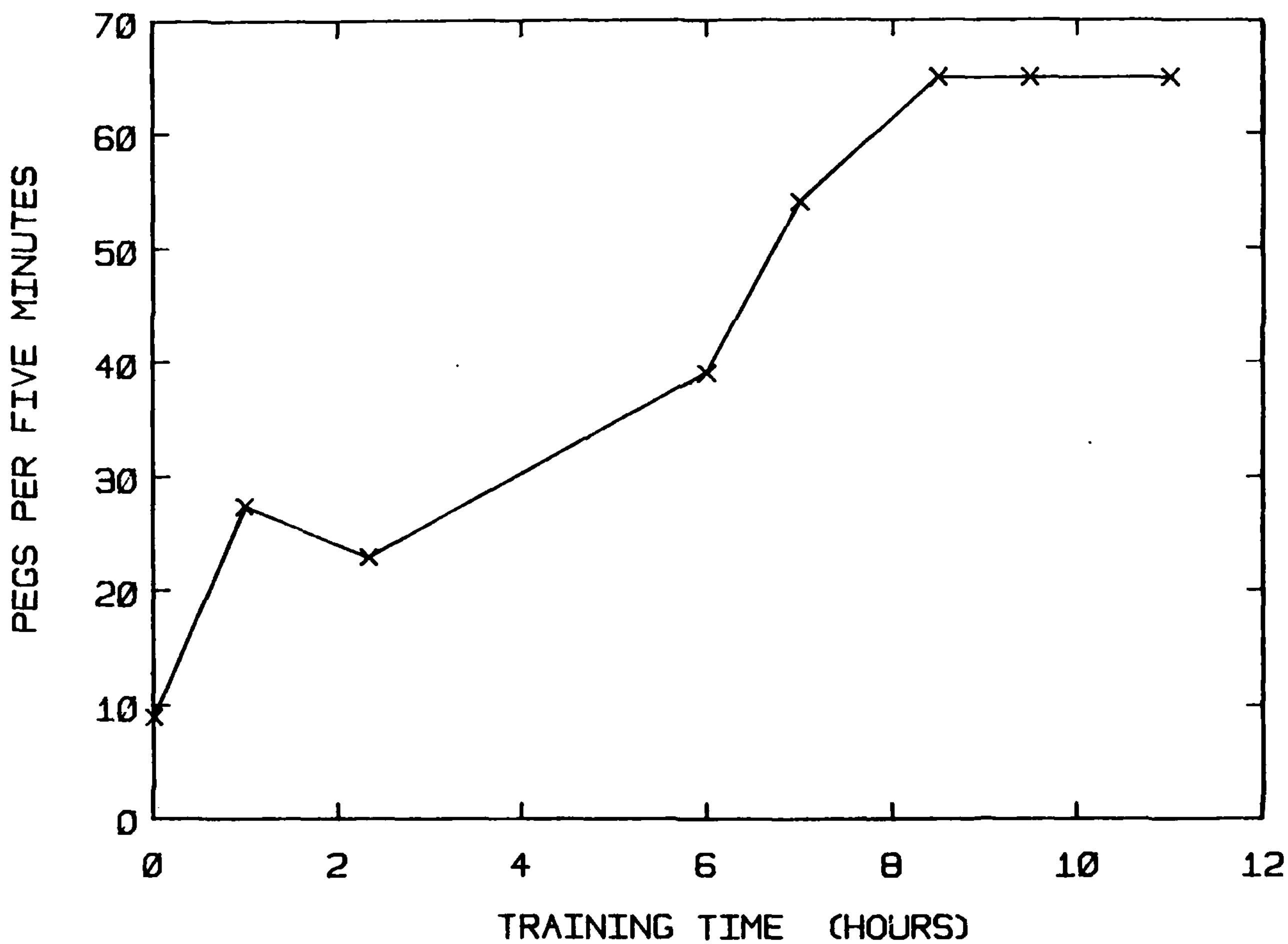


Figure 6a Learning Curve for Subject 3 PEG Task

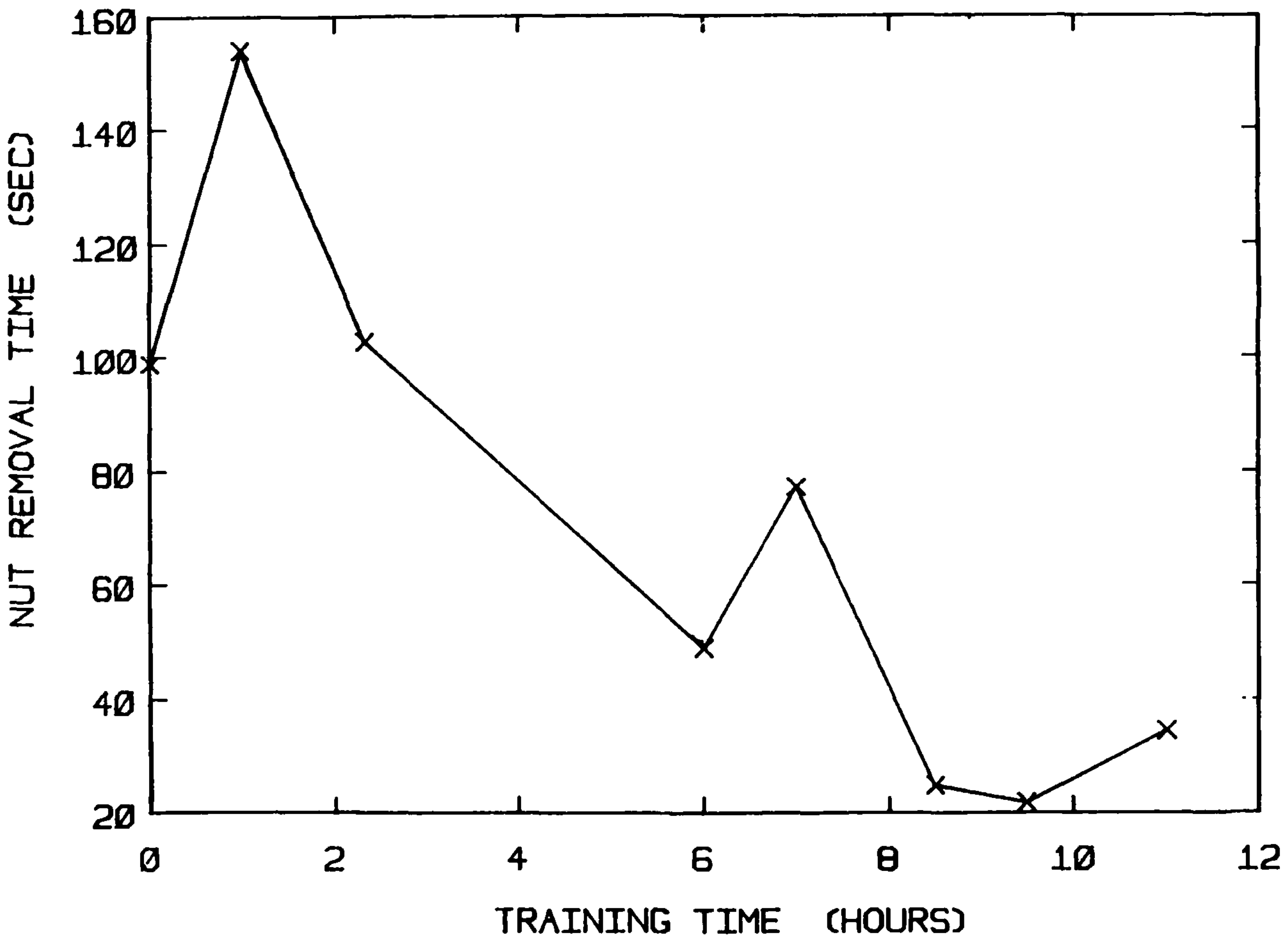


Figure 6b. Learning Curve for Subject 3 TON Task

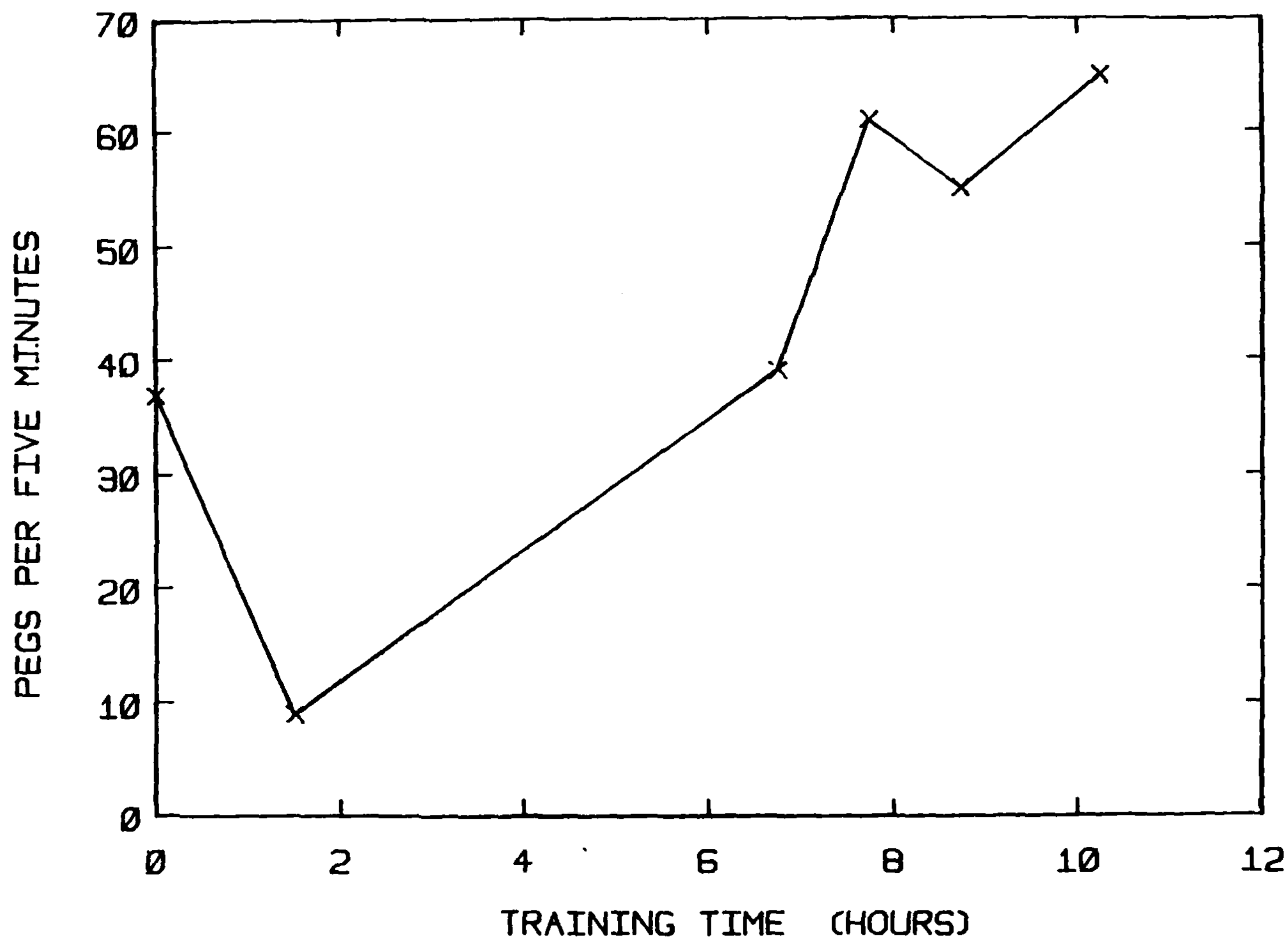


Figure 7a. Learning Curve for Subject 4 PEG Task

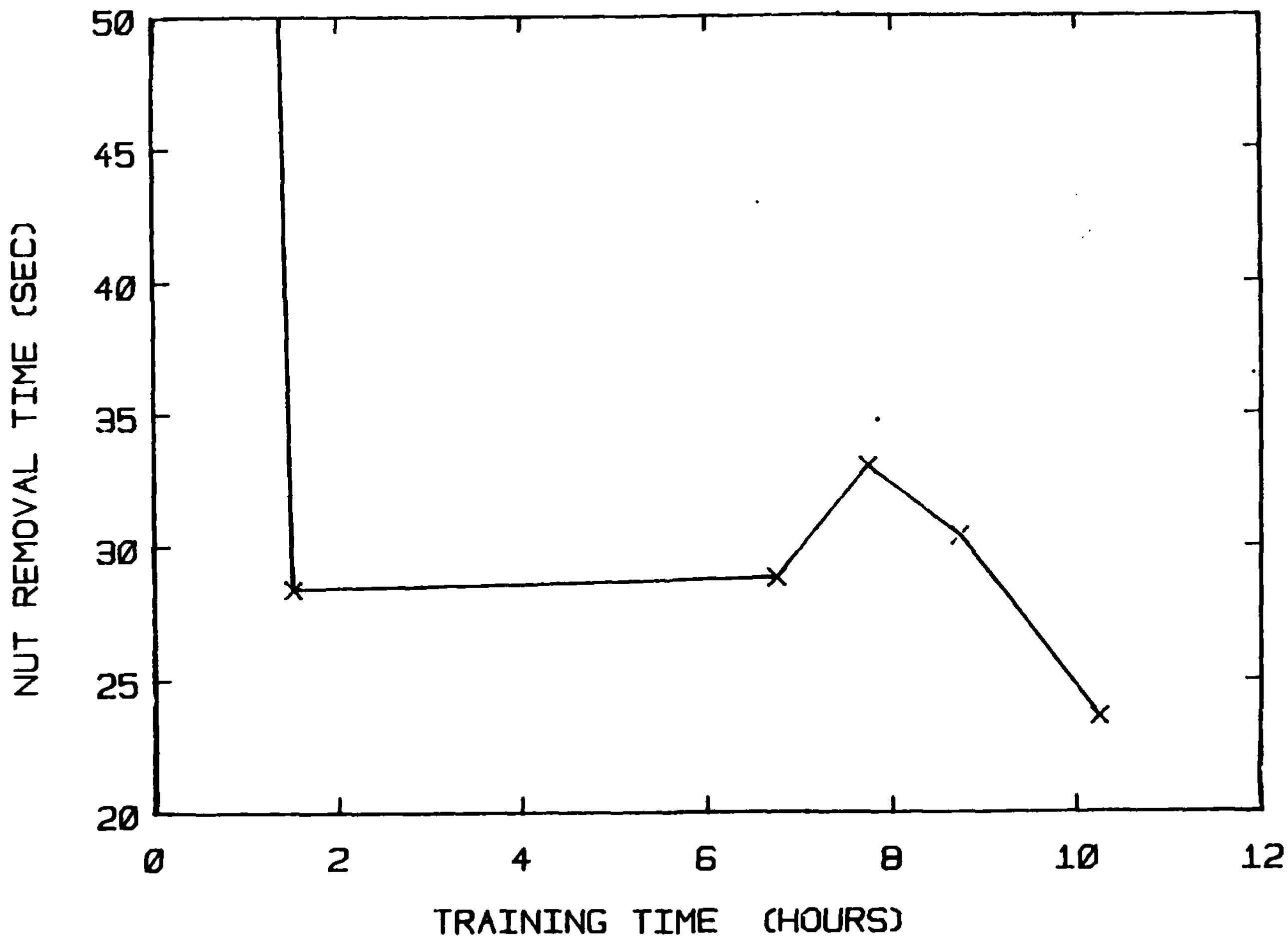


Figure 7b. Learning Curve for Subject 4 TON Task

subjects' learning curves for the PEG and TON tasks. There was considerable variability between subjects and tasks in the amount of training time required. Some subjects required only a few hours to reach a steady state performance (especially in the TON task) while others climbed or dropped more slowly. One subject, (no.5) appeared to still be improving after 13 hours of training and could not be included in this analysis. The difference in training required between the two tasks was expected. Many tricks and subtle visual clues were possible in performing the PEG task (shadows, references, etc.) so that scores steadily improved as the subjects learned to use them. This also resulted in a broader range of final scores in the PEG task than in the more straightforward TON task. The large gaps between some of the test points resulted from an equipment breakdown that prevented testing but allowed practice to continue.

Procedure - The order in which tests were run was chosen at random to eliminate this factor from consideration. Each subject repeated every combination of bit rate, task, and control mode four times.

Three factors for analysis and four subjects result in a 4 X 2 ** 3 experiment which may be shown in tabular form as follows:

	control				no control			
	TON		PEG		TON		PEG	
	B1	B2	B1	B2	B1	B2	B1	B2
S1								
S2								
S3								
S4								

FOUR RUNS FOR EACH COMBINATION

where B1 and B2 are bit rates
and S1, S2, S3, and S4 are subjects

Experimental Design

GRAY SCALE

RESOLUTION		4	3	2	1
	128	0.11	0.22	*	0.44
	64	0.44	0.86	*	1.66
	32	1.66	3.14	5.65	9.42
	16	9.42	14.13	*	28.26

MAX BIT RATE = 11571

GRAY SCALE

RESOLUTION		4	3	2	1
	128	0.22	0.44	*	0.86
	64	0.86	1.66	*	5.65
	32	5.65	*	9.42	14.13
	16	14.13	28.26	*	*

MAX BIT RATE = 23142

POSSIBLE F-R-G COMBINATIONS

Chapter 6

Results

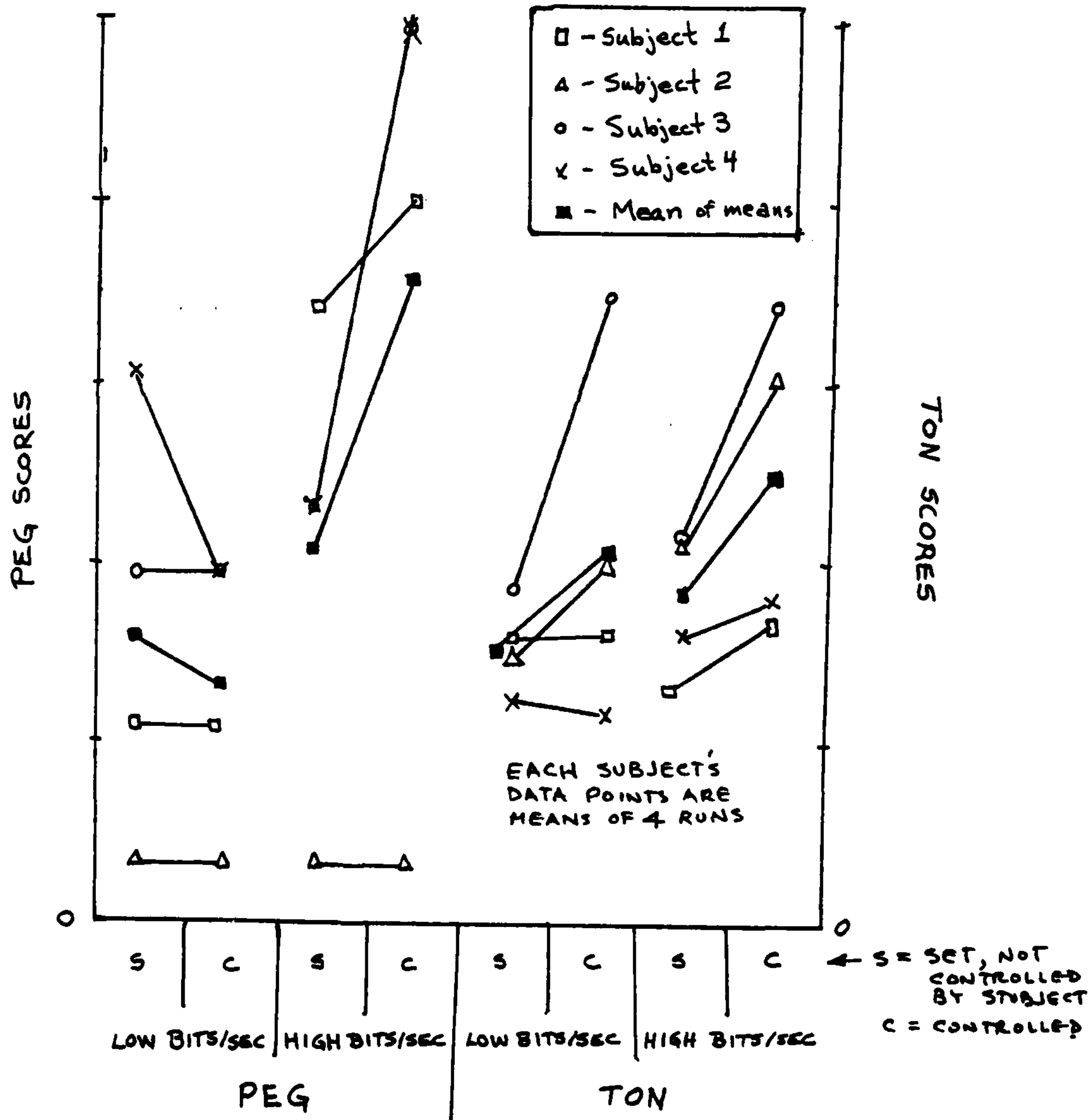
Analysis - In order to obtain a consistent type of measurement for both tasks, the run time in the TON task and the number of pegs in the PEG task were normalized. The number of pegs scored in the PEG task was divided by the number of pegs moved during the last practice run of the training period. The inverse of the run time in the TON task was multiplied by the time required to remove the nut for the last practice session of training.

For PEG task score;
P = (pegs scored in run) / (pegs scored in training)
UNDER "SET" CONDITION

For TON task score;
P = (task time in training) / (task time in run)
UNDER "SET" CONDITION

This resulted in a consistent, dimensionless unit of performance measure for both tasks. The performance scores for each subject and run are found in Appendix D.

The data was analyzed using analysis of variance to determine if the control of F-R-G had a statistically significant effect on operator performance and if any other factors interacted with the primary factor. Since each combination of variables was repeated four times for each subject, the repititions were used to find the 'within group sum of squares' for the F ratio tests. The results of the analysis of variance are shown if Table 1 below. The F values show the effects of control, task, and subject to be significant to the 95%, 99.9%, and 90% percentiles, respectively. Suprisingly, bit rate was not found to be a statistically significant factor at the levels tested. The strongest interactions occured between task and subject, at the 99% confidence level and between control and task, at the 90% level. Each of these results is investigated more thoroughly below.



SUMMARY OF SCORES

TABLE 1. Analysis of Variance

	F	
Control	5.15	**
Bit rate	2.5	
Task	162	****
Subject	3.91	*
CB	< 1	
CT	3.64	*
BT	< 1	
CBT	< 1	
CS	1.32	
BS	< 1	
CBS	< 1	
TS	4.93	***
CTS	1.19	
BTS	< 1	
CBTS	< 1	

significant to

* - 90.0%

** - 95.0%

*** - 99.0%

**** - 99.9%

<u>Control</u> - The primary factor to be investigated in this experiment was shown to be statistically significant to the

performance of the remote manipulator operator. To study this result further, an analysis of variance was performed on each subject's data independent of the remaining subjects. Tables 2 through 5 display the results of these analyses. As seen by the F values in these tables, when analyzed separately, control of the frame rate, resolution, and gray scale combination is statistically significant in only one of the four cases. An explanation for this result was found by examining the way in which subjects used the control when it was available. One way this could have been done was to count the total number of times the operator changed the F-R-G combination during each run. However, this measure of system use does not take into account how long the subject remained at each combination. One operator may have flipped through many combinations but spent a majority of the time at one combination while another subject could slowly change from one setting to another and both would show the same number of changes. But the second operator has probably made better use of the system than the first. To take care of this possibility, another measure of how well the operator utilized the variable combination system was calculated. The percentage of the total run time that the subject was using a particular F-R-G combination was calculated from the raw data reports. The standard deviation of these percentages was then determined for each experimental run. The values found are shown in Table 8 of Appendix D. When the standard deviations are compared

TABLE 2. Analysis of Variance
Subject 1

	F	
Control	< 1	
Bit rate	< 1	
Task	69.0	****
CB	< 1	
CT	< 1	
BT	2.0	
CBT	< 1	

TABLE 3. Analysis of Varaince
Subject 2

	F	
Control	< 1	
Bit rate	< 1	
Task	29.2	****
CB	< 1	
CT	< 1	
BT	< 1	
CBT	< 1	

TABLE 4. Analysis of Variance
Subject 3

	F	
Control	5.9	**
Bit rate	< 1	
Task	60.5	****
CB	< 1	
CT	4.5	**
BT	< 1	
CBT	< 1	

TABLE 5. Analysis of Variance
Subject 4

	F	
Control	< 1	
Bit rate	3.4	*
Task	47.2	****
CB	1.3	
CT	< 1	
BT	1.3	
CBT	< 1	

to the analysis of variance results, a correlation is found between the system use measure and the statistical significance of allowing control of the F-R-G tradeoff. The subject (no.3) upon whom control had the greatest effect also had the lowest standard deviations in the percentage of time spent at each setting. This was especially true in the PEG tasks when the control factor was expected to have the greatest effect.(see interactions section below and task descriptions earlier) Although subject no.2 also had a low standard deviation, examination of the raw data showed that it had been obtained by almost constantly switching back and forth between settings. Subjects no.1 and no.4 had very high standard deviations, the result of choosing one combination and sticking with it. In the TON tasks, all four subjects remained at one setting for most of the run, although, in general, the particular setting preferred varied from subject to subject, from trial to trial and from task to task. This will be discussed more fully in the next chapter.

Task - The task was by far the most significant factor affecting the operator performance. The interpretation of this result is that one task makes the transition from the full frame rate, resolution, and gray scale of the training period to the degraded picture more easily than the other. From the higher performance scores (of approximately an order of magnitude) in Appendix D of the TON task, it is evident that this task is less affected by low frame rate, resolution, and gray scale than the PEG task. Possible reasons for this are proposed in the next chapter.

Subject - Even though subject variability was lessened by normalizing scores with training test values, there was still a statistically significant difference in subjects. Part of this difference was due to the system use discussed above, although the subject showing the greatest control effect did not have the highest average scores.

Bit rate - The lack of significance in the bit rate statistics was suprising since it was expected that a lower rate of information transmission would seriously affect performance. Three possible explanations for this unexpected result come to mind. First, the two bit rates may not have been sufficiently different to show any significance. Second, the bit rates may be so low that a nearly impossible task becomes only a more nearly impossibe task when the bit rate goes from 20,000 bits per second to 10,000 bits per second. Lastly, the bit rates may not be low enough to cut out important information when redundancy is removed. A combination of the first two possibilities is most likely judging by subject's comments regarding the difficulty of the tasks.

Interactions - Control was expected to affect different tasks differently. This was confirmed to the 90% percentile significance in the analysis of variance. Since the visual scene in the PEG task changed more with time, the adaptable system proved a greater assistance than in the relatively unchanging TON task.

The subject-task interaction simply demonstrates the not-too-suprising fact that some operators are better at one task and worse at another than the other subjects.

Chapter 7

Discussion

The experimental results just presented have confirmed some of the expectations discussed in Chapters 2 through 5 and denied others. The primary question of the investigation regarding the effect of using an operator-adjustable frame rate, resolution, and gray scale has been partially answered. This chapter discusses these results and suggests ways in which operator performance might be further improved.

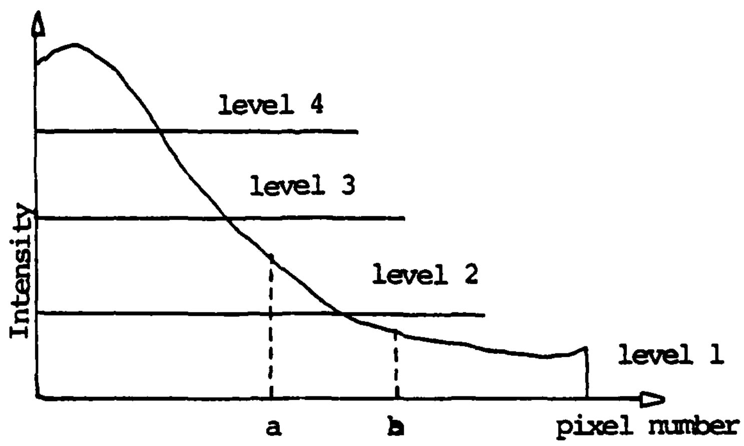
It was found that well-trained operators were capable of performing relatively difficult tasks under very low rates of information transmission. Subjects who required five minutes or more to remove the nut in the TON task using the 2 Mbits/sec rate at the start of training were able to complete the task in as short a time as 65 seconds during the experimental runs using a bit rate of only 1.1 kbits/sec. However, it was felt that this may be approaching the lower limit for these particular tasks with the equipment used. Lower resolution, frame rate, or gray scale would probably mean the task could not be completed except through pure luck. A decrease in resolution or gray scale would disable recognition of the features of the scene. A lower frame rate would create excessive problems in keeping the manipulator arm in a constant position between frames. A master capable of holding a static position might ease this limitation.

A number of advantages and disadvantages of the operator-adjustable system were discovered. One of the principal uses of the adjustable F-R-G system was to confirm that the peg was in the hole. When the subject felt that the peg was in the hole, he could switch to the maximum resolution and gray scale to be sure before releasing the peg. In the set combination case, the subjects often had the peg in the hole, but lacked the confidence to release it. The low frame rate picture was also used to get a better idea of the position of the nut in relation to the manipulator gripper. When actually turning the nut, a higher frame rate was generally used.

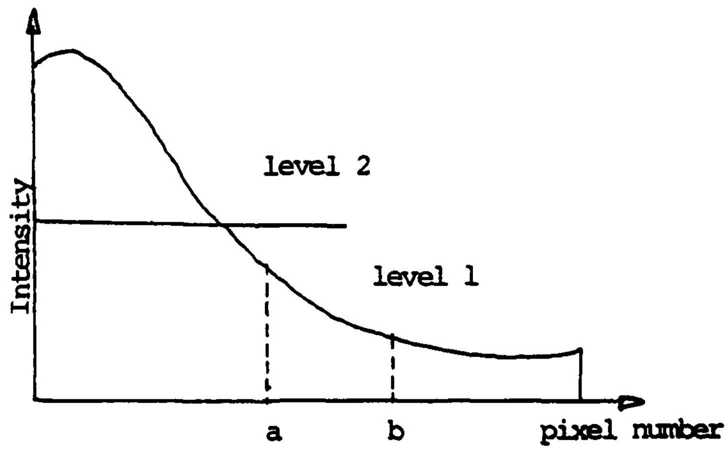
It was not possible to tell if the subjects were using the 'optimal' combination at any given instant since this depends on personal preference, but one subject felt he was using a lower frame rate at the expense of performance because the low resolution picture required more mental concentration than a low frame rate. Perhaps this effect could be verified using a computer generated graphics task in which picture redundancy is under greater control and fewer factors influence performance than the more realistic tasks performed in this experiment.

One problem discovered with this system involved the physical action necessary to change the F-R-G combination. Even though there were only three keys and they were within easy reach of the operator, the subjects sometimes found it necessary to look at the CRT terminal when making adjustments, which created problems in holding the manipulator steady. The controls should be moved to either the television monitor where they can be viewed peripherally or onto the master manipulator arm for easy location. It was also felt that displaying the current frame rate, resolution, and gray scale created a problem. Rather than adjust the picture to the desired quality, the subjects seemed to adjust the numbers on the display to get some predetermined combination.

A final problem with the test setup involved the lighting. Since the lighting was not adjustable during the task, changing the number of bits of gray scale was less effective. For example, if the gray scale was set at two bits per pixel, the intensity spectrum would be quantized as follows:



For the same intensity distribution, ont bit would divide the spectrum as follows:



If the operator were trying to distinguish between pixels A and B, it would no longer be possible. If the lighting were adjustable along with the gray scale, the spectrum could be raised to allow this distinction. A lower gray scale could then be used than would otherwise be possible.

Chapter 8

Conclusion

It has been shown that a variable frame rate, resolution, and gray scale combination does have a statistically significant effect on the performance of remote manipulator operators. This effect depends on how the operator uses the adjustable system and also on the type of task being attempted. At the levels tested, the bit rate did not have a significant effect on the operator performance, possibly due to the difficulty of the tasks.

Future experiments may show even greater advantages with this type of system as tasks become more realistic and complex.

Appendix A

Acoustic Communication Links

<u>Attenuation</u> - High frequency sound waves are strongly attenuated by water, forcing the acoustic link to be a limited bandwidth channel. Attenuation is a reduction in acoustic intensity, defined as power per unit area perpendicular to the direction of travel of the sound wave. The intensity may be determined from the following equation:

$$I = K * p * \overline{u}$$

where I is the wave intensity,
K is a constant dependant on the choice of units,
p is the excess pressure,
u is the particle velocity,
and the bar indicates time average.

Intensity level is defined in relation to some reference intensity, I_o, as

$$L = 10 * \log (I / I_o)$$

so that a difference in intensity level is independent of the chosen reference level

$$L = 10 * \log (I / I_o)$$

Attenuation may result from two causes; scattering and absorption. Scattering is the propagation of acoustic energy into areas not covered by the receiver. Absorption may be divided into four categories; 1.) thermal conductivity, 2.) viscosity, 3.) structural and chemical relaxations, and 4.) resonant absorption. The total attenuation is a function of frequency and distance from the source and may be expressed as

$$TL = -10 * \log (I / I_o) = \alpha * (r - r_o)$$

where TL is the total level loss
α is called the attenuation coefficient and is a function of frequency,
I_o is the source intensity,
r is the distance from the source,
and r_o is conventionally 1 yard.

Figure 8 gives a plot of the attenuation coefficient as a function of frequency. As can be seen from the graph, higher frequencies are strongly attenuated, necessitating the use of the lower and mid ranges of frequency in acoustic communication systems.

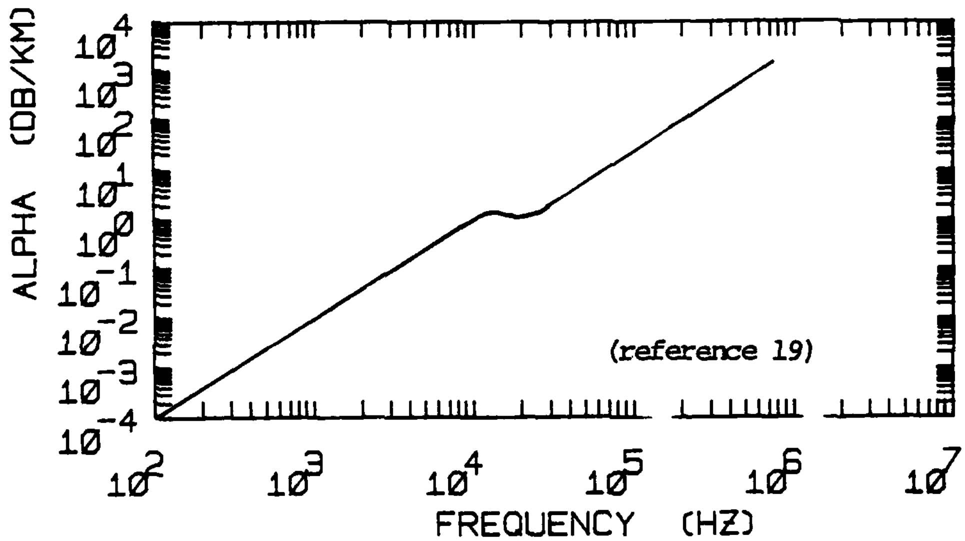
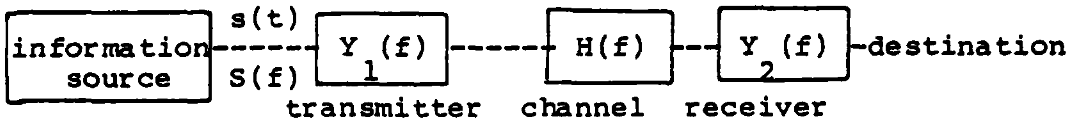


Figure 8. Attenuation Coefficient

__Transmission Rate__ - Because of their relative immunity to interference, discrete rather than analog signals are used in acoustic communication systems. Sound pulses are sequentially transmitted through the water to indicate the presence or absence of a binary digit in the message. The rate at which these pulses may be sent is determined by the bandwidth of the channel. This relation may be shown by considering the block diagram of a noiseless communication system shown below.(Bennet, 1970)



$S(f)$, $Y_1(f)$, $H(f)$, and $Y_2(f)$ are the Fourier transforms of the signal, transmitter, channel, and receiver, respectively. Let $T = 1/f_s$ be the duration of each elementary signaling interval and the output wave of the transmitter be represented by

$$s(t) = \sum_{n=-N}^{N} b_n g(t-nT)$$

where each b_n is one of the permissable values of the signal and $g(t)$ is the standard pulse emitted by the transmitter. If there are only two permissable values of b_n, the signals are termed bits. Then the Fourier transform of the original signal is

$$S(f) = \int_{-\infty}^{\infty} s(t)e^{-j2\pi ft}dt$$

$$= \sum_{n=-N}^{N} b_n \, G(f)e^{-j2n\pi fT}$$

If we let $Q(f) = Y_1(f)H(f)Y_2(f)G(f)$, the signal from the receiver will then be

$$r(t) = \int_{-\infty}^{\infty} Y_2(f)H(f)Y_1(f)S(f)e^{j2\pi ft}\,df$$

$$= \sum_{n=-N}^{N} b_n \int_{-\infty}^{\infty} Q(f)e^{j2\pi f(t-nT)}\,df$$

$$= \sum_{n=-N}^{N} b_n q(t-nT)$$

The ideal pulse form, q(t), would be rectangular of width T and height A. This form would have no overlap between sequential pulses. However, as seen from the Fourier Transform of this waveform, Fig. 9 , this would require a wide band of frequencies.

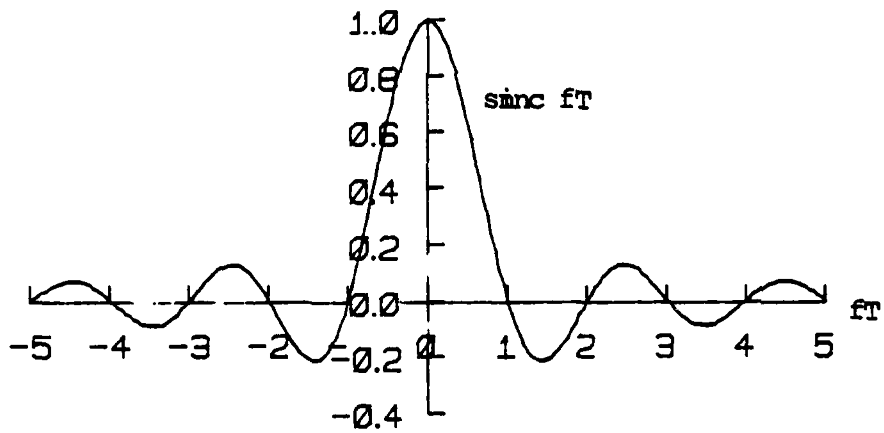


Figure 9. Graph of sinc fT

The theoretical maximum rate at which pulses may be sent over a channel of bandwidth f_0 may be found using Nyquist's Sampling Theorem. The following derivation (from Bennett) describes Nyquist's first method which requires that q(0) be a nonzero constant A and that q(mT) vanish when m is any positive or negative integer. At each sampling point, one and only one pulse would be nonzero, i.e.;

$$q(mT) = A\,\delta_{mo} \qquad \text{(I)}$$

where $\delta_{m,n}$ is the Kronecker delta

Then the received signal, r(mT) is

$$r(mT) = \sum_{n=-N}^{N} b_n\, q((m-n)T)$$
$$= A \sum_{n=-N}^{N} b_n\, \delta_{m-n,o}$$
$$= Ab_m$$

The b_m are then found from the received signal be dividing r by the constant A. Using the Inverse Fourier Transform,

$$q(mT) = \int_{-\infty}^{\infty} Q(f)e^{j2\pi fmT}\,df$$
$$= \sum_{n=-\infty}^{\infty} \int_{(2n-1)f_{s/2}}^{(2n+1)f_{s/2}} Q(f)e^{j2\pi mf/f_s}\,df$$
$$= \sum_{n=-\infty}^{\infty} \int_{-f_{s/2}}^{f_{s/2}} Q(f'+nf_s)e^{j2\pi m(f'+nf_s)/f_s}\,df'$$
$$= \int_{-f_{s/2}}^{f_{s/2}} e^{j2\pi mf/f_s} \sum_{n=-\infty}^{\infty} Q(f+nf_s)\,df$$

Requirement (I) is satisfied if and only if

$$\sum_{n=-\infty}^{\infty} Q(f+nf_s) = A/f_s$$

The narrowest band is obtained by permitting only one nonzero component in the series for each f in the range $-f_s/2$ to $f_s/2$, or

$$Q(f) = (A/f_s)\text{rect}\,(f/f_s)$$

from which $q(t) = A$ sinc $f_s t$. This q(t) satisfies the condition in (I) for no intersymbol interference when the signaling rate is f_s and the samples are taken at multiples of $1/f_s$. The band required is exactly the range from $-f_s/2$ to $f_s/2$, which means that no frequencies of absolute value greater than one half the sampling frequency are required.

Thus, the maximum rate at which pulses can be sent is theoretically two for every frequency in the bandwidth. However, in practice, this system is never used due to the high susceptability to error. Slight discrepencies in synchronization or noise can result in high error rates. There is an exchange rate between signal power to noise ratio and transmission rate for a given bandwidth channel as shown in the figure below.

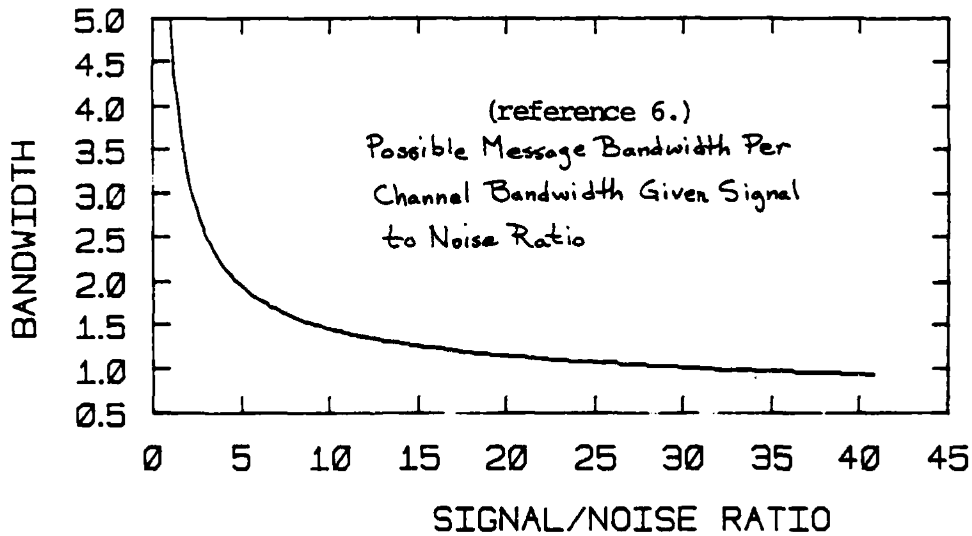


Figure 10. Transmission Rate:Signal-Noise Ratio Tradeoff

The actual rate at which information may be transmitted depends on where along this curve the particular system is operating.

Appendix B

Hardware

The hardware for this work consisted of the following equipment in the Man-Machine Systems Lab:

1.) General Electric TN2200 Solid-State Automation Camera
2.) General Electric PN2110 Automation Interface
3.) Special Purpose Box Electronics (SPOX)
4.) Digital Electronics Co. PDP 11/34
5.) Zenith CRT Terminal
6.) Tektronix 608 X-Y Oscilloscope Monitor
7.) Panasonic Television Camera and Monitor
8.) Argonne Lab E-2 7 D.O.F. Master-Slave Manipulator
9.) Task Apparatus

Camera - The GE TN2200 Solid-State Automation Camera is a charge-coupled device which features small size, low power consumption, flexible interfacing, and integrating detectors. The TN2200 C.I.D. Microsensor contains a square array of 128 X 128 (16,384) light sensitive elements, which consists of a pair of capacitors that share charge through a P-coupled region. Horizontal electrodes connect to one set of capacitors and vertical electrodes connect to the other set. Light striking an array element generates positive carriers on the capacitors (holes). Negative bias on the electrodes holds the charge until removal of the bias from both the vertical and horizontal electrodes causes the accumulated charge to be injected into the substrate and sent to the remaining circuitry. The TN2200 also provides the circuit logic to perform a raster scan of the C.I.D. array and produce synchronization signals for the PN2110 Automation Interface.

Interface - The PN2110 is designed to support the TN2200 Solid-State Automation Camera. Power, control, and clock signals are provided to the camera which returns analog video and synchronization signals to the interface. Outputs from the PN2110 include analog video, analog horizontal sweep, analog vertical sweep, 8-bit digitized video, strobe, end of line, and end of frame signals. Analog video from the camera is converted to a digital signal with an 8-bit successive approximation A/D converter and then back to analog through a D/A converter. For a more detailed description of the TN2200 Camera and PN2110 Interface, refer to their respective manuals. The digital signal along with various control and synchronization signals are used by the special interface built for this system.

SPOX - The special purpose box, SPOX, was designed to convert the 128 X 128 pixels per frame with eight levels of gray at a frame rate of 28.26 frames per second into an analog video signal with switch-selectable frame rate, resolution, and gray scale. The reduction in frame rate was accomplished by storing the digital information from the

PN2110 Automation Interface for a single frame in a 16K RAM (random access memory) and refreshing the display monitor with the picture until time for the next frame. Switches controlled the input to presettable asynchronous counters that counted end of frame pulses from the PN2110. When the count equaled the input value, a new frame replaced the one in memory. The counters allowed the original frame period to be multiplied by (2N-1) for N=1,2,3,...,11 and giving the following possible frame rates;

28.26, 14.13, 9.42, 5.65, 3.14, 1.66, 0.856,
0.435, 0.219, 0.11, 0.055 (frames per second)

The resolution was also chosen through switches on the front panel of SPOX, with possible selections of 128, 64, 32, or 16 horizontal and/or vertical elements per frame. The divisions by two were accomplished by repeating a single pixel two, four, or eight times along the row and/or column.

Levels of gray available were 16, 8, 4, or 2 (4, 3, 2, or 1 bits). These were selected by pairing the four most significant bits from the PN2110 with four switches on the SPOX panel into AND gates. Setting a switch then caused the corresponding bit to be ignored in the D/A conversion. The four least significant bits were grounded to reduce the memory requirement since it was felt that a greater number of gray levels was only barely distinguishable. The following section describes modifications made to SPOX to allow computer control of the frame rate, resolution, and gray scale.

As originally designed, frame rate, resolution, and gray scale were varied by setting certain codes on the switches on SPOX. In order to give an adjustable F-R-G system a fair test, it was necessary to devise a much simpler man-machine interface to SPOX. This was done by replacing the switches and pull-up resistors with direct connections to a parallel interface in the PDP 11/34. The codes sent to SPOX may then be under program control (see Fortran subroutine OUTPT2). The connections and modified SPOX schematics are shown in Table 7 and Figure 11.

Display - The analog video output of SPOX is displayed on a Tektronix 608 X-Y Oscilloscope. Two aspects of this monitor made it unsuitable as the final display to the operator. First, the screen is only 4.5 X 4.5 inches, too small to permit easy viewing. The second problem is the green color of the screen was found to be distracting to the operator. For these reasons, a second camera, a Panasonic, was used to view the Tektronix screen and display the picture on a 8.5" diagonal Panasonic monitor.

The manipulator used was a seven degree of freedom Argonne Labs E-2 master-slave manipulator. Extensive discussion of this apparatus and the modifications to it may be found in reference 21.

Specific dimensions of the task apparatus are listed in Table 6 below.

TABLE 6. Task Dimensions

PEG task:	Peg block ----------	2" x 2.5" x .75"
	Peg dowel ----------	1.25" long, .375" dia.
	Hole ---------------	.438" dia.
	Hole separation ----	3.25"
	Board separation ---	10"
	Board width --------	2.5"
TON task:	Nut size -----------	3/4"
	Turns --------------	4 turns
Task distance from camera ----		approx. 5'

TABLE 7a.
Connections for DR11-C and SPOX
Code:

Row 1 - Signal name from DR11-C

2 - Pin 1 of DR11-C

3 - Ribbon cable #1

4 - DB-25 connector at rear of 11/34

5 - DB-9 connector at rear of 11/34

6 - Ribbon cable #2

7 - Alpha connector 1A

8 - Alpha connector 2A

9 - Ribbon cable #3

10 - Ribbon cable #4

11 - Frame rate on SPOX

12 - Resolution on SPOX

13 - Gray scale on SPOX

TABLE 7b.
Connections for DR11-C and SPOX continued

1.	OUT00	OUT01	OUT02	OUT03	OUT04	OUT05
2.	C	K	NN	U	L	N
3.	38	32	7	24	31	28
4.	7	9	11	13	15	17
5.						
6.	1	2	3	4	5	6
7.	19	9	18	8		
8.					19	9
9.					18	17
10.	18	17	16	15		
11.					1	2
12.						
13.	5	6	7	8		

TABLE 7c.
Connections for DR11-C and SPOX continued

1.	OUT06	OUT07	OUT08	OUT09	OUT10	OUT11
2.	R	T	W	X	Z	AA
3.	27	25	22	21	19	18
4.	19	21				
5.			1	2	3	4
6.	7	8	9	10	11	12
7.						
8.	18	8	17	7	16	6
9.	16	15	14	13	12	11
10.						
11.	3	4	5	6	7	8
12.						
13.						

TABLE 7d.
Connections for DR11-C and SPOX continued

1.	OUT12	OUT13	OUT14	OUT15
2.	BB	FF	HH	JJ
3.	17	13	12	11
4.				
5.	5	6	7	8
6.	13	14	15	16
7.				
8.	15,13	5,3	14,12	4,2
9.	10, 6	9,5	8, 4	7,3
10.				
11.				
12.	1, 5	2,6	3, 7	4,8
13.				

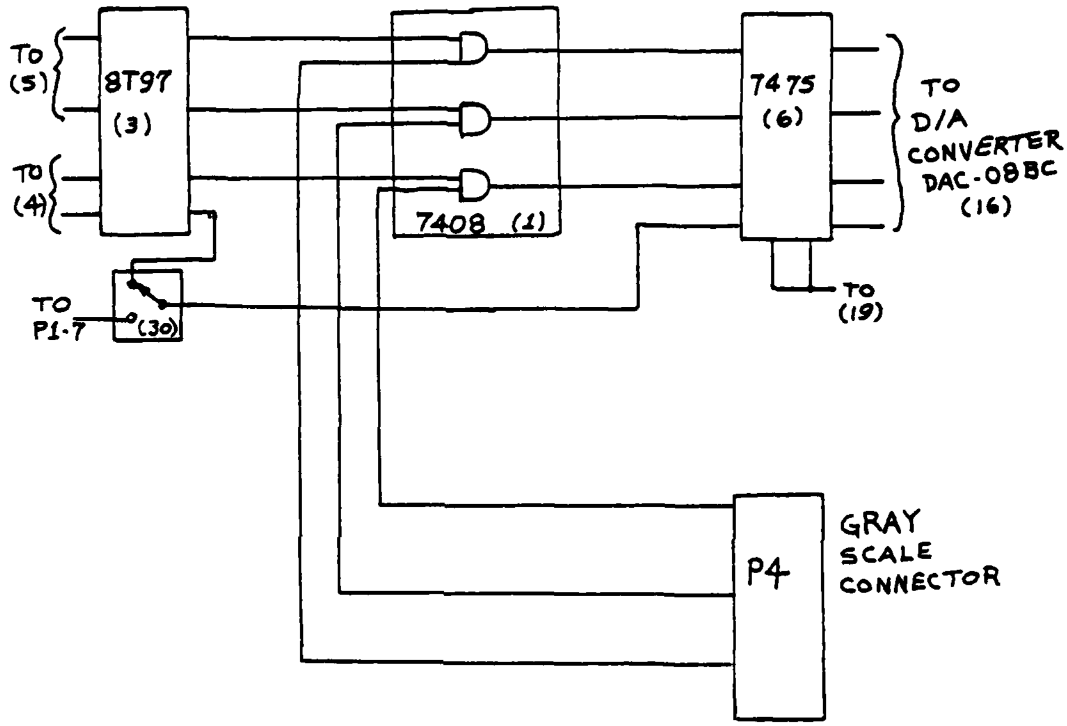


Figure 11a. SPOX Modifications

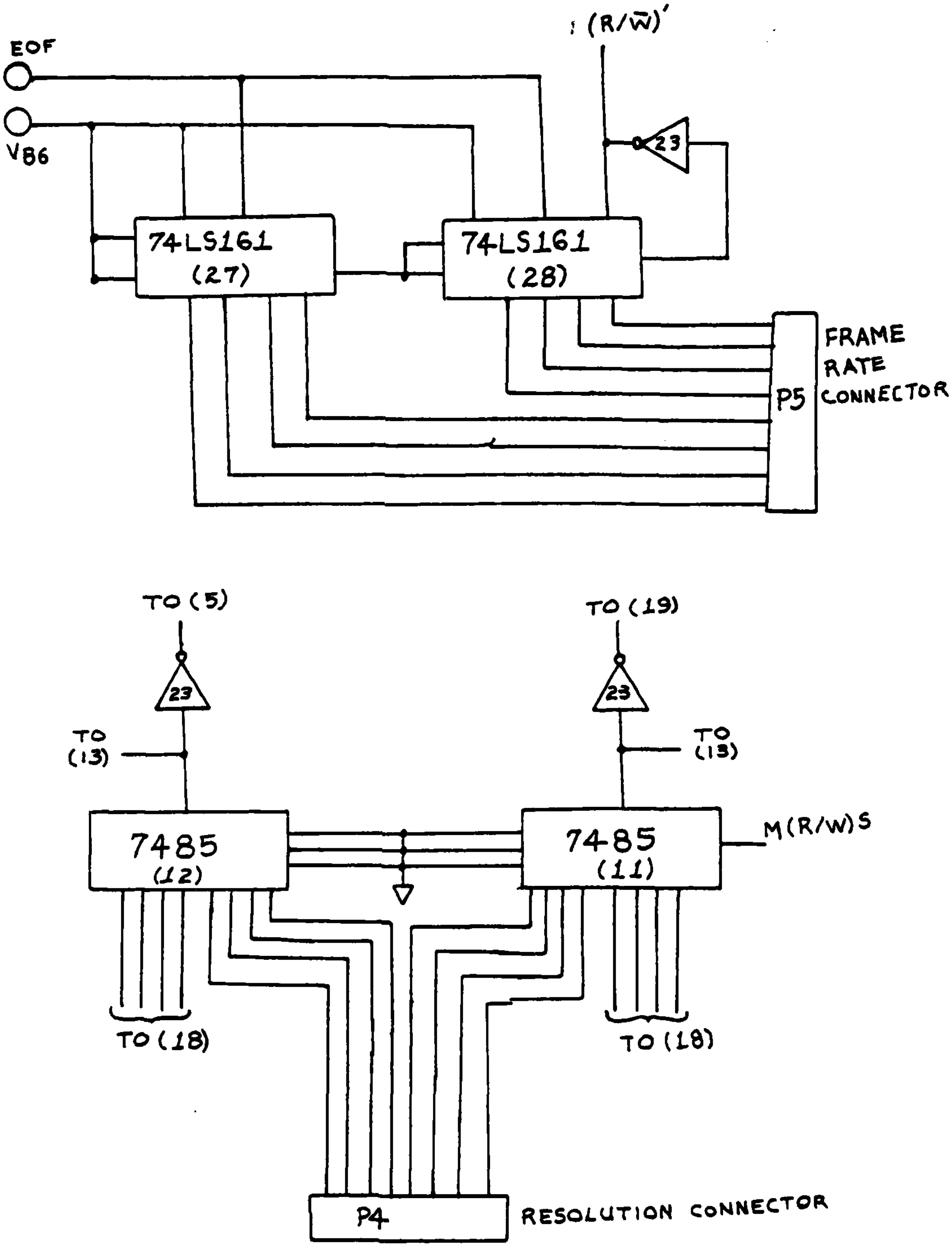


Figure 11b. SPOX Modifications

Appendix C

Software

OUTPT2 - Subroutine OUTPT2 is used to output the codes to SPOX through a DR11-C parallel interface. CMD is the output register of the DR11-C in device common ANCOM. The first four bits of CMD are used to control gray scale, the next eight bits are used for frame rate and the next three bits are used to control resolution. The last bit of CMD is not used. With four choices of gray scale, eleven different frame rates, and four resolutions, a total of 4 X 11 X 4 = 88 combinations are possible. Since $\log_2 88 = 6.4$, only 7 bits are actually necessary to select a given combination if these bits must be sent over a limited channel.

SRFG - The purpose of the main program SRFG is to receive input from the operator and determine the proper combination of F-R-G. Depending on which of three keys are typed at the terminal, either the frame rate, resolution, or gray scale is increased and one or both of the other factors are decreased to keep the bit rate at or below the maximum entered at the start of the experiment. If the frame rate is to be increased, the gray scale is dropped until the bit rate is below the maximum. If the gray scale reaches its minimum before the bit rate is low enough, resolution is decreased. If resolution is to be raised, gray scale is lowered first, then frame rate, Finally, if gray scale is to be increased, resolution is dropped first, then frame rate.

A general flowchart for program SRFG follows. The following abbreviations were used:

INC F - increase frame rate

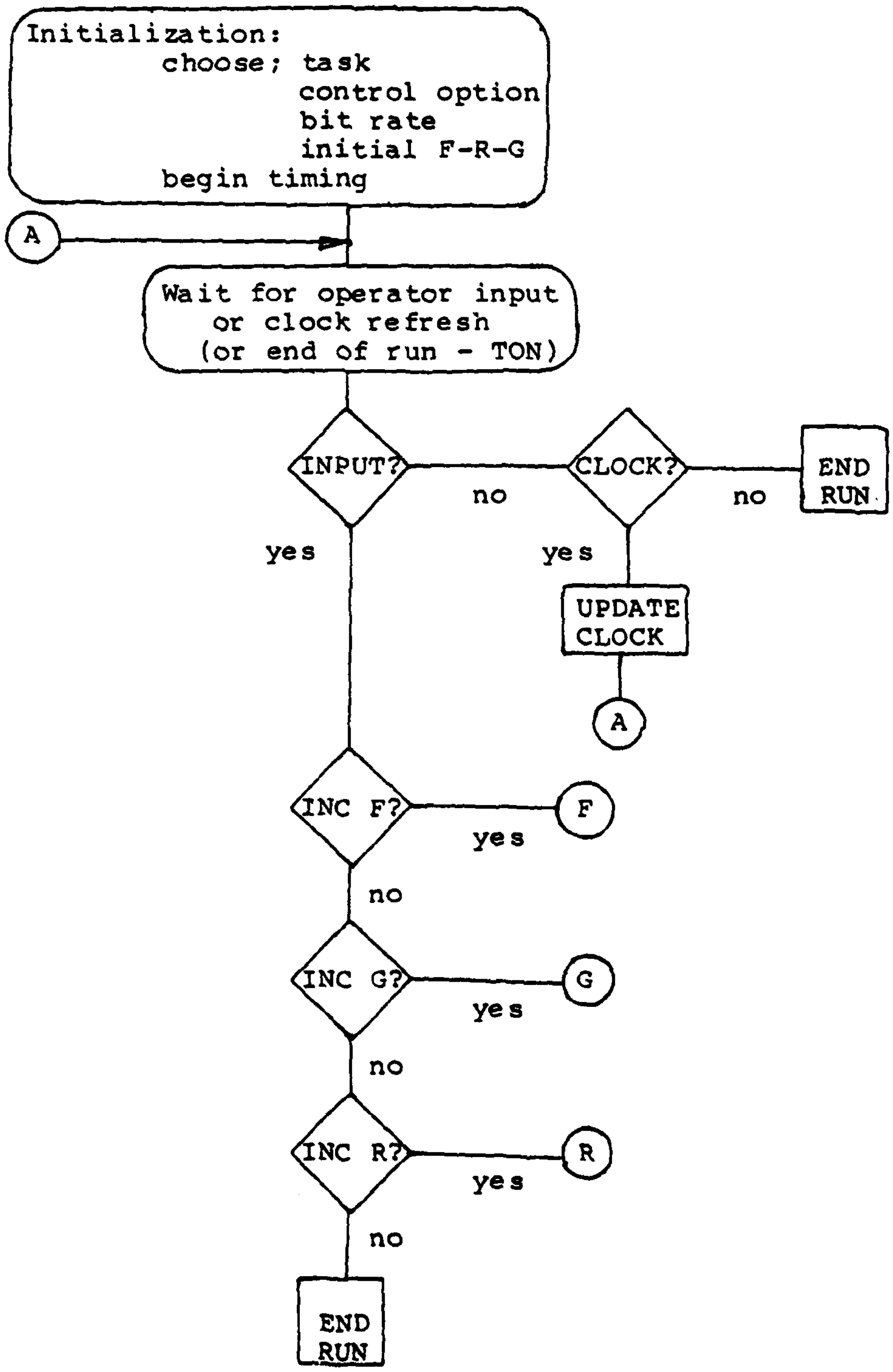
DEC R - decrease resolution

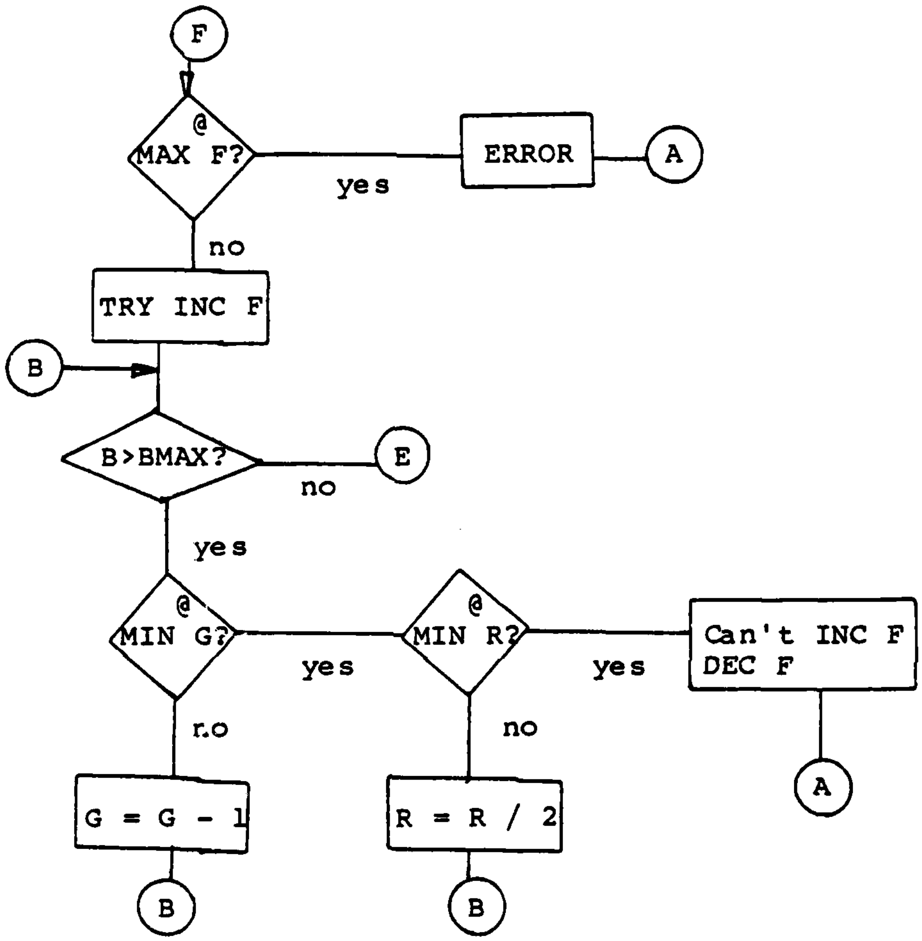
@ MIN G? - Is gray scale at its minimum value?

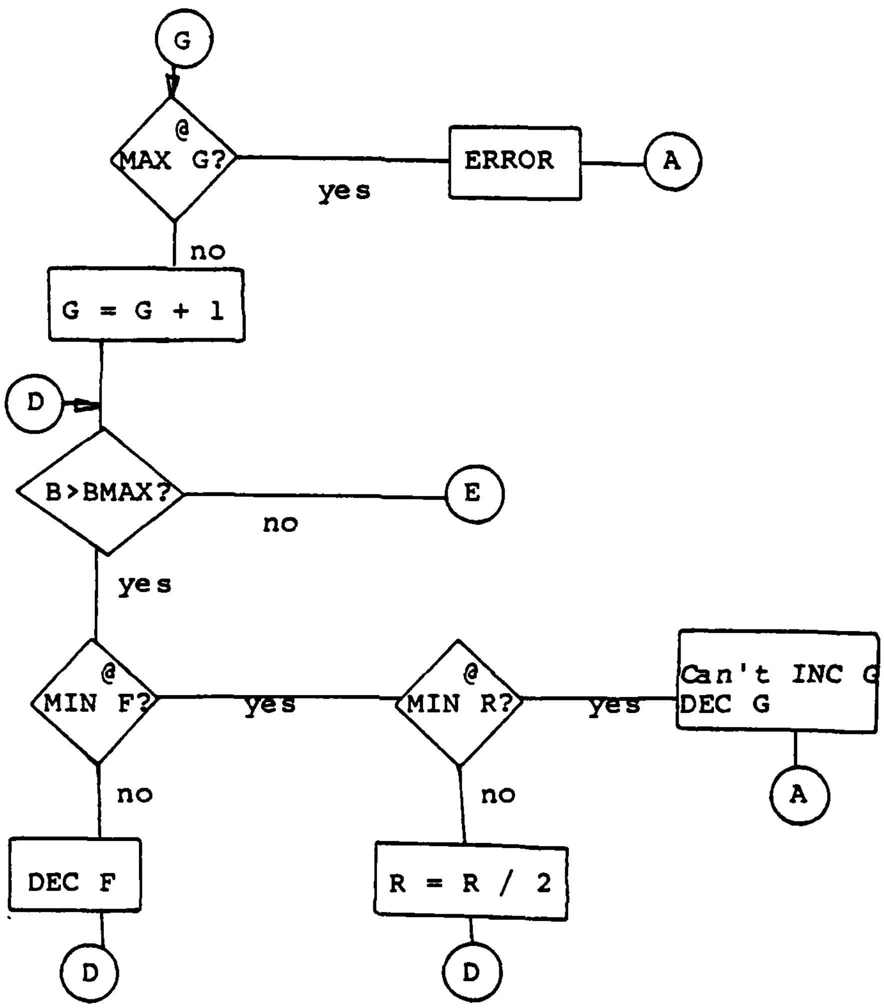
@ MAX F? - Is frame rate at its maximum value?

ERROR - Print an error message

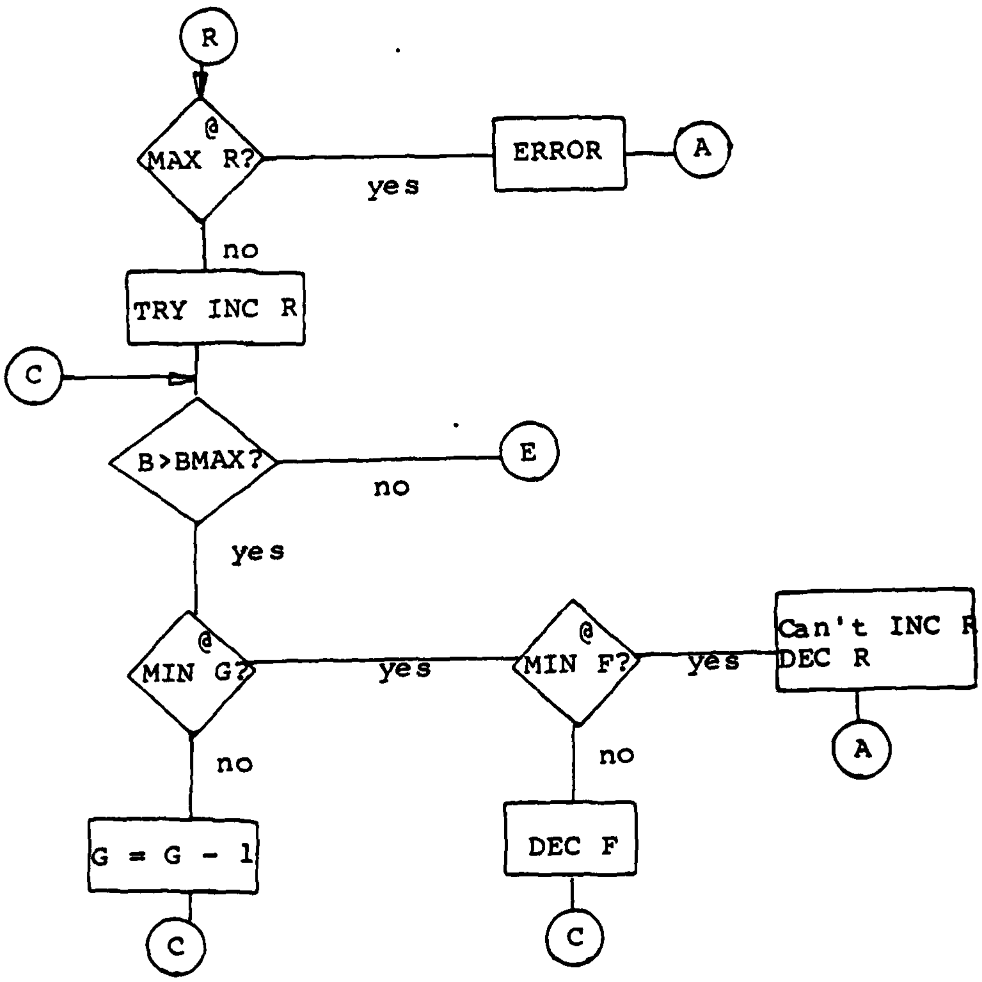
FLOW CHART FOR SRFG.FTN

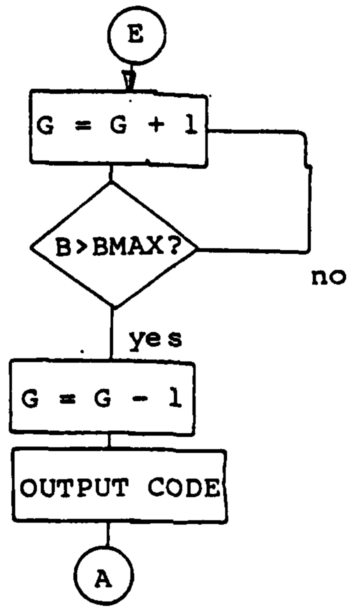



F
@
MAX F?
yes
ERROR
A
no
TRY INC F
B
B>BMAX?
no
E
yes
@
MIN G?
yes
@
MIN R?
yes
Can't INC F
DEC F
no
no
A
G = G - 1
R = R / 2
B
B



G
@
MAX G?
yes
ERROR
A
no
G = G + 1
D
B>BMAX?
no
E
yes
@
MIN F?
yes
@
MIN R?
yes
Can't INC G
DEC G
A
no
no
DEC F
R = R / 2
D
D


R
@
MAX R?
yes
ERROR
A
no
TRY INC R
C
B>BMAX?
no
E
yes
@
MIN G?
yes
@
MIN F?
yes
Can't INC R
DEC R
A
no
G = G - 1
C
no
DEC F
C


E
G = G + 1
B > BMAX?
no
yes
G = G - 1
OUTPUT CODE
A

```
C     SRFG.FTN
C             PROGRAM TO CONTROL FRAME RATE, RESOLUTION,
C             AND GRAY SCALE USING SPOX.  BIT RATE IS
C             KEPT AS NEAR TO MAXIMUM VALUE AS POSSIBLE.
C
      LOGICAL LCONT,LPEG
      DIMENSION FTAB(100),RTAB(100),GTAB(100), TTAB(100)
      DIMENSION IPARAM(6),IOSB(2),SYSTIM(3)
      BYTE DAY(10)
C
C             CONSTANTS FOR CURSOR CONTROL
      NESC=27 !ESCAPE
      NE=69   !CAP E
      NY=89   !CAP Y
      NBEL=7  !RINGS BELL
      ITKS=600        !TIME REFRESH INTERVAL
C
C             CHOOSE TASK
      WRITE(5,1069)NESC,NE
 1069 FORMAT(' ',2A,'CHOOSE TASK: 1=PEG, 2=TON')
      ACCEPT*,ITSK
      LPEG=.FALSE.
      IF(ITSK.EQ.1) LPEG=.TRUE.
C
C             CONTROLLED F-R-G?
      WRITE(5,1070)
 1070 FORMAT(' DO YOU WANT CONTROL OF F-R-G? 1=YES')
      ACCEPT*,ICONT
      LCONT=.FALSE.
      IF(ICONT.EQ.1) LCONT=.TRUE.
C             INFOR FOR CHOOSING BIT RATE
    5 WRITE(5,103)NESC,NE
  103 FORMAT(' ',2A,'POSSIBLE MAXIMUM BIT RATES ARE',
     1' FOUND USING POSSIBLE PARAMETER VALUES AND THE',
     2' EQUATION:'/10X,' B=F*R*R*G'/
     3' INPUT DESIRED BIT RATE BY CHOOSING POSSIBLE',
     4'  VALUES OF:'//' FRAME RATE',5X,'GRAY SCALE',5X,
     5'RESOLUTION'/)
      IR=256
      DO 11 I=1,3
      F=28.26/I
      IG=5-I
      IR=IR/2
      WRITE(5,104)F,IG,IR
  104 FORMAT(' ',F6.3,13X,I1,13X,I3)
   11 CONTINUE
      F=5.65
      IG=1
      IR=16
      WRITE(5,104)F,IG,IR
      IN=5
      DO 12 I=5,11
```

```
      IN=IN*2-1
      F=28.26/IN
      WRITE(5,105)F
  105 FORMAT(' ',F6.3)
   12 CONTINUE
      WRITE(5,107)
  107 FORMAT(' ENTER THE FRAME RATE, RESOLUTION,'
     1' AND GRAY SCALE')
C
C             INPUT MAX BIT RATE INFO
      READ(5,*) F,R,G
      BMAX=F*R*R*G
      WRITE(5,108)BMAX
  108 FORMAT(' MAX. BIT RATE =',F15.3)
C
C             TO ALLOW FOR ROUND-OFF ERRORS,
C             ADD 10. TO BMAX
   57 BMAX=BMAX+10.
C
C             INFO FOR USING PROGRAM
      IF(.NOT.LCONT) GO TO 56
   55 WRITE(5,109)
  109 FORMAT('0','IN THIS MODE, THE FRAME RATE,',
     1' RESOLUTION, AND GRAY SCALE ARE INCREASED AS',
     2' FOLLOWS:'//' FRAME RATE    7'/' RESOLUTION    8'/
     3' GRAY SCALE    9'/' NOTE THAT INCREASING ONE MAY',
     4' CAUSE ONE OR BITH OF THE OTHERS TO DECREASE')
C
C             INITIALIZE COUNTER AND GET RUN INFO
   56 N=1
      WRITE(5,102)
  102 FORMAT(' ENTER SUBJECT NUMBER AND TRIAL NUMBER')
      ACCEPT*,ISUB,ITRY
      IF(.NOT.LPEG) GO TO 65
      WRITE(5,1045)
 1045 FORMAT(' ENTER TIME LIMIT FOR THIS RUN (MIN.)')
      ACCEPT*,ITMG
C
C             INPUT TRIAL INITIAL VALUES
   65 WRITE(5,1008)
 1008 FORMAT(' ENTER INITIAL FRAME RATE')
      READ(5,*) TF
      WRITE(5,110)
  110 FORMAT(' ENTER THE INITIAL RESOLUTION')
      READ(5,*) TR
      WRITE(5,111)
  111 FORMAT(' ENTER THE INITIAL GRAY SCALE')
      READ(5,*) TG
C
C             CHECK TO INSURE SETTING LESS THAN
C             MAX BIT RATE AND RESET TIME FOR A
C             NEW RUN
C
```

```
      TB=TF*TR*TR*TG
      TIM=0.0
      TTOT=SECNDS(0.0)
      CALL SETEF(4)    !SET TIME FOR FIRST SHOT
      IF(TB.GT.BMAX) GO TO 211
C
C             BEGIN TIMING
      IF(.NOT.LPEG) GO O 77
      CALL MARK(2,ITMG,3,IDS)
      IF(IDS.NE.1) GO TO 997
   77 CALL GETADR(IPARAM(1),K)
      IPARAM(2)=1
      WRITE(5,1071)NESC,NE     !ERASE SCREEN
 1071 FORMAT(' ',2A)
      IF(.NOT.LCONT) GO TO 400
      WRITE(5,1081)NESC,NY,NESC,NY
 1081 FORMAT(' ',2A,'+ ',23X,'TYPE'/' TO INCREASE',
     1' FRAME RATE    7'/13X,'RESOLUTION         8'/13X,
     2' GRAY SCALE     9'/4X,'ABORT',18X,'0',2A,'1 ')
      GO TO 400
C
C             IF INITIAL TRIAL RATE EXCEEDS BMAX,
C             TRY AGAIN
  211 WRITE(5,112) TB
  112 FORMAT(' THE BIT RATE =',F10.2,'EXCEEDS THE',
     1' MAX. BIT RATE.  ')
      GO TO 65
C
  222 CALL MARK(4,ITKS,1,IDS) !RESET REFRESH CLOCK
      IF(IDS.NE.1) GO TO 996
C             GET NEW CONTROL DIGIT FROM TT1
C             QUE FOR INPUT
  223 CALL QIO("10400,5,3,,IOSB,IPARAM,IDS)
      IF(IDS.NE.1) GO TO 998
      CALL WFLOR(2,3,4)         !WAIT FOR FLAG
      CALL READEF(3,IUU)        !CHECK QIO FLAG
      IF(IUU.NE.2) GO TO 587
      IF(.NOT.LCONT) GO TO 999
      K=K-54  !MAKE 7,8,9 LOOK LIKE 1,2,3
      IF(K.EQ.-6) GO TO 999
      IF(K.EQ.3) GO TO 223
      IF(K.LT.1) GO TO 223
      GO TO 588
  587 CALL READEF(4,ITT)        !CHECK 5 SEC FLAG
      IF(ITT.NE.2) GO TO 546   !SKIP IF NOT SET
      RTIM=SECNDS(TTOT)
      MIN=RTIM(/60.
      ISEC=RTIM-60.*MIN
C             CANCEL QIO
      CALL QIO("12,5,3,,IOSB,IPARAM,IDS)
      IF(IDS.NE.1) GO TO 995
      WRITE(5,1092)NESC,NY,MIN,ISEC,NESC,NY,NESC,NESC
 1092 FORMAT(' ',2A,'"Q','TIME  ',I2,':',I2,2A,'1 ',
```

```
     1  A,'1',A,'A')
        GO TO 222
  546 CALL READEF(2,ITS)       !CHECK STOP FLAG
      IF(ITS.EQ.2) GO TO 999
      GO TO 222
C
C              NOTE TIME AND DIRECT ACCORDING
C              TO INPUT
  588 TIM=SECNDS(T)
      GO TO (225,250,260),K
      GO TO 999
C
C              INCREASE FRAME RATE
C
C              CHECK IF AT MAX ALREADY
  225 IF(TF.LT.21) GO TO 226
      WRITE(5,1002)NESC,NY,NESC,NY,NESC,NESC
 1002 FORMAT(' ',2A,'3 ','YOU ARE ALREADY AT',
     1' MAXIMUM FRAME RATE',2A,'1 ',A,'1',A,'A')
      GO TO 223
C
  226 L=28.26/TF
      NL=(L+1)/2
      TF=28.26/NL
C              CHECK AGAINST BMAX
  227 TB=TF*TR*TR*TG
      IF(TB.LE.BMAX) GO TO 400
C              IF OVER, TRY DECREASING G
      IF(TG.LE.1) GO TO 300
      TG=TG-1
      GO TO 227
C              IF G IS AS LOW AS POSSIBLE,
C              TRY DECREASING R
  300 IF(TR.GE.32) GO TO 310
      WRITE*5,1003)NESC,NY,NESX,NY,NESC,NESC
 1003 FORMAT(' ',2A,'3 ','YOU CAN NOT INCREASE',
     1' FRAME RATE AT THIS BIT RATE',2A,'1 ',A,'1',
     2  A,'A')
      GO TO 223
  310 TR=TR/2
C              CHECK AGAINST BMAX
      TB=TF*TR*TR*TG
      IF(TB.GT.BMAX) GO TO 300
C              TRY INCREASING G AGAIN
  308 IF(TG.EQ.4) GO TO 400
      TG=TG+1
      TB=TF*TR*TR*TG
      IF(TB.LE.BMAX) GO TO 308
      TG=TG-1
      GO TO 400
C
C              INCREASE RESOLUTION
C
```

```
C              CHECK IF ALREADY AT MAX
  250 IF(TR.LT.96) GO TO 251
      WRITE(5,1004)NESC,NY,NESC,NY,NESC,NESC
 1004 FORMAT(' ',2A,'3 ','YOU ARE ALREADY AT',
     1' MAXIMUM RESOLUTION',2A,'1 ',A,'1',A,'A')
      GO TO 223
  251 TR=TR*2
C              CHECK AGAINST BMAX
  252 TB=TF*TR*TR*TG
      IF(TB.LE.BMAX) GO TO 400
C              TRY DECREASING G
      IF(TG.LE.1) GO TO 255
      TG=TG-1
      GO TO 252
C              TRY DECREASING F
  255 IF(TF.GT.0.1095) GO TO 256
      WRITE(5,1005)NESC,NY,NESC,NY,NESC,NESC
 1005 FORMAT(' ',2A,'3 ','YOU CAN NOT INCREASE',
     1' RESOLUTION AT THIS BIT RATE',2A,'1 ',A,'1',A,'A')
      GO TO 223
  256 L=28.26/TF
      IF(L.EQ.1) GO TO 259
      NL=2*L-1
      TF=28.26/NL
C              CHECK AGAINST BMAX
  309 IF(TG.EQ.4) GO TO 400
      TG=TG+1
      TB=TF*TR*TR*TG
      IF(TB.LE.BMAX) GO TO 309
      TG=TG-1
      GO TO 400
  259 TF=14.13
      GO TO 257
C
C              INCREASE FRAY SCALE
C
C              CHECK IF ALREADY AT MAX
  260 IF(TG.LT.3.5) GO TO 261
      WRITE(5,1006)NESC,NY,NESC,NY,NESC,NESC
 1006 FORMAT(' ',2A,'3 ','YOU ARE ALREADY AT',
     1' MAXIMUM GRAY SCALE',2A,'1 ',A,'1',A,'A')
      GO TO 223
  261 TG=TG+1
C              CHECK AGAINST BMAX
  262 TB=TF*TR*TR*TG
      IF(TB.LE.BMAX) GO TO 312
C              TRY DECREASING F
      IF(TF.LT.0.1095) GO TO 270
      L=28.26/TF
      IF(L.EQ.1) GO TO 269
      NL=2*L-1
      TF=28.26/NL
      GO TO 262
```

```
  269 TF=14.13
      GO TO 262
C               TRY DECREASING R
  270 IF(TR.GT.24) GO TO 271
      WRITE(5,1007)NESC,NY,NESC,NY,NESC,NESC
 1007 FORMAT(' ',2A,'3 ','YOU CAN NOT INCREASE',
     1' GRAY SCALE AT THIS BIT RATE',2A,'1 ',A,'1',
     2  A,'A')
      GO TO 223
  271 TR=TR/2
C               CHECK AGAINST BMAX
      TB=TF*TR*TR*TG
      IF(TB.GT.BMAX) GO TO 270
C
C               TRY INCREASING F AGAIN
  311 IF(TF.GT.21) GO TO 312
      L=28.26/TF
      NL=(L+1)/2
      TF=28.26/NL
      TB=TF*TR*TR*TG
      IF(TB.LE.BMAX) GO TO 311
      TF=28.26/L
C
C               TRY INCREASING G AGAIN
  312 IF(TG.EQ.4) GO TO 400
      TG=TG+1
      TB=TF*TR*TR*TG
      IF(TB.LE.BMAX) GO TO 312
      TG=TG-1
C
C               PRINT NEW VALUES ON TT1
  400 WRITE(5,1072)NESC,NY     !MOVE TO LINE 10
 1072 FORMAT(' ',2A,') ')      !COL 1
      WRITE(5,1009)TF,TR,TG
 1009 FORMAT(' FRAME RATE=',F8.3,3X,'RESOLUTION=',
     1          F5.0,3X,'GRAY SCALE=',F4.0)
C               ERASE ERROR
      WRITE(5,1073)NESC,NY,NESC,NY,NESC,NESC
 1073 FORMAT(' ',2A,'3 ',A,'1',2A,'1 ',A,'1',
     1          A,'A')
      T=SECNDS(0.0)
      TTAB(N)=TIM
      FTAB(N)=TF
      RTAB(N)=TR
      GTAB(N)=TG
      N=N+1
      CALL OUTPT2(TF,TR,TG)
      GO TO 223
C
C               CANCEL I/O REQUEST
  999 CALL QIO("12,5,3,,IOSB,IPARAM,IDS)
      IF(IDS.NE.1) GO TO 995
C
```

```
C             OUTPUT RESULTS TO PRINTER
C             AND STOP RUN
      WRITE(5,1056)NESC,NE,NESC,NY,NBEL,NBEL,
     1        NBEL
 1056 FORMAT(' ',4A,') TIME IS UP',4A)
      CALL OUTPT2(.11,16.,1.)
      TOTIME=SECNDS(TTOT)
      WRITE(5,10630
 1063 FORMAT(' STORAGE ON DISK OR PRINTER?',
     1' DISK=1)
      ACCEPT*,ISTORE
      IF(ISTORE.NE.1) GO TO 511
      OPEN(UNIT=3,NAME='DL1:THESIS.DAT',
     1        TYPE='NEW')
      CALL TIME(SYSTIM)
      CALL DATE(DAY)
      ICO=0
      IP=0
      IF(LPEG) IP=1
      IF(LCONT) ICO=1
      IF(.NOT.LPEG) TO TO 1013
      WRITE(5,1016)
      ACCEPT*,NPEGS
 1013 WRITE(3,*)IP,ICO,ISUB,ITRY,BMAX,TOTIME,
     1        NPEGS, SYSTIM,DAY,N,TTAB(1),(TTAB(I+1),
     2        FTAB(I),RTAB(I),GTAB(I),I=1,N-1)
      CLOSE(UNIT=3)
      GO TO 1000
  511 WRITE(5,1064
 1064 FORMAT('0',70(1H_)//)
      CALL TIME(SYSTIM)
      WRITE(6,1057)SYSTIM
 1057 FORMAT(' ',40X,3A)
      CALL DATE(SYSTIM)
      WRITE(6,1057)SYSTIM
      IF(LPEG) WRITE(6,1088)
      IF(.NOT.LPEG)WRITE(6,1089)
 1088 FORMAT(' ',//' PEG TASK')
 1089 FORMAT(' ',//' TON TASK')
      IF(LCONT) WRITE(6,1099)
      IF(.NOT.LCONT) WRITE(6,1098)
 1099 FORMAT('  CONTROLLED F-R-G')
 1098 FORMAT('  SET F-R-G')
      WRITE(6,1012)ISUB,ITRY
 1012 FORMAT(' ',' SUBJECT NO. ',I3,10X,
     1' TRIAL NO. ',I4/)
C             RESET BMAX TO ORIGINAL VALUE
      BMAX=BMAX-10.
      WRITE(6,1011)TOTIME,BMAX
 1011 FORMAT(' TOTAL TIME FOR RUN WAS ',F10.2,'
     1' SEC.'/' BIT RATE LIMIT WAS     ',F10.2,
     2' BITS/SEC.'//' ',5X,' TIME     FRAME RATE',
     3'      RESOLUTION    GRAY SCALE')
```

```
      DO 2000 I=1,N-1
2000  TOTIME=TOTIME-TTAB(I)
      TTAB(N)=TOTIME
      WRITE(6,1010) (TTAB(I+1),FTAB(I),RTAB(I),
     1          GTAB(I),I=1,N-1)
1010  FORMAT(' ',F10.2,5X,F10.2,9X,F6.1,11X,F4.1)
      IF(.NOT.LPEG) GO TO 1019
      WRITE(5,1016)
1016  FORMAT(' ENTER NUMBER OF PEGS')
      ACCEPT*,NPEGS
      WRITE(6,1017)NPEGS
1017  FORMAT('0','NUMBER OF PEGS FOR RUN WAS ',
     1          I4///)
1019  WRITE(6,1064)
      GO TO 1000
 998  PRINT*,'COULD NOT QIO'
      GO TO 1000
 997  PRINT*,'COULD NOT MARK TIME'
      GO TO 1000
 996  PRINT*,'COULD NOT MARK TIME AGAIN'
      GO TO 1000
 995  PRINT*,'COULD NOT KILL QIO'
1000  STOP
      END
```

```
C              OUTPT2.FTN
C       SUBROUTINE TO OUTPUT CODES TO SPOX FROM
C              SRFG.FTN
C
        SUBROUTINE OUTPT2(F,R,G)
        INTEGER*2 IDATA,CMD,IDUM(24),BPSTAT,BITPAD,
       1       SPACER,STATUS, OUTBUF, INBUF
        COMMON /ANCOM/ IDUM, BPSTAT, CMD, BITPAD,
       1       SPACER, STATUS, OUTBUF, INBUF
        IDATA="0
        IF(G.GT.3.5) GO TO 10
        IF(G.GT.2.5) GO TO 15
        IF(G.GT.1.5) GO TO 20
        GO TO 25
     20 IDATA="10
        GO TO 25
     15 IDATA="14
        GO TO 25
     10 IDATA="17
     25 IF(F.GT.21.195) GO TO 30
        IF(F.GT.11.775) GO TO 35
        IF(F.GT.7.535) GO TO 40
        IF(F.GT.4.395) GO TO 45
        IF(F.GT.2.4) GO TO 50
        IF(F.GT.1.258) GO TO 55
        IF(F.GT..643) GO TO 60
        IF(F.GT..3245) GO TO 65
        IF(F.GT..1825) GO TO 70
        IF(F.GT.1095) GO TO 75
        IDATA=IDATA .OR. "0760
        GO TO 80
     75 IDATA=IDATA .OR. "1760
        GO TO 80
     70 IDATA=IDATA .OR. "3760
        GO TO 80
     65 IDATA=IDATA .OR. "5760
        GO TO 80
     60 IDATA=IDATA .OR. "6760
        GO TO 80
     55 IDATA=IDATA .OR. "7360
        GO TO 80
     50 IDATA=IDATA .OR. "7560
        GO TO 80
     45 IDATA=IDATA .OR. "7660
        GO TO 80
     40 IDATA=IDATA .OR. "7720
        GO TO 80
     35 IDATA=IDATA .OR. "7740
        GO TO 80
     30 IDATA=IDATA .OR. "7760
     80 IF(R.GT.96) GO TO 100
        IF(R.GT.48) GO TO 90
```

```
      IF(R.GT.24) GO TO 95
      IDATA=IDATA .OR. "10000
      GO TO 100
   95 IDATA=IDATA .OR. "20000
      GO TO 100
   90 IDATA=IDATA .OR. "40000
  100 CMD = IDATA
      RETURN
      END
```

AD-A091 623 MASSACHUSETTS INST OF TECH CAMBRIDGE MAN-MACHINE SYS--ETC F/G 17/2
OPERATOR-ADJUSTABLE FRAME RATE, RESOLUTION, AND GRAY SCALE TRAD--ETC(U)
SEP 80 B J DEGHUEE N00014-77-C-0256

UNCLASSIFIED NL

2 of 2

END
DATE
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12 80
DTIC

```
C               REPORT.FTN
C
C       PROGRAM FOR PRODUCING REPORT FROM INFORMATION
C       STORED ON DISK FROM SRFG.FTN
C
        DIMENSION FTAB(100),RTAB(100),GTAB(100)
        DIMENSION TTAB(101), SYSTIM(3)
        BYTE DAY(10)
        DATA FTAB?100*0.0/
        OPEN(UNIT=3,NAME='DL1:THESIS.DAT',TYPE='OLD')
        READ(3,*,END=10,ERR=10)IP,ICO,ISUB,ITRY,BMAX,
       1        TOTIME,NPEGS,SYSTIM,DAY,N,TTAB(1),(TTAB(I+1),
       2        FTAB(I),RTAB(I),GTAB(I),I=1,100)
   10 CONTINUE
        CLOSE(UNIT=3)
        WRITE(6,1064)
 1064 FORMAT('0',70(1H_)//)
        WRITE(6,1057)SYSTIM
 1057 FORMAT(' ',40X,3A)
        WRITE(6,1058)(DAY(I),I=1,9)
 1058 FORMAT(' ',40X,9A)
        IF(IP.EQ.1) WRITE(6,1088)
        IF(IP.NE.1) WRITE(6,1089)
 1088 FORMAT(' ',//' PEG TASK')
 1089 FORMAT(' ',//' TON TASK')
        IF(ICO.EQ.1) WRITE(6,1099)
        IF(ICO.NE.1) WRITE(6,1098)
 1099 FORMAT('  CONTROLLED F-R-G')
 1098 FORMAT('  SET F-R-G')
        WRITE(6,1012)ISUB,ITRY
 1012 FORMAT(' ',/' SUBJECT NO. ',I3,10X,
       1' TRIAL NO. ',I4/)
        BMAX=BMAX-10.    !RESET BMAX TO ORG. VALUE
        WRITE(6,1011)TOTIME,BMAX
 1011 FORMAT(' TOTAL TIME FOR RUN WAS ',F10.2,
       1' SEC.'//' ',5X,' TIME     FRAME RATE     ',
       2'       RESOLUTION    GRAY SCALE')
        DO 1900 I=1,N-1
 1900 TOTIME=TOTIME-TTAB(I)
        TTAB(N)=TOTIME
        WRITE(6,1010)(TTAB(I+1),FTAB(I),GTAB(I),I=1,N-1)
 1010 FORMAT(' ',F10.2,5X,F10.S,9X,F6.1,11X,F4.1)
        IF(IP.NE.1) GO TO 1019
        WRITE(6,1017)NPEGS
 1017 FORMAT('0','NUMBER OF PEGS FOR RUN WAS ',I4///)
 1019 WRITE(6,1064)
        STOP
        END
```

SAMPLE DATA SHEET

16:52:23
14-AUG-80

TON TASK
SET F-R-G

SUBJECT NO. 3 TRIAL NO. 3

TOTAL TIME FOR RUN WAS 186.55 SEC.
BIT RATE LIMIT WAS 23142.40 BITS/SEC.

TIME	FRAME RATE	RESOLUTION	GRAY SCALE
186.55	1.66	64.0	3.0

SAMPLE DATA SHEET

11:29:29
14-AUG-80

PEG TASK
CONTROLLED F-R-G

SUBJECT NO. 4 TRIAL NO. 1

TOTAL TIME FOR RUN WAS 300.05 SEC.
BIT RATE LIMIT WAS 11571.20 BITS/SEC.

TIME	FRAME RATE	RESOLUTION	GRAY SCALE
5.55	5.65	32	2
0.52	1.66	64	1
2.52	0.43	128	1
13.72	0.22	128	3
1.48	0.43	128	1
0.10	0.86	64	3
0.05	1.66	64	1
0.05	3.14	32	3
0.03	5.65	32	2
0.05	9.42	32	1
0.05	14.13	16	3
0.95	28.26	16	1
2.12	14.13	16	3
0.93	9.42	16	4
1.05	9.42	32	1
2.52	5.65	32	2
0.87	1.66	64	1
35.13	0.86	64	3
232.37	0.43	64	4

NUMBER OF PEGS FOR RUN WAS 2

APPENDIX D

TABLE 8a.

S	R	T	B	Set Score	Controlled Score	Controlled Standard Deviation
1	1	P	L	.0000	.0000	12
			H	.0349	.0233	14
		T	L	.1271	.1632	29
			H	.1462	.2067	30
	2	P	L	.0116	.0233	29
			H	.0465	.0581	30
		T	L	.1582	.1590	30
			H	.1342	.2480	28
	3	P	L	.0349	.0116	30
			H	.0465	.0465	30
		T	L	.1245	.0873	30
			H	.1030	.1348	29
	4	P	L	.0000	.0116	30
			H	.0116	.0349	30
		T	L	.2768	.2650	29
			H	.1240	.1013	30
2	1	P	L	.0141	.0000	10
			H	.0000	.0000	15
		T	L	.0529	.2038	25
			H	.1111	.0563	15
	2	P	L	.0000	.0000	10
			H	.0000	.0000	13
		T	L	.2091	.3107	21
			H	.1711	.2909	30
	3	P	L	.0000	.0141	19
			H	.0000	.0000	9
		T	L	.1798	.0658	21
			H	.1356	.2091	23
	4	P	L	.0000	.0000	18
			H	.1408	.1408	17
		T	L	.1905	.2177	28
			H	.4267	.6531	30

TABLE 8b.

S	R	T	B	Set Score	Controlled Score	Controlled Standard Deviation
3	1	P	L	.0308	.0000	9
			H	.0154	.1538	11
		T	L	.1429	.0671	8
			H	.1921	.2720	28
	2	P	L	.0000	.0462	13
			H	.0462	.0462	12
		T	L	.1063	.5313	28
			H	.1848	.3208	30
	3	P	L	.0154	.0308	18
			H	.0154	.0615	13
		T	L	.3063	.5231	28
			H	.1818	.3864	22
	4	P	L	.0308	.0000	15
			H	.0154	.0769	15
		T	L	.1921	.2787	27
			H	.3036	.3864	29
4	1	P	L	.0308	.0308	23
			H	.0000	.0154	21
		T	L	.1890	.0702	25
			H	.2526	.1429	24
	2	P	L	.0308	.0462	29
			H	.0462	.0615	25
		T	L	.0757	.1690	26
			H	.2182	.2450	29
	3	P	L	.0462	.0000	19
			H	.0462	.0615	29
		T	L	.1404	.0542	27
			H	.0609	.1875	24
	4	P	L	.0154	.0000	23
			H	.0000	.0615	28
		T	L	.1031	.1791	25
			H	.1040	.1778	24

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