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ESL-TR-91-02

MACHINE VISION FIRE DETECTOR SYSTEM (MVFDS)

A. D. GOEDEKE, B. DRDA, G. HEALEY, S. VIGLIONE, H. G. GROSS

DONMAR LIMITED
901 DOVER DRIVE, SUITE 120
NEWPORT BEACH CA 92660

APRIL 1991

FINAL REPORT

MAY 1990 - NOVEMBER 1990

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

1b. RESTRICTIVE MARKINGS
NONE

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
APPROVED FOR PUBLIC RELEASE

4. PERFORMING ORGANIZATION REPORT NUMBER(S)

5. MONITORING ORGANIZATION REPORT NUMBER(S)
ESL-TR-91-02

6a. NAME OF PERFORMING ORGANIZATION
Donmar Limited

6b. OFFICE SYMBOL *(If applicable)*

7a. NAME OF MONITORING ORGANIZATION
ENGINEERING AND SERVICES LABORATORY

6c. ADDRESS *(City, State, and ZIP Code)*
901 DOVER DRIVE, SUITE 120
NEWPORT BEACH, CA 92660

7b. ADDRESS *(City, State, and ZIP Code)*
AIR FORCE ENGINEERING AND SERVICES CENTER
TYNDALL AFB, FL 32403-6001

8a. NAME OF FUNDING / SPONSORING ORGANIZATION
HQ/AFESC

8b. OFFICE SYMBOL *(If applicable)*
RDCF

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
CONTRACT NO. F08635-C-90-0394

8c. ADDRESS *(City, State, and ZIP Code)*
TYNDALL AFB, FL 32403-6001

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.

11. TITLE *(Include Security Classification)*
MACHINE VISION FIRE DETECTOR SYSTEM (MVFDS) ©

12. PERSONAL AUTHOR(S)
GOEDEKE, A. DONALD, DRDA, B., HEALEY, G., VIGLIONE, S., AND GROSS, H. G.

13a. TYPE OF REPORT
FINAL REPORT

13b. TIME COVERED
FROM 5/90 TO 11/90

14. DATE OF REPORT *(Year, Month, Day)*
April 1991

15. PAGE COUNT
96

16. SUPPLEMENTARY NOTATION
Availability of this report is specified on reverse of front cover.

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
OPTICAL FIRE DETECTORS, FALSE ALARMS, AIRCRAFT FIRES, MACHINE VISION, ARTIFICIAL INTELLIGENCE, VIDEO CAMERA, IMAGE PROCESSING, COMPUTER CLASSIFICATION, ALGORITHMS

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

Current UV and/or IR optical fire detectors can be deceived. A new detector based upon machine vision, image processing, video camera, pattern recognition, and microcomputer technologies provides immunity to false alarms and, at the same time, provides for the ability to detect very small fires at great distances in 1 second or less. In addition, the newly developed concept provides the fire sizes, location, and growth rate. Fires can be resolved and discriminated from bright moving lights and other phenomena. The detector knows <u>when</u> a fire reaches a specified threshold size and <u>where</u> it is located, thus allowing for the <u>first</u> time instantaneous dump of suppressant in selected zones where the fire threat exists. The "intelligent" machine vision fire detector system (MVFDS) can be operated as a system with multiple camera detector units, as well as with single units. It is also adaptable to work with current installed fire protection systems. Its size is relatively smaller than current detector units and their control panels. The MVFDS concept has application to many fire, survivability, and security problems. 25

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL
OUGLAS SCHWARTZ

22b. TELEPHONE *(Include Area Code)*
904/283-3746

22c. OFFICE SYMBOL
HQ/AFESC/RDCF

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted
All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

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EXECUTIVE SUMMARY

A. OBJECTIVES

The objective of this study was to determine the feasibility of using machine vision technology to effectively and reliably identify fires and to discriminate them from nonfire (false alarm) sources. The study was directed to applying machine vision technology to a number of assumed Air Force goals in fire protection, including: (1) Increased reliability of fire detection; (2) Elimination of false alarm problems; (3) Provision for faster and more specific information on fire size, location, type, and threat; (4) Provision for wider applications (such as security and surveillance); (5) Provision for higher performance capabilities in detecting smaller fires at greater distances in very short times; and (6) Adaptability to and compatibility with current installed fire protection systems. The research and development performed in this Phase I study confirmed that all these goals are attainable with the Machine Vision Fire Detector System (MVFDS)© concept, and that such a product can be readily developed with current technology and off-the-shelf hardware at no technical risk.

B. BACKGROUND

Some problems in fire detection and suppression are directly related to how fires are detected. Almost all of today's detectors rely upon the emissions of ultraviolet (UV) and/or infrared (IR) radiations during combustion. All fires emit radiation in these bands. Unfortunately, so do many other objects and phenomena, thus possibly "fooling" these detectors into alarming or releasing suppressant when no fire exists. Conventional detection methods are "indirect" in that they do not know the nature of the source, where it is located, its size, its distance, or its threat (in terms of growth/intensity and association with another item). The technique developed in this study used direct methods to discriminate fire from nonfire sources, and to determine the fire's location, distance, size, growth and growth rate, and other features that may be important in protecting mission essential assets.

C. REQUIREMENTS

The requirements for most AF applications involving aircraft facilities and ground-based systems are to detect medium sized fires of 12-100 ft^2 at about 100-foot distance within 5 or so seconds (after fire has reached specified size). In some instances these requirements may not be stringent enough and call for detection of much smaller fires at greater distances in a time as fast as 1 second or so from fire start. One possible reason for more stringent requirements is due to the rapid (10-12 ft/sec) spread of flame across a JP-4 fuel spill. Within only 1 second of ignition, such a fire could reach hundreds of square feet in area and raise temperature at wing height to 1800°F in a few seconds, possibly resulting in aircraft damage. Setting conventional detectors to higher sensitivities to rapidly detect small events also increases their susceptibility to false alarming from low intensity, spurious UV and IR radiations.

This study demonstrated that state-of-the-art machine vision technology, combined with pattern recognition, artificial intelligence, and computer image processing techniques, provides the capability to identify very small fires at large distances in 1 second or less, and determine their size, growth, distance, and other features.

D. STUDY APPROACH

The approach was to use real fire data, such as JP-4 fires, as input to develop identification and classification algorithms. During fire tests, various types of objects considered as possible false alarm sources were included in the scene in attempts to "fool/confuse" the algorithms. The color video data was then digitized, frame-to-frame, and processed for various fire-associated features.

A number of fire-specific properties were found that could be used to discriminate fire from other light sources. These properties were translated into algorithms that were then tested against real fire data and false-alarm sources (nonfire light emitters and reflectors). A detection, discrimination, and measurement strategy was then developed.

E. FIRE DETECTION APPROACH

The process which was selected included the use of sensitive UV and IR discrete detectors to signal the presence of UV and IR radiation. Prior to such signals the MVFDS CCD camera operates in a standby mode of capturing a scene every few seconds or so. Each scene is digitized and stored into memory, replacing the previous "base" reference frame. Once UV and IR radiation is detected in the scene, the MVFDS enters "alert mode", whereby the frame capture rate increases to say 1 frame every 100 milliseconds. Immediately upon entering this mode, MVFDS locates bright regions that are not background regions and computes the scene position corresponding to these regions. After identifying these active regions, MVFDS processes incoming frames at 0.1 second intervals (or some other preselected frequency) and for each new frame computes the following properties for each active region: size, growth rate, stationarity, mean spectral content, spatial variation, and temporal variation.

For any of the active regions MVFDS can take any of these actions: (1) discontinue tracking, (2) label as fire, (3) alarm and/or dump suppressant when the size reaches the preset value requiring dump. A region is labeled as fire if it exhibits appropriate stationarity, spectral signature, spatial variation, and flicker. If it does not, tracking is discontinued. This process was successfully demonstrated at the conclusion of the program, thus proving the feasibility of the concept as well as the hardware.

F. CONCLUSIONS

The MVFDS concept is feasible and can be cost-effectively implemented with current hardware. The concept can provide a very large advance in fire detection and protection technology. It was recommended that (1) the Air Force proceed with diligence to develop the MVFDS, (2) give consideration to its initial integration into existing installed fire protection systems, and (3) evaluate it for other applications that may be associated with survivability of mission essential systems and operations, including operational aircraft shelters such as the Hardened Aircraft Shelters.

PREFACE

This final report was prepared by Donmar Limited, 901 Dover Drive, Suite 120, Newport Beach, California 92660, under Contract #F08635-C-90-0394, with Headquarters Air Force Engineering and Services Center, Engineering and Services Laboratory (HQ AFESC/RD), Tyndall AFB, FL 32403-6001, as the sponsor.

The period of performance for this contract extended from May 21, 1990, through November 21, 1990. The HQ AFESC/RDCF Project Officer was Mr. Douglas Schwartz.

This technical report was submitted as part of the Small Business Innovative Research (SBIR) Program and has been published according to SBIR Directives in the format in which it was submitted.

This report is releasable to the National Technical Information Service (NTIS) and will be available to the general public and foreign nationals.

This technical report has been reviewed and is approved for publication.

DOUGLAS B. SCHWARTZ
Project Officer

NEIL H. FRAVEL, Lt Col, USAF
Chief, Engineering Research
Division

RICHARD N. VICKERS
Chief, Air Base Fire Protection
and Crash Rescue Systems Branch

FRANK P. GALLAGHER, Col, USAF
Director, Engineering and
Services Laboratory

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SECTION I

INTRODUCTION

A. OBJECTIVES

The objectives of this research were twofold: (1) to verify the feasibility of using machine vision technology to identify fires and discriminate them from nonfire (false alarm) sources; and (2) to develop machine vision concepts that provide important real time information on fire event size and location/position. This provides for the first time a direct technique (as opposed to indirect techniques by current detectors) to determine actual fire size and location, which can be used as the basis to automatically release fire-extinguishant agent in selected "zones" (if total flooding is not required) for preselected sizes of fires. Current detectors do not know where the fire is located or whether it is a small fire near the detector or a large fire some distance away.

A major factor underlying the objectives of this research is the need to solve the problems caused by false alarms due to electromagnetic emissions from various types of nonfire sources. It was, therefore, a major consideration in this study to develop a Machine Vision Fire Detection System (MVFDS)© that provided immunity to nonfire, false alarm sources.

In addition to satisfying the above objectives, it was also deemed necessary to prove that the technology exists and presents minimum risk to further development of the MVFDS© product. Demonstrations were provided of the MVFDS concept and of candidate hardware configurations, using currently available state of the art components.

The third and final objective was to prove the feasibility of successfully completing a Phase II/III effort, and producing a product that would satisfy the goals of the USAF, herein assumed to be:

1. Increase reliability of fire detection
2. Eliminate false alarm problems
3. Provide more specific information on fire type, size, location, and nature of event, thus allowing for "intelligent" detector decisions
4. Wider applications
5. Higher performance specifications
6. Adaptable to and compatible with current fire protection system installations

B. BACKGROUND

The problem of fire detector false alarms and accidental releases of suppressant is well-known, but certainly not acceptable (Reference 1). The nature and complexity of operations within military facilities pose many potential fire threats and expose fire protection systems to a large variety of ultraviolet (UV), infrared (IR), visible, and X-ray radiations. High power, low- and high-frequency electromagnetic radiation from communications and aircraft navigation systems are also present, as well as acoustic emissions from such sources as aircraft engines. Fire detectors are expected to detect fires in the presence of such radiation emissions and, at the same time, to be immune to these emissions. This expectation has not yet been fulfilled.

Many types of fire detectors can measure direct properties and indirect effects of fire. This includes measurement of one or more of the following physical properties or phenomena: combustion aerosols; gases; smoke/particulate matter; flames; temperature; temperature rate-of-rise; and emissions of UV, IR, and/or visible radiations. Specific detection techniques vary widely and include the following:

1. Optical flame detectors measure selective electromagnetic emissions from the combustion process in UV, IR, and visible wavelengths. These are the most common detectors used today. They can be fooled by objects/events/phenomena that also emit radiations in these wavelength regions, either selectively or broad band, and/or reflect radiations in wavelength bands that emanate from other sources.

2. Smoke detectors operate by (a) detecting changes in light intensity of an emitting source over a defined path length, caused by the presence of light-scattering particulates, or (b) ionization changes within a chamber due to the influx of particulates. These detectors can be set off by the presence of aerosols, dust, fumes, fog, insects and obscuration in a light path. Also, slow-smoke must reach the detector.

3. Thermal detectors measure heat from fires by either (a) a solid state infrared detector or other device that is set to respond when a certain threshold temperature is reached, or (b) a rate-of-rise of temperature detector that operates over a preset range of temperature increase within a preset time interval. These detectors are also sensitive to hot effluents of aircraft engines and aircraft ground equipments (AGE). Instances have been reported when such detectors were activated by aircraft engine starts and aircraft taxiing past an open hangar door.

Optical flame and thermal detectors are most often used for

Air Force applications, especially within aircraft shelters and aircraft support facilities. However, only optical flame detectors apply to fire threats that require rapid detection and suppressant response. These detectors must be able to detect fires of a few square feet (e.g. 16 ft^2) at some distance (e.g. 100 feet), within 3-5 seconds. As the requirements increase for detection of smaller fires at larger distances in shorter time periods, the susceptibility of the detector to respond to "false alarm" sources also increases. This undesirable feature of UV and IR detectors jeopardizes fire protection when the fire threat to which the system is designed dictates a very rapid and reliable response time, say 2 or less seconds.

Efforts have been made to overcome this problem of increased susceptibility to false alarms versus increased sensitivity to fire detection by adding requirements in the detection logic such as ratioing between UV and IR intensities and time gating of detector response. These added features have provided some improvement in false alarm susceptibility, but have not solved the problem, as is evident by the continuing frequency of occurrence of such events (Reference 1). Other attempts have included the addition of more spectral-specific wavelength measurements, whereby the fire detector operates more like a spectrometer.

Other features of current fire detectors/flame detectors that could also be improved upon. An important performance capability of a fire detector is to determine when a fire event has reached a certain geometrical size. Present AF requirements (Reference 2) state that a flame detector must be able to identify a hydrocarbon fire of size 100 ft^2 (10 foot by 10 foot square pan) at a distance of 150 feet in 5 seconds or less. A fire of this size located under the wing of a fighter aircraft could cause damage in less than 5 seconds. Such fire threats may also have serious effects on aircraft structures, including composite materials as well as aluminum. Accurate and timely determination of the size (and location, if possible) of a fire is very important to the survivability of certain weapon systems and mission critical assets.

The method employed in current UV/IR detectors is an indirect technique that is "intensity"-based. Usually, a pan fire of the size specified in the performance requirements of the purchase order/contract is set at the specified distance from the detector. The detector electronics is then adjusted until a "fire" signal is registered. This process of setting the fire threshold level can also be carried out in the manufacturing facility. The problem with this indirect technique is that the intensities of the fire-emitted UV and IR radiations are inversely proportional to the square of the distance of the emitting source. This means that such a detector cannot accurately determine the size of a fire because it does not know its distance, yet alone its dimensions. A small fire only a few feet from a detector looks the same to the detector as a large fire at much greater distance.

It is impossible then, with current UV/IR detectors, to monitor the physical growth of a fire and to activate alarms of different status depending upon fire size and, perhaps, location. For example, it may be desirable in some instances to know the presence of a fire in a facility when the fire is only one second old and very small, but growing rapidly (a JP-4 fire spreads at a flame front rate of 10-12 feet per second). An alarm could be activated when the fire is very small to allow for the use of hand-held extinguishers, if available. If the fire continues to grow, as monitored by the detector, a full dump of suppressant could be programmed to occur when (if) the fire reaches a threatening size. Other examples include knowing the association of the fire event in determining how to suppress the fire. Jet Fuel Starter (JFS) fires/nacelle fires usually do not require a major suppressant dump because they can be extinguished by the ground crew with small extinguishers. However, if the fire gets out of hand and spreads to a three-dimensional fire involving the floor, and the fire continues to grow, it would be helpful to have a "smart" detector that "knows" when the fire has reached a threatening status, and then activates the suppressant system. This capability appears to be possible with the MVFDS.

Regardless of the technique or concept employed to date, no previously employed or disclosed fire detector device or system concept has been able to provide immunity against false alarms and false activations of suppressant, or provide the capabilities referred to above. The detector concept discussed herein offers for the first time a capability to provide immunity/discrimination and, at the same time, increased sensitivity to detect fires of smaller sizes, at greater distances, and in much shorter time than previously available. It also provides the capability to add discrimination of any unforseen new false alarm source.

The "ideal" fire detector could be described as a human being with full field-of-view of the area to be protected, who never gets tired and could react with a decision and manual response within a "blink-of-an-eye" (0.1 seconds). The machine vision technology discussed in this document functions like a human being. By experience, we "instantly" know when we see a fire that it _is_ a fire of certain size, located at some estimated distance, and possibly associated with some object. We recognize fire by its brightness, color, color variations, time-intensity changes, shape, flame edge (tongues) flicker, stationarity, and growth. We also know almost instantly its location and that it is growing in intensity and size. If one had an electrical switch that could be activated on first seeing the fire to sound an alarm, and another switch that could release the suppressant when we feel that the fire size has reached threatening proportions, this would be a model of the machine vision technology fire detector, but would be much slower, less accurate, and much more costly.

C. POTENTIAL COMMERCIAL BENEFITS OF MVFDS

Technology now exists to produce "smart" detectors that can monitor a variety of physical phenomena, including their spatial, temporal, and spectral characteristics. Robotic systems and intelligence gathering space platforms such as Landsat are examples of the use of sophisticated electronic logic in providing specificity of the observed object/phenomena. Machine vision technology utilizes one or more cameras to obtain image information such as brightness, depth, color, shape, texture and other characteristics. An electronic interface between the optics and a computer or specialized processor is provided to process images and their information content. Artificial intelligence, pattern recognition, and image processing techniques are used to process the incoming images/information. Special purpose mathematical algorithms are derived to deduce specific information needed to make certain decisions. The hardware includes existing camera devices, simple optics, and personal computer (PC) components and microprocessors. All the necessary hardware for a machine vision fire detector exists. The artificial intelligence, pattern recognition, and image processing technologies also exist and have been proven in many applications more complex than fire detection/discrimination.

The advent of the MVFDS will provide a new market of interest to two sectors of high-tech industry. Both fire detector manufacturers and optical camera manufacturers are viable candidates to produce an MVFDS product. Because the applications of the MVFDS design and concept cover a broad range, there are many potential customer outlets for its use. Intrusion detection, motion detection, damage assessment, identification/presence of persons or objects, status of environments/facilities (e.g., open or closed doors with aircraft present), fires associated with various objects in various locations, presence of unwanted objects such as UV (e.g., cracked light lens) and IR (hot bodies/fire ignition threats) sources, and discrimination between hydrocarbon and hypergolic fuel fires, are examples of how the machine vision fire detector could be used in multiple or special-purpose applications.

The present market for optical fire detectors consists primarily of the defense/aerospace complex and high-tech industry. Many old technology fire/flame detectors previously installed in aircraft shelters/hangars have been replaced with more current dual UV/IR detectors that are less likely to false alarm (although certainly not immune to all false alarm sources) but are still greatly limited in their information output. Also, many fire protection/suppression systems are being updated and new controller panels and extinguishant plumbing are being installed. Although newer, these systems still do not provide the reliability or functionality that could be provided by the MVFDS.

The MVFDS would be a substantial improvement over present conventional detectors and could be an obvious replacement of or addition to existing installed systems, especially in more demanding complex applications. The major factor influencing initial purchase decisions will be the degree of reliability and performance desired vs. the fire threat. The availability of a more capable and reliable detector will also have some impact on initial purchase for new installations, especially if the price is similar. Fires as small as one or so square feet at large distances could be detected and action taken automatically when the fire <u>reached</u> the specified size, not seconds <u>after</u> it reached the specified size and continued to grow. Such coverage would require a multitude of UV/IR detectors.

There is a real need for such capabilities as well as a need for a new approach to fire detection and discrimination; one that is reliable in protecting valuable and mission-essential weapon systems and assets, as well as that is fool-proof and adaptable to a variety of complex applications.

The cost of camera/video and computer component hardware is decreasing at a very rapid rate. New, faster, more compact computers are entering the market on a regular basis. The lifetime in the marketplace for computer processors, random access memory chips, and integrated logic chips is very short. Today's design of an MVFDS will certainly cost considerably less 2 years later.

One immediate application of the new detector would be to integrate it with existing installed fire protection systems so as to provide a very large increase in the system's reliability and immunity to false dumps/alarms. The MVFDS can be easily retrofitted into current configurations and panels. The existing UV, IR, or UV/IR detectors could be used as "ANDS" in the logic decision path and/or as "switches" to alert the MVFDS of the presence of such radiations, thus turning on the MVFDS alert mode (discussed in detail later).

Representatives of both the detector industry and the video/optical camera industry have voiced interest in manufacturing and marketing the product. The actual manufacturing process would be simple and involve only a few steps. Most of the components would be obtained as an OEM manufacturer.

D. SCOPE/APPROACH

The Phase I study consisted of seven major parts: (1) investigation of the nature and properties of fires and possible sources of false alarm/detector confusion; (2) investigation of artificial intelligence, pattern recognition, and image processing technologies related to classification and discrimination of fire events; (3) development of appropriate algorithms; (4) collection of real fire data and other optical/visible stimuli data for use in developing and testing algorithms; (5) selection of preliminary image classification steps and software; (6) determination of a first-generation hardware configuration; and (7) demonstration of the approach selected for the MVFDS operation.

This study went much further than normally expected of a Phase I effort. In fact, considerable effort was conducted in the actual development of algorithms and hardware design, thus establishing a firm technical basis on which to continue in Phase II full scale development. To prove feasibility through the use of actual demonstrations, much of the mathematics had to be developed and software programs written.

Existing technology was used throughout the study to minimize technical risk. Commercial high-tech cameras, frame grabbers, and state-of-the-art small computer hardware were used to obtain and process video data. The fire data were obtained from controlled burns of JP-4 and Aviation-A (same spectral signature as JP-8) jet fuels, thus representing real fire threats. In the development of certain algorithms, the color video data taken of the Hardened Aircraft Shelter Fire Protection System tests at Tyndall AFB in 1985 were used. The false-alarm source data were obtained and digitized with the same camera and computer equipment as were the fire data. In some instances various possible false alarm sources were introduced into the scene along with fires for the purpose of trying to "fool" or confuse the classification and discrimination algorithms. These sources consisted of very bright lights, strobe lights, rotating red dome lights, chopped reflected colored lights, and colored pattern reflecting surfaces. In keeping with the basic approach stated above, the first conceptual hardware model of the MVFDS was configured using current technology, available hardware items, devices and components. No new technology or unproven, not readily available hardware was postulated for the end product.

The scope and results, then, of this study extended from (1) the basic analysis of the properties and nature of fire, fire events, and false alarm sources, to (2) the development of techniques to classify/discriminate such events/sources unequivocally; (3) the testing of these algorithms against real data; (4) the development of a practical, first-generation hardware unit; and finally, (5) demonstration of the high performance level of the MVFDS and proof of the technical as well as product feasibility, and desirability to continue into a Phase II/III effort.

SECTION II

REQUIREMENTS

The MVFDS requirements addressed in this study consisted of three operational performance characteristics: fire detection/ identification, false-alarm discrimination, and system applications; and one practical consideration: the producibility of the product with minimum technical risk.

A. FIRE DETECTION/IDENTIFICATION

The first and foremost requirement of the MVFDS is to detect a fire of some minimum size, at some maximum distance, and within some minimum time after fire start. The selection of quantitative values for these three variables is dependent upon the application of the fire protection system and, of course, the fire threat.

In cases where the dynamics of the fire threat requires very rapid detection, the detector's sensitivity must be set high to enable fast response to small events (growth rate may be high). In this scenario, the detector may be required to identify a 4 ft^2 (2 foot X 2 foot) pan fire anywhere in the facility (say at a maximum distance of 100 feet) in 3 or less seconds after fire start. If the time was 3 or less seconds <u>after</u> the fire size <u>reached</u> 4 ft^2, the fire could have grown to many hundreds of square feet (flame fronts of moving or large stationary pool JP-4 fuel fires spread at a rate of 10-12 ft/sec) before some action could occur to release suppressant. By this time, damage could have occurred to the aircraft or mission essential asset. There is a need, therefore, in many applications to require fire detectors and detection systems to detect "small" fires at large distances <u>when</u> they reach a certain specified size, <u>not seconds after they have attained a certain size and are still in the process of growing.</u>

There are also applications where the fire threat does not require automatic suppressant release until the size is about 16 ft^2 or larger. The recent B-2 hangar application specified detection of a 12 - 16 ft^2 fire anywhere in the facility (about 100 feet from detector) in 5 seconds (Reference 3). In most standard AF applications, the requirement is to detect a 10 foot X 10 foot (100 ft^2) pan fire at 150 feet distance in 5 seconds (Reference 2). Other published information, however, quotes a time of 90-120 seconds from fire start as the time required to have 90 percent of the fire under control (Reference 4). Such a long time would, in some instances, result in total aircraft loss.

Considering all the various applications and needs for high performance, it was assumed in this study that it would be highly desirable for any next generation detector to be able to detect very small fires (e.g. 1-4 ft^2) at distances of 100 feet or so in 1 second or less, and still be immune to false alarms and false activations.

The ability of a fire detector to <u>directly</u> determine the size of a floor fire, and also its location, was deemed to be a very valuable additional detector attribute that could be effectively employed in many complex fire protection applications, which cannot be accomplished with current fire detectors. This feature was not originally included in the study objectives but, as discussed later, was accomplished as a direct fallout of the algorithm development effort.

B. FALSE ALARM SOURCE DISCRIMINATION

One of the major problems associated with current and past fire detectors is their history of false alarming to nonfire sources that emit/reflect radiation in the same wavelength regions in which they operate, resulting in financial loss (suppressant replacement cost and clean-up costs), environmental impacts, interruption of operations, and down-time of mission essential weapon systems (Reference 3). In some instances, these mishaps were frequent and actions were taken to disable the fire detection system when aircraft engines were started or run at high power levels, certain aircraft ground equipments (AGE) were present, or when certain operations occurred such as x-raying, welding, and tests of navigation radars and communication systems.

Current flame detectors operate primarily in ultraviolet and infrared wavelength regions, where hydrocarbon fire has strong emissions and where solar background emissions are minimized by atmospheric absorption. Emissions from such objects as hangar lights, outside utility lights, aircraft and vehicle lights, tools, aircraft engines, aircraft subsystems and special devices (e.g. jammers), heaters, hot manifolds of AGE and vehicle items, photographic equipment, welding torches, matches, lighters, and many other items can possibly influence UV/IR detectors. Some manufacturers have added features such as ratioing and/or gating operations to reduce false alarm susceptibility. This has helped to some degree but the problem still remains and detectors continue to false alarm.

A very important requirement then is to reduce as much as possible the susceptibility of the MVFDS to false-alarm problems, and to hopefully make it "false-alarm proof." Again using the human analogy, a considerable amount of fire-specific information is available in the visible region and, with visual data input, the brain can discriminate real fire from other objects/events/ phenomena through comparison with previously stored knowledge, such as brightness, color, shape, spectral and temporal variations, growth, flicker, edges/tongues, and stationarity. He can also determine relative size, location, and association with some other object. Although UV and IR radiations are obviously present, the human being does not need (and cannot use, other than possibly high heat) this input to determine presence of fire and the properties of the fire. The MVFDS operates in the same manner with the same type of visible information input and processing. However, an additional step has been added to require the presence of UV and IR as a "switch" to initiate a high-speed "event search mode", and as an "AND" in the logic decision tree.

The required presence of UV and IR was determined to be a possible added reliability feature in the fire discrimination process, at least at this time in the MVFDS development. At present, there is no known compelling reason to require the presence of UV and/or IR radiation at any wavelength because no known false alarm sources in the visible spectral region have yet been identified that can not be discriminated by the MVFDS from fire. Because of the processing intensity required for some of the pattern classification algorithms being used, their presence was also considered to be a method of "switching" from slow speed scene processing (e.g. one new image frame every 10 seconds) to a fast event processing mode (e.g. 10-30 frames/second). However, the option exists to always operate the MVFDS in a fast image/frame process speed (e.g. 10-30 frames per second). A detailed timing analysis and hardware (memory, processor speed, cost, etc.) is required to finalize the scene processing time. This subject will receive further attention during a Phase II effort.

If conventional detectors are set to very high sensitivity levels to enable them to rapidly detect small fires, they will also be very sensitive to nonfire UV and IR emissions and easily fooled. However, the MVFDS's UV and IR detectors can be safely set at very high sensitivity levels. The MVFDS should not care if the UV and IR it "sees," from either its own detectors or other already installed detectors that it may use in the fire discrimination process, are from real or false alarm sources. The visible information obtained by the camera, and processed via special algorithms, should be sufficient to either confirm "fire" or identify the source as being a nonfire source. This is a requirement placed upon the MVFDS in this study.

As an MVFDS performance requirement of not being fooled by any UV and/or IR nonfire source, what then are the other (non-UV/IR) possible false alarm sources that may confuse/fool the MVFDS? As will be discussed later, moving lights, chopped reflected color lights, strobe lights, moving bright objects, highly reflective surfaces, and other optical/visible phenomena must not be able to cause the MVFDS to make a wrong decision, or keep it from making a decision. This MVFDS requirement will be shown later to be a major attribute of the new detector.

C. MVFDS SYSTEM PARAMETERS

The MVFDS must be able to function as a system with multiple detection/camera units, depending upon the application. In addition to the basic requirements discussed above, other system requirements that should be imposed upon the MVFDS consist of tolerance to environments such as vibration, shock, water immersion, fungus, hazardous atmosphere/explosion, dust, and EMI. The UL or FM approval is certainly not sufficient verification that detectors can withstand military or other harsh environments. These harsh environments have been the cause in the past for some false alarms and releases of suppressant.

Other features that the MVFDS should possess include wide-field-of-view coverage, and built-in automatic tests of window cleanliness and internal system electronic "health".

The MVFDS should be able to use existing installed UV/IR detectors, if appropriate, and to be compatible with already installed fire control/communication panels. It is not certain at this time if there would be any benefit for the former ability, but there is benefit in the latter. This does not present a problem as the MVFDS can be easily designed to produce appropriate outputs.

The MVFDS should also be required to provide other types of information such as the association of a fire to specific objects (e.g. aircraft fuselage, AGE, etc.), zone in which the fire is located to facilitate use of zonal suppression as opposed to total flood, and size of fire (as could possibly be represented by different stages, colors, or frequencies of alarms). These features could be considered during the Phase II development effort, if required.

D. PRODUCIBILITY/AVAILABLE TECHNOLOGY

In addition to the performance requirements above, a minimum risk requirement must be imposed. Minimum risk is an understandable objective in any development process; so is minimum cost. During the Phase I effort it was deemed a requirement that the hardware configuration must utilize commercially available components such as those in the PC marketplace. It was also a design consideration whether it would be desirable that the hardware technology chosen for the preliminary design be in a state of rapid change and therefore provide major cost savings for 1-2 year old technology that still satisfied the product needs. In other words, it is important to select hardware for the initial product that will experience near-future price reductions which can then be passed on to the buyers.

The Phase I effort concluded that the complete MVFDS concept can be incorporated into existing hardware with no technical risk and at an initial cost similar to that of old technology detectors. It was also concluded that both camera and computer technologies are advancing so rapidly that the initial MVFDS capabilities and hardware design could change significantly in a short time and experience large cost reduction. In a system application such as the B-2 hangars, where 12-13 conventional UV/IR detectors are required, the MVFDS system may require fewer units and electronic interfaces and cost about the same or less than a conventional detector system, thus providing considerably more capability for the same or less cost.

SECTION III

APPROACH TAKEN TO PROVE FEASIBILITY

The Phase I approach was to use existing technology and real fire and false alarm data to test technical performance. Mathematical models of fire events were developed along with specific algorithms to process the fire and false alarm data and to test the software's abilities to accomplish various functions related to discriminating fire characteristics. Analyses were made of hardware configurations/designs concurrently with the development of the software. Demonstrations were then made of the ability of the MVFDS to satisfy all the requirements so edicted in this study and outlined in Section II, thus proving the feasibility of developing and producing an advanced machine vision fire detector system in a Phase II effort.

A. FIRE DATA

Only real fire data were used in the development and testing of the MVFDS concept. This consisted of taking videos of controlled pan fires of JP-4 and Aviation-A (same spectral signature as JP-8). Consecutive, as well as selected frames in the videos, were then digitized into a 16-bit format using a TARGA-Plus frame grabber card, thus providing five bits each per red (R), green (G), and blue (B) color planes. The frame grabber and a laboratory grade VCR were used to grab, process, and analyze video frames exhibiting specific fire information. These digitized data were then used in the software algorithm development and algorithm tests.

Fires were set in 7-inch round, 11-inch X 16-inch rectangular, 15-inch round, and 36-inch X 6-inch rectangular pans set in various combinations at distances from the camera of 18 inches to 100 feet.

The camera (discussed in Section IV F-2) used in the data acquisition was the Cohu 6815, which was selected as the state of the art camera hardware for the initial MVFDS design concept. A 4.5 mm, 92-degree wide-angle manual exposure lens was used. The automatic gain control (AGC) was turned off for most test runs. The manual lens "f" stop exposure number and internal electronic signal integration time were set at various positions during the tests to determine their effect upon color resolution as a function of light intensity.

In addition to the fire data, data from possible false alarm sources were also obtained with the same video camera and digitized. Potential false alarm, or confusion sources were included in scenes along with fires to attempt to "fool" the computer software processing. Bright, high-wattage halogen lamps, rotating red dome lights, yellow-orange Xenon strobe lights, yellow/orange/green/red/black striped reflecting signs, and aluminum foils together with a variable speed fan (to simulate a signal chopping effect) were used in various combinations and conditions. Some sources were set at various positions in the scene with respect to the camera and to locations of fires (e.g. bright Xenon lamp set 10 feet in front of camera and 7 inch pan fire set 50 feet away to determine foreground effects on small fire detection). Others were hand carried or run toward the camera to simulate rapid moving lights/vehicles in attempts to fool the detector. The reflecting color striped signs were moved toward and away from the camera as well as waved in front of the camera to simulate a moving fire truck or other colored surface. This subject is discussed further in Section IV D.

The described fire data were used to conduct detailed analyses of the nature and properties of fires as seen in the visible spectrum. Much was learned from this research, including some characteristics that are specific to fire and, to the knowledge of the investigative team, not associated with any other light source or reflecting surface in any condition. These specific, unequivocal fire characteristics were incorporated into the software algorithms used in the MVFDS logic decision and discrimination processes.

The maximum fire threat to be considered in the MVFDS application was a major spill from a fuel truck, dropped wing tank, or panograph fueling system. For this purpose, data from the Hardened Aircraft Shelter (HAS) Fire Protection System test at Tyndall AFB in 1985 were used. This consisted of the spill (manually) of 165 gallons of JP-4 on the floor, directly behind and moving toward a simulated fighter aircraft full-scale model. Ignition points were set at three locations using 4 inch pans of burning alcohol. The resulting JP-4 fire was an excellent example of a major threat. Within only a few tenths of a second after ignition, the fire grew under the aircraft to a size of over 100 ft^2, and within 2 seconds, had reached a size of major proportions, and a wing height temperature near 1800° F. The data used from this fire consisted of video tapes recorded inside the hangar from a height of about 20 feet, looking down at an angle of about 45 degrees.

The video camera used in the tests evidently did not have an adjustable "f" stop, but used automatic gain control. The fire event, which was very intense, was exceptionally bright and much of the color was "washed" out due to saturation in all three color planes. Some yellow-orange color was visible in the edges of the flame profiles. These data were used explicitly to develop and verify algorithms pertaining to identifying/discriminating bright objects, and determining growth and growth rate. No spectral analysis was made with this data.

During the same HAS test as discussed above, 35mm color still slides were taken of the event from the opposite hangar door, looking "head-on" to the aircraft nose and to the moving spill of JP-4. These photographs were digitized and their color histograms used along with those obtained from the controlled pan fire tests mentioned above, for development of spectral discrimination algorithms.

B. IMAGE/DATA PROCESSING AND ALGORITHM DEVELOPMENT

An algorithmic approach to fire detection has been developed based on physical models for image formation. The physical models encompass the properties of fires and false alarm sources as well as the properties of image sensors. From these models several image observables were identified that can be used to distinguish fires from other stimuli. A logic structure was developed to combine the various sources of information that can be recovered from images to reliably identify the presence, size, and location of a fire event.

Distinguishing properties of fires that can be estimated from sequences of color images include intensity, size, stationarity, color, spatial texture, and temporal flicker. Using these properties, suppressant can be dumped on detected fires that exhibit sufficient size and growth rate. Algorithms to compute these properties were developed and implemented. These algorithms were tested on several sequences of fire events and false alarms. The results of these tests indicated the effectiveness of the approach based upon these algorithms for fire detection.

C. HARDWARE ANALYSIS

The videotapes of the HAS JP-4 fire tests were used in analyzing requirements for MVFDS data acquisition rates, algorithms, computational timing and overall system response speeds. These analyses helped to determine the equipment necessary to obtain and process the data.

The initial approach was to use image processing minicomputer work stations to simulate and test fundamental fire edge detection and spectral discrimination algorithms. The work station software consisted of a large library of image processing algorithms available to process simulated fire data. The choice and order of selection of several algorithms, particularly the ability to perform change detection for verifying a growing high intensity area, and spectral intensity discrimination for initial fire identification, resulted from these early study efforts.

Additionally, the results of the simulated fire data image processing and algorithm testing indicated that low cost hardware components such as the typical 80386 advanced technology class of personal computer, equipped with a frame grabber and a color video camera, could acquire the real time data at speeds as fast as 30 or more video frames per second (0.033 second intervals) and readily perform these fire detection algorithms at 100 millisecond intervals over the 2-3 second elapsed time of the HAS fire event.

Several instrumentation cameras were evaluated to determine the best choices for a very flexible system for initial test and evaluation with a clear path to developing a final production design. The Cohu 6815 CCD color video camera with a large number of standardized output signal formats (NTSC, Y-C, analog RGB) was obtained to use as the primary MVFDS R&D visual sensor. Several frame grabber specifications were obtained from manufacturers to compare capabilities. The TARGA Plus card was obtained to satisfy the MVFDS performance and processing requirements. Commercially available image processing programs and software support libraries of "C" language drivers and graphic processing routines were also obtained. The above hardware and software were then installed in a 80386 PC for processing selected fire and false alarm video data and demonstration of MVFDS feasibility. In support of this computer capability, a laboratory grade video recorder and monitor were included in the investigative system to enable frame freeze capture and analysis of fire data.

Further live fire tests were performed using the Cohu camera to capture fire events on tape. The aperture and the internal electronic integration time were varied for fire distances up to 100 feet from the camera to determine optimum exposure settings. Several frame sequences were digitized from the new fire event tapes to verify spectral and spatial characteristics.

D. DEMONSTRATIONS

Two demonstrations were made during the study. The first one occurred early in the project and exemplified existing software concepts related to frame subtraction, growth, and other features associated with pattern recognition and image processing technologies. The purpose of this first demonstration was to show that the base mathematical/computer processing technology existed and could be easily adapted to the MVFDS.

A second in-depth and comprehensive demonstration was given at the end of the program. This demonstration consisted of six parts: (1) Presentation of the objectives, approach, fire discrimination factors, false alarm source factors and system performance factors used in the study; (2) Presentation and demonstration of fire data used in the study; (3) Presentation of the mathematics, algorithms, and computer processes used by the MVFDS for fire discrimination and false alarm identification; (4) computer demonstration of each and every step used by the MVFDS in its logic tree decision process; (5) Presentation of conclusions and examples of time profiled events and how the MVFDS discriminates fire from nonfire sources; and (6) Presentation of hardware design and configuration.

The above final demonstration covered in detail the mathematical models and algorithms that were developed during the Phase I effort.

SECTION IV

TECHNICAL DISCUSSION AND ACCOMPLISHMENTS

This section discusses the technical basis of the operation of the MVFDS© and results obtained during the Phase I effort. The system hardware concepts are also discussed.

A. STATE OF THE ART OF MACHINE VISION TECHNOLOGY

Machine vision systems have been in use for military and commercial applications for well over two decades. Coupled with image processing and image classification algorithms and software, they have been applied to tasks including:

1. Visual inspection for manufacturing
2. X-ray imagery analysis for detecting tumors, bone fractures and defects in soft tissue.
3. Parts sorting and screening for subsystem assembly.
4. Robotic manipulator control.
5. Targeting and photo interpretation support in various DOD applications.

1. Commercial Applications

Machine vision has been applied successfully to the problem of automatically inspecting parts at various stages in the manufacturing process. Visual inspection is an effective means of detecting many different kinds of defects. Recent technological advances in computer hardware and sensors have made automatic visual inspection systems cost effective for a wide range of industrial applications. Vendors have started producing flexible systems that can be programmed for various inspection problems. Custom systems are now available for inspection tasks that cannot be performed manually.

In the past 10 years, a great deal of effort has been devoted to developing systems to inspect printed circuit boards. Current systems are available to locate many kinds of defects such as shorts, opens, over-etching, and spurious metal before the component insertion and soldering processes. Such systems are capable of high throughput, high detection accuracy, and low false-alarm rates.

Since the seventies, many systems have been built to inspect integrated circuit (IC) photomasks that transfer patterns for semiconductor lithography. The systems successfully find defects such as registration errors and dimension variations at high speeds. Several commercial systems are available and used by IC manufacturers.

Systems have also been developed that inspect integrated circuit chips. Such systems can check line widths and defects such as contamination and voids.

Autonomous vehicles can be guided by machine vision. Such applications are difficult because the vehicle must plan its actions, perceive its usually complex environment, and adapt to changes in the environment and new situations. Despite these difficulties, autonomous vehicles have been developed that are capable of road following and other tasks.

Machine vision is useful for many robotics applications. These typically involve recognizing and locating objects for such tasks as automated assembly. Available systems have successfully dealt with domains where objects are spatially unconstrained and may occlude each other.

Many advancements have been made in the processing of medical images. The ability of humans to interpret these images is often limited by obscuration, distortion, or blurring. Machine vision techniques are currently used in medical image processing for enhancement, detection, compression, measurement, visualization, and reporting.

2. Military Applications

The military machine vision applications include change detection to highlight military unit redeployment as viewed from airborne or spaceborne TV and/or IR imagery; damage assessment following an engagement or disturbing phenomena; or development patterns associated with military or civilian build-up (roads, buildings, etc.). Similarly, machine vision systems have a variety of military reconnaissance and surveillance applications. These are particularly applicable to site security surveillance for intrusion detection and alerting to incoming threats against ships, vehicles or military installations.

In the late sixties, military change detection systems were developed for optical platforms that permitted scanning, digitizing, and storing an image frame, then comparing this reference image with a frame of imagery taken at a later time. The system checked for registration points on the image scenes, then compared these references to generate a change detected frame. The system proved effective in highlighting changed areas and was used for a variety of post-mission analysis tasks. Evolution of this concept, and the image processing hardware and software, led the way to the development of imagery screening systems to accommodate the high volume of data acquired by satellite imaging systems. The advances made in optical and digital image processing spawned a number of video analysis workstations with continually augmented capability, including image enhancement, target recognition, and a corollary to change detection, moving target indication (MTI).

As with change detection, detecting motion on video imagery required that a reference scene be generated, the subsequent scene be registered and compensated for scene illumination variation, then subtracted from the reference. With MTI, a change in the image is tracked frame to frame to detect object motion (and velocity). This technique is used in many optical sensor targeting systems, particularly to cue an operator of a possible threat or target.

A related area of machine vision, and one that has achieved the most emphasis in the past decade, is that of automated imagery analysis and target recognition. Optical imagery is processed using feature extraction and statistical pattern recognition methods to detect, track and attempt to identify targets in thermal and video imagery. Numerous systems are currently employed in missile guidance systems and electro-optical tracking systems using a variety of signal processing and pattern recognition algorithms. Real-time hardware implementation is realized using high-speed DSP and pipe line processing systems. This trend and development effort have enabled the application of this technology to problems such as fire detection. Combining the developed methods of image processing, image registration and subtraction, and image analysis with the continuing reduction in the cost and size of the required hardware, allows a timely and cost efficient solution. Machine vision technology has been used in many complex problems, much more severe and complicated than fire detection and discrimination. The technology exists, has been proven, and does not provide any technical risk for the development and application of the MVFDS.

3. Machine Vision Benefits to Fire Detection

Machine vision technology can readily and effectively be applied to fire detection. Using a physical model for fire events, it has been shown (see Section IV C) that sequences of visible color images contain sufficient information to reliably identify and locate fire events. Such image sequences can be obtained using a standard CCD color video camera and digitizing hardware. The relevant information in these images can be extracted using the machine vision algorithms derived from fire models developed in this study.

In many respects, fire detection is a simpler application than many of the problems for which machine vision has been successful. As compared to most inspection problems where a system must distinguish several different materials, fire detection involves only distinguishing fire events from false alarm sources. The many attributes of a fire event such as intensity, size, growth, stationarity, color, texture, and flicker that can be derived from the fire models herein make a fire event relatively easy to detect in sequences of images. The projection model for the imaging system developed in this study makes it straightforward to compute the scene location of identified fires in three dimensions.

B. DETECTION METHODOLOGY

During this study, a number of characteristics of fire were reviewed for their uniqueness in discriminating fire from other objects, events, and phenomena that may have some similar characteristics. The selected characteristics were analyzed and tested with real fire data and with false alarm source data to attempt tc "fool" the software identification criteria. The following general characteristics were included in the detection/discrimination/classification algorithms as major steps in the logic decision tree: (1) intensity level of "bright" area; (2) color of bright area; (3) growth and growth rate; (4) continuity/stationarity; (5) edge profile variations; (6) certain spectral characteristics within a frame and spectral flicker from frame-to-frame; and (7) presence of UV/IR. After all these conditions are satisfied, the fire alarm is activated. The MVFDS continues to monitor the fire event until its size and other characteristics reach the predetermined requirements for size and/or association with some object to warrant an automatic release of suppressant.

The MVFDS relies on standard silicon charge coupled device (CCD) color camera outputs in three color (red, green, blue) analog signals. As previously discussed, the MVFDS simulates the detection and logic process of a human being, using only visual sensory input data in the visible region. The video camera outputs one frame at a time, encompassing the entire scene as covered by the camera's field-of-view (chosen here to be 90 or more degrees). The frame rate is predetermined by the amount of information required to be processed within some interval of time. For purposes herein, the MVFDS operates at a standby rate of one frame every 1-10 seconds until it switches to a fast "event mode" where the processing rate is increased to 10-30 frames per second.

The MVFDS uses one or more (in a system configuration) cameras to routinely monitor the area/volume being protected. A new frame/scene is "grabbed", digitized, and stored in memory every 1-10 seconds, replacing the previous frame. This process can continue indefinitely until some change or characteristic in the scene occurs for which the MVFDS was preprogrammed to identify.

Encompassed within the MVFDS are small UV and IR detectors that are very sensitive to wavelengths at 200-300 nanometers and 4.3 micrometers, respectively. They are purposefully set at very high sensitivities to instantly respond to any UV/IR emitting source. The presence of these wavelength emissions during hydrocarbon fire events is the basis on which conventional flame detectors depend. As stated earlier, because of this dependency and sensitivity they are also likely to alarm to a variety of nonfire sources, of which there are many.

These detectors are used by the MVFDS as a precursor switch to increase the frame processing rate ("alert/event mode"). The MVFDS does not care if the UV and IR detectors see an actual fire or not, because confirmation is made by computer processing of the camera data. Immediately upon registering the presence of these radiations, the MVFDS initiates an alarm (if desired) in the facility that a UV/IR source exists and a new frame is grabbed, digitized, processed and stored. This frame now becomes the new base frame, replacing the previous frame in memory. Another frame is then obtained, say within 1/10th of a second or sooner. The computer processing performed on each frame and between frames is described as follows.

1. The first frame, grabbed after the UV/IR detectors have activated the event mode, is processed for bright areas consisting of pixels above threshold intensity levels in preselected fire associated color bands. If such a bright area is identified, the pixels it occupies are registered in position coordinates and the scan line corresponding to the base of the bright area, on the floor, is also registered. The distance of the bright area from the camera is automatically determined via a stored lookup table that references each scan line number according to its calibrated distance from the detector unit. The calibration is accomplished at installation with the use of markers set at known distances on the floor which correspond to the camera scan line numbers. The size of the bright area is also known because the size of pixels in the area are automatically known. The bright area is edge enhanced and edge profiled and this information, along with position information, is stored.

If no bright areas are found in the first alert mode frame, consecutive frames are grabbed and processed until one is identified or until the MVFDS decides that no visible fire event exists and, therefore, the UV/IR signals came from a false alarm source. The elapsed time before the MVFDS decides that an event is a false alarm and returns to standby mode can be adjusted, depending on the nature of the fire threat.

2. For example, assume a bright area is identified in the first event mode frame above. One tenth of a second later the next frame is grabbed, digitized and processed in the same manner as the previous frame. This frame, say F2, is subtracted from F1, the new base frame, and the size of the remainder of the subtracted bright area determined. Growth, if any, and growth rate are then known over the last one tenth second. The edge profile is determined as well as certain spectral features within the profile of the bright object. Certain pixel continuity features are compared frame-to-frame. All this information is stored and position referenced.

3. The next frame, F3, is grabbed, subtracted from frame F2, and the bright area(s) processed the same as above for growth, growth rate, edge frequency flicker, pixel continuity between frames, and certain characteristics of the spectral signatures within frame F3 and in comparison to pixels in frame F2 and F1.

4. The process continues with frames F4, F5, etc., until the preset conditions that uniquely discriminate fire from other objects/sources/phenomena are all satisfied and the size of the identified fire area reaches the predetermined specified size for the MVFDS to activate the suppressant. Assuming a fire threat similar to the HAS 165 gallon JP-4 spill/fire, the growth and other spatial, temporal, and spectral characteristics could be satisfied within only 0.3-0.4 seconds after fire start, and the MVFDS would be certain that the event is a real fire. This would be investigated further in a Phase II effort.

Once fire is determined, appropriate alarms are activated. suppressant dump, however, can be delayed until the fire size has grown to the specified threshold for automatic dump. There are other options at this point, including zonal suppression since the location of the fire is known. Other options may include alarm only for some time to allow for manual extinguishment, especially if the fire or its location does not warrant a total or partial dump.

C. IMAGE AND DATA PROCESSING METHODOLOGY

The algorithmic approach taken to fire detection is derived from physical models for the formation of images of fires and other stimuli. These models incorporate the physical characteristics of both events in the world and image sensors. These physical models, can be used to quantify various properties derived from color images that can be used to reliably distinguish fires from other events. These properties can be computed at high speed and, along with a decision procedure, form the basis of the fire detection system. The effectiveness of these properties for fire identification has been demonstrated on several sequences of images of fires and false alarm data.

The imaging system consists of a color CCD camera and a lens. The lens guarantees that each visible point in the world will project to a unique point in the image according to the perspective transformation. The two dimensional spectral irradiance function recorded in the image plane will be proportional to the scene radiance over corresponding patches in the scene. The CCD imager consists of a two dimensional array of collection sites that are sensitive to light. We can model a measured color pixel at (x,y) in the image by the triplet (S_R, S_G, S_B) where

©

$$S_R(x,y) = \int I(x,y,\lambda)\, f_R(\lambda)\, d\lambda$$
$$S_G(x,y) = \int I(x,y,\lambda)\, f_G(\lambda)\, d\lambda$$
$$S_B(x,y) = \int I(x,y,\lambda)\, f_B(\lambda)\, d\lambda$$

and where $I(x,y,\lambda)$ is the incident spectral irradiance at (x,y) and $f_R(\lambda)$, $f_G(\lambda)$, and $f_B(\lambda)$ are the response of the red, green, and blue sensing elements respectively. The response of a sensing element is equal to the transmission of the color filter (in this case red, green, and blue) times the quantum efficiency of the CCD. Typical curves $f_R(\lambda)$, $f_G(\lambda)$, and $f_B(\lambda)$ are shown in Figure 1.

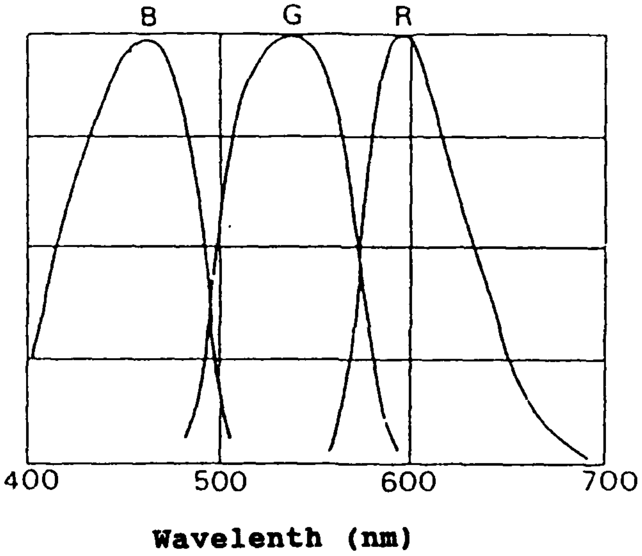


Figure 1. Typical Spectral Response Curves

The spectral radiance of a fire in the scene can be modelled by the equation

$$E(x',y',\lambda,t) = E(\lambda) + V(x',y',t,\lambda)$$ ©

where (x',y') denotes coordinates in the scene projecting to the image, the function $E(\lambda)$ describes the mean spectral radiance of a fire, and the process $V(x',y',t,\lambda)$ quantifies spatial variation (x',y'), temporal variation or flicker (t), and color variation (λ)

in the appearance of a fire. In terms of this model, the measured pixel values for a fire are given by

©

$$S_R(x,y,t) = \int E(x',y',\lambda,t) f_R(\lambda) d\lambda$$

$$S_G(x,y,t) = \int E(x',y',\lambda,t) f_G(\lambda) d\lambda$$

$$S_B(x,y,t) = \int E(x',y',\lambda,t) f_B(\lambda) d\lambda$$

Using this model, the image of a fire will exhibit the properties of (1) high intensity, (2) characteristic mean spectral content, (3) characteristic spatial variation, and (4) characteristic flicker. A fire event that must be suppressed will exhibit all of these four properties, plus a size and growth rate above a specified threshold and stationarity. Algorithms to compute these properties are described in following sections.

1. Fire Detection/Fire Event Detection

An overview of the MVFDS logic structure is illustrated in Figure 2. The system operates in a standby mode before UV/IR radiation is detected and shifts to alert mode after UV/IR radiation is detected. The algorithms associated with individual decisions within the system are described in Sections IV C-2 through IV C-8

If UV/IR radiation has not been detected in the scene, the MVFDS operates in standby mode. In standby mode, the system monitors for bright regions in the image. Such bright regions which have persisted for a certain length of time are assumed to not correspond to fire threats and will be called background

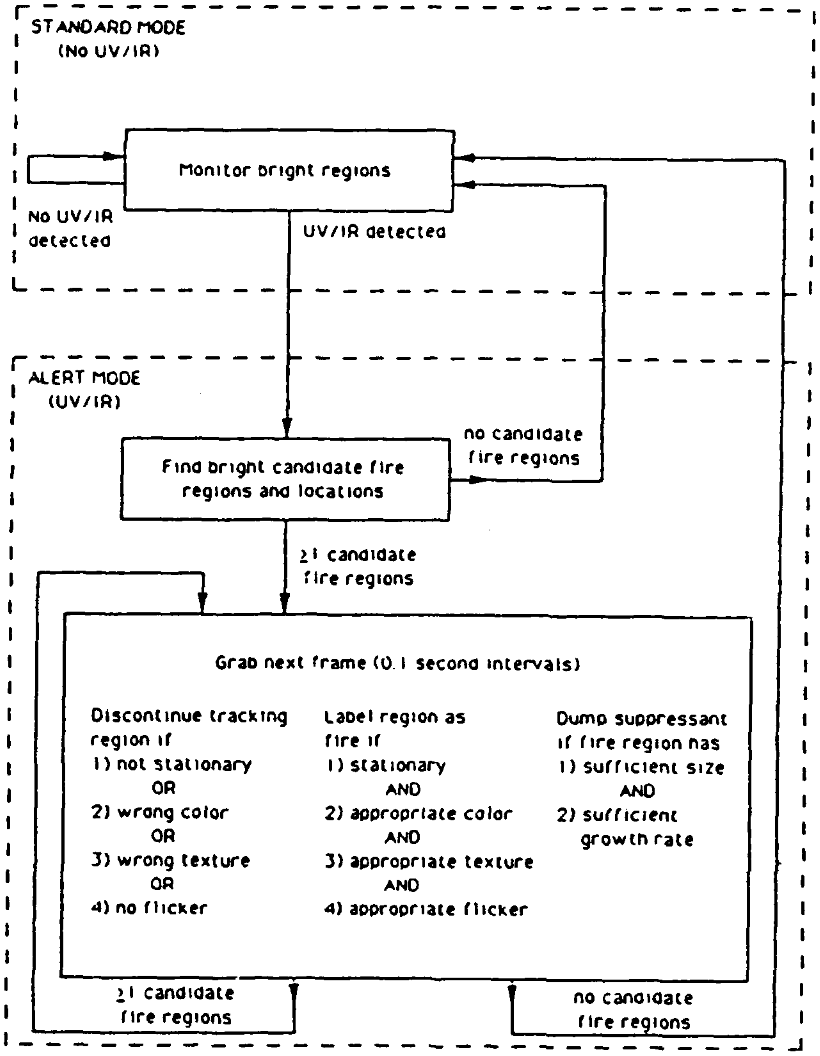


Figure 2. Overview of MVFDS© Logic Structure

regions. Tracking background regions in standby mode will ensure that they are not considered as potential fires after UV/IR radiation has been detected.

Once UV/IR radiation is detected in the scene, the MVFDS enters alert mode. Immediately upon entering this mode, MVFDS locates bright regions R_i that are not background regions and computes the scene position corresponding to these regions. After finding these active regions, MVFDS processes incoming frames at 0.1-second intervals and, for each new frame, computes the following properties for each active region: size, growth rate, stationarity, mean spectral content, spatial variation, and temporal variation.

Following each frame for any of the active regions MVFDS can take any of the actions (1) discontinue tracking, (2) label as fire, (3) dump suppressant. Tracking is discontinued for any region that fails to exhibit appropriate (1) stationarity, (2) spectral signature, (3) spatial variation, (4) flicker. A region is labeled as fire if it exhibits appropriate (1) stationarity, (2) spectral signature, (3) spatial variation, and (4) flicker. Suppressant is activated for regions that have been labeled as fires and which exhibit appropriate size and growth rate.

2. Identification of Bright Areas

Once the system enters alert mode, bright regions that are not background regions must be identified. Such regions will be called initial active regions. To find these regions, MVFDS grabs frames until regions are found with an intensity in the red band that exceeds a predetermined threshold value. For each of these initial active regions, MVFDS constructs a bounding box and computes the base of the corresponding event in the scene as shown in Figure 3.

The position of regions in the image can be localized according to the resolution of the CCD sensor. A typical CCD containing 512 x 512 collection sites is shown in Figure 4.

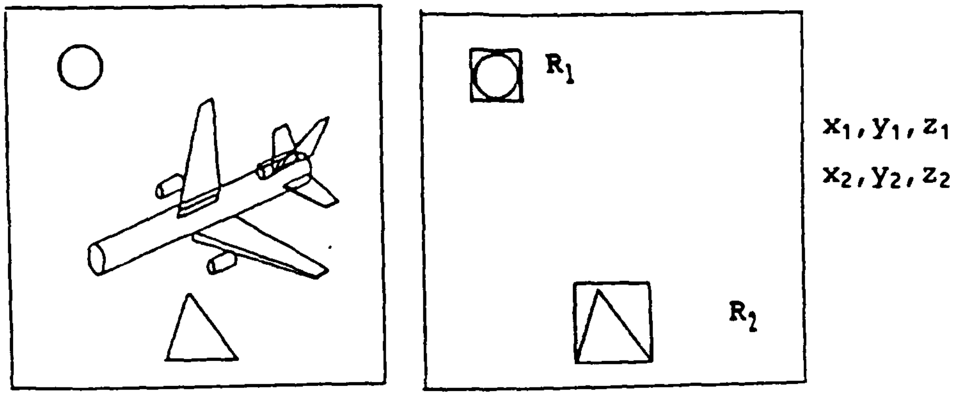
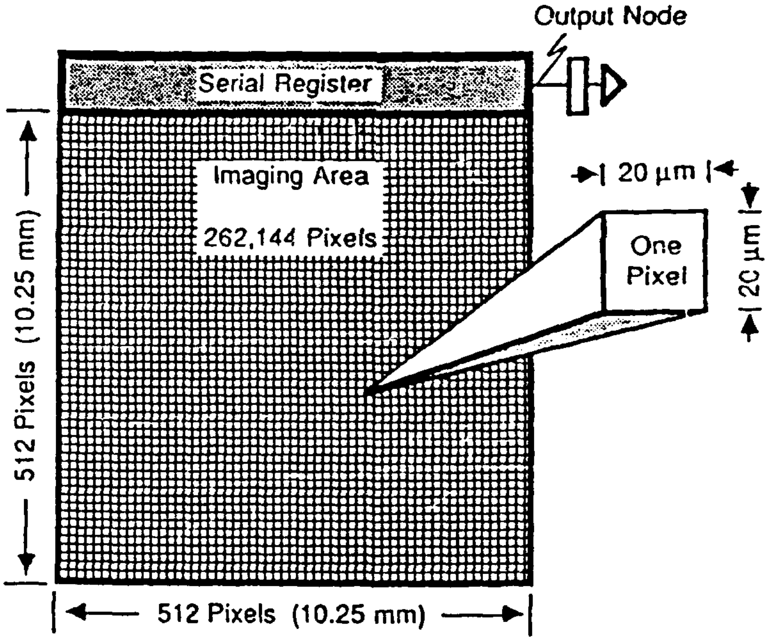


Figure 3. Finding Initial Active Regions



Typical 512 × 512 CCD

Figure 4. Typical CCD Sensor Array

Each point P' in the sensor plane is the image of a point P in the scene that lies on the ray from P' through the center of projection of the imaging system (Figure 5).

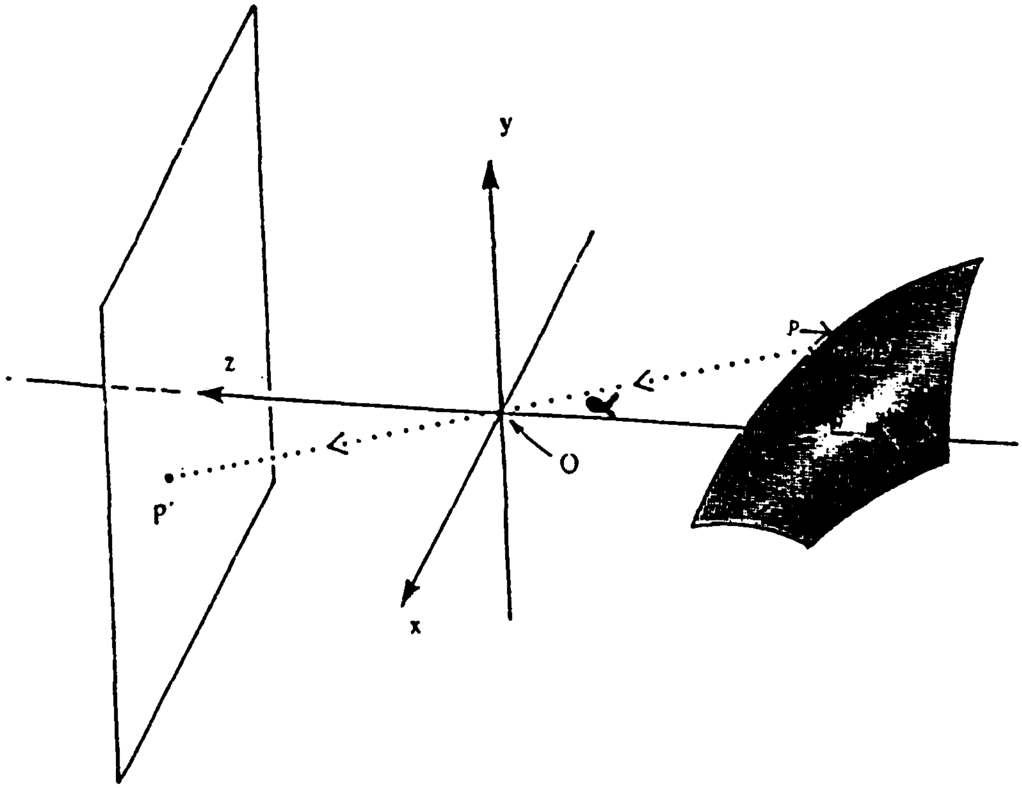


Figure 5. Projection Model

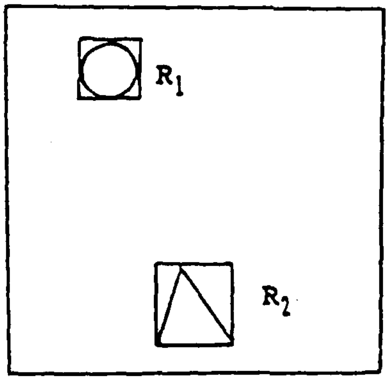
The base of the event in the scene may be computed by using a lookup table that models the projection of the imaging system and by assuming that the base of the scene event is located on the floor. This provides the location distance.

3. Determination of Size

The size of a region in the image is computed by counting the number of pixels in the region that exceed a threshold in the red band. From this pixel count and the inferred distance of the event from the camera, MVFDS computes the area of the event in the scene. Computing the scene area corresponding to an image region requires consideration of the projection geometry shown in Figure 5. Each pixel subtends a certain solid angle Ω with respect to the center of projection of the imaging system. Thus, each pixel corresponds to this solid angle in the scene as viewed from the center of projection. The area A in the scene imaging to this pixel that is normal to the viewing direction is given by

$$A = R^2\Omega$$

where R is the distance of the event in the scene from the camera. Using this relationship, the scene area of an event may be computed from the image pixel count. Figure 6 shows an example of the scene area computation for two regions with similar pixel counts but different distances.



R_1: AREA 30 FT^2
R_2: AREA 10 FT^2

Figure 6. Scene Area Computation

4. Determination of Growth and Growth Rate

Since the size of each region is computed for each new frame, it is straightforward to compute the average growth rate for each active region R_i. The average growth rate of region R_i up to time t is defined by

$$G_i = \frac{Size(R_i)_t - Size(R_i)_0}{t - t_0}$$

where t_0 is the time at which the initial region R_i was identified. Figure 7 gives an example of the growth rate computation for two regions.

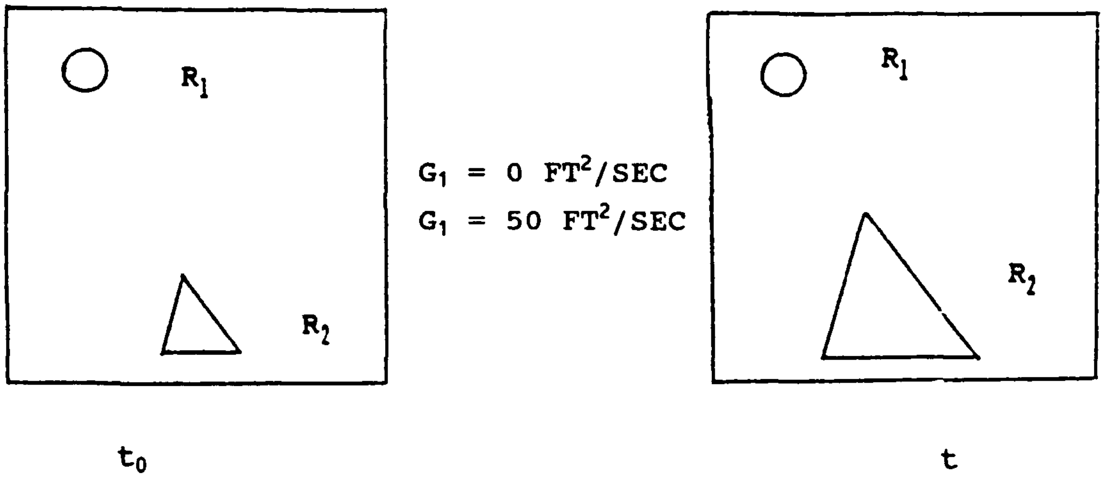


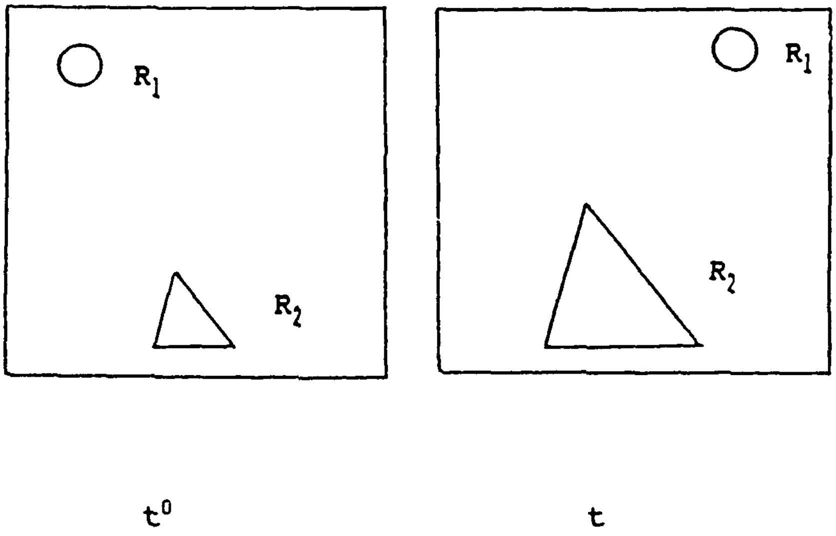
Figure 7. Growth Rate Computation

5. Determination of Stationarity

Stationarity measures the extent to which an event remains in a single place in the scene. Fires which pose threats will exhibit strong stationarity since, even though they may grow, the fire will continue to occupy the area where it started in the scene. Many false alarm sources, such as moving headlights, do not exhibit strong stationarity. For a region R_i at time t, stationarity is quantified by

$$S_i(t) = \text{fraction of pixels in initial region occupied at time } t$$

A threshold value of stationarity is used to determine if a region R_i is sufficiently stationary to correspond to a fire event. Figure 8 illustrates the stationarity computation for two regions.



R_1: $S(t) = 0$

R_2: $S(t) = 1$

Figure 8. Stationarity Computation

6. Determination of Spectral Signature

Fires will have a characteristic mean color or spectral signature given by the function $E(\lambda)$. Using the color imaging system measurements of $E(\lambda)$ integrated with the response function of the sensing elements f_R, f_G, and f_B, can be obtained. As described by the function $V(x',y',t,\lambda)$, fires will also have a characteristic spectral variation.

The spectral properties of a fire, as measured by a color image sensor, may be characterized by the probability density p(R,G,B) of fire pixels in the digitized sensor measurement space. Since sufficient data are usually not available to accurately estimate p(R,G,B) explicitly as a three-dimensional function, it is necessary to exploit the structure of p(R,G,B) to allow characterization. An efficient and accurate parametric representation for many color distributions p(R,G,B) is the multivariate normal density given by

$$p(A) = \frac{1}{(2\pi)^{1.5}|\Sigma_A|^{0.5}} e^{-0.5(A-\bar{A})^T \Sigma_A^{-1} (A-\bar{A})}$$

where A = (R,G,B) indicates the sensor measurement, $\bar{A} = (\bar{R},\bar{G},\bar{B})$ is the mean vector of the distribution, and Σ_A is the covariance matrix of the A distribution that describes the dispersion of the data in any direction in color space. Contours of constant density are then ellipsoids satisfying

$$^{\copyright}(A-\bar{A})^T \Sigma_A^{-1} (A-\bar{A}) = C$$

where C is a constant. For fire pixel classification, a threshold T is selected to define the ellipsoid so that vectors A for which

$$^{\copyright}(A-\bar{A})^T \Sigma_A^{-1} (A-\bar{A}) < T$$

are within the ellipsoid and considered to be pixels belonging to the distribution p(R,G,B) (i.e. fire pixels). Measurements outside the ellipsoid are assumed to not belong to the distribution p(R,G,B) (i.e. not fire pixels).

From a sample set of fire pixels obtained with a given sensor, the vector A is easily estimated by the sample mean and the independent parameters of $\sum_A$ are easily estimated from the sample covariance matrix. Once p(R,G,B) has been estimated according to this model and a threshold T has been selected, the classification results may be stored in a lookup table to allow high speed pixel classification.

7. Determination of Spatial Variation

Fires will exhibit spatial variation in spectral content and intensity within single frames according to the function $V(x',y',t,\lambda)$. The ability to measure this spatial variation will depend on the distance of the fire from the sensor and the spatial resolution of the sensing device. Near fires will produce images with significant measurable spatial variation, while for distant fires most of this spatial variation will be lost as radiance from large areas of the fire is integrated at single collection sites in the CCD array.

The spatial variation of a fire region R_i is characterized by the variance vector $(\sigma_r^2,\sigma_g^2,\sigma_b^2)$ defined by

©

$$\sigma_r^2 = \frac{1}{N}\sum_R (r - \bar{r})^2$$

$$\sigma_g^2 = \frac{1}{N}\sum_R (g - \bar{g})^2$$

$$\sigma_b^2 = \frac{1}{N}\sum_R (b - \bar{b})^2$$

where N is the number of pixels in R_i, (r,g,b) are individual color pixel measurements, and $(\bar{r},\bar{g},\bar{b})$ is the mean color vector for R_i. A region R_i is considered to have appropriate spatial variation for a fire if the corresponding vector $(\sigma_r^2,\sigma_g^2,\sigma_b^2)$ is in the appropriate range for a fire at the distance estimated for the potential fire imaging to R_i.

8. Determination of Temporal Variation

Fires will exhibit temporal variation (flicker) in spectral content and intensity from frame to frame according to the function $V(x',y',t,\lambda)$. The ability to measure this flicker depends upon the distance of the fire from the sensor and the number of frames per second processed by the imaging system. Near fires will produce image sequences with significant flicker, while distant fires will exhibit less image flicker.

The temporal variation of an individual pixel (i,j) is quantified by the temporal variance vector $(\sigma_r^2(i,j),\sigma_g^2(i,j),\sigma_b^2(i,j))$, defined by

©

$$\sigma_r^2(i,j) = \frac{1}{N}\sum_t (r_{ij} - \bar{r}_{ij})^2$$

$$\sigma_g^2(i,j) = \frac{1}{N}\sum_t (g_{ij} - \bar{g}_{ij})^2$$

$$\sigma_b^2(i,j) = \frac{1}{N}\sum_t (b_{ij} - \bar{b}_{ij})^2$$

where N is the number of frames over which the vector is computed,

(r_{ij},g_{ij},b_{ij}) are measured pixel vectors at location (i,j) over the sequence of frames, and (r_{ij},b_{ij},g_{ij}) are the mean color pixel values at (i,j) over the N frames.

The temporal variation for a region R_i is defined to be the mean $(\sigma_r^2,\sigma_g^2,\sigma_b^2)$ of the vectors $(\sigma_r^2(i,j),\sigma_g^2(i,j),\sigma_b^2(i,j))$ taken over all pixels in R_i in each of the N frames. A region R_i is considered to have appropriate temporal variation for a fire if its temporal variation $(\sigma_r^2,\sigma_g^2,\sigma_b^2)$ is in the appropriate range for a fire at the distance estimated for the potential fire imaging to R_i.

9. False Alarm Source Discrimination

The sources/objects/phenomena that cause conventional detectors to false alarm or to be confused are related to UV and/or IR emissions or reflections. The MVFDS, operating primarily in the color/visible spectrum, cannot be fooled by such sources.

During this study efforts were made to confuse the MVFDS processing algorithms by the introduction into the scene of various types of bright lights and reflecting surfaces. As discussed in Section IV D, Experimental Results, no misidentifications were made and all were discriminated as "nonfire" sources. The following are some representative descriptions of how the MVFDS responds to various types of light sources.

a. Lights: Fixed in-place facility or utility: MVFDS will identify as bright objects that do not satisfy the requirements of growth, edge flicker, spectral flicker, or appropriate color histogram. MVFDS will recognize position continuity. MVFDS will eliminate from the standard base stored scene.

b. Lights: Vehicle, aircraft, AGE, or hand held lights moving in front of or toward MVFDS detector unit: MVFDS will recognize as bright object and possible growth. MVFDS will identify as nonfire source because of wrong spectral signature, no edge profile flicker, no spectral variations, and no continuity frame to frame (unless object is moving exactly in direct line of sight of detector). In the system approach, where two or more MVFDS detection units are involved, one detector may see the object growing (moving toward it), but the other camera sees it moving away. It cannot, therefore, be a fire.

c. Lights as above, but of different colors, rotating, strobe, being chopped by movements and fans, etc. Again, the MVFDS will see them as bright lights and determine their positions. They will be eliminated as fire candidates because they do not satisfy all the conditions of growth, growth rate, continuity, spatial flicker, spectral signature, and spectral flicker.

d. Welding torch (flame and sparks): MVFDS will identify as bright object but will take no dump action because of no growth over consecutive frames, lack of continuity, small size, no high frequency spatial and spectral flicker.

e. Aircraft afterburner: MVFDS will discriminate because of no edge flicker, smooth contour, no spectral flicker. If the aircraft is in the distance, the afterburner does not portray a contiguous source in consecutive frames as seen by the MVFDS.

f. Matches, cigarette lighters: If moving directly toward a MVFDS detector, they will be identified as bright objects, with edge flicker, spectral flicker, but probably no continuity. It is difficult to imagine a situation where the small flame is moved exactly along the line of sight to the center of the detector, and always remaining on the base line where fire was first identified.

The flame would appear as a small, almost point source, and even in the worst case, the flame would be determined to be too small to justify a dump. If the flame was held directly in front of the camera, only inches away, the MVFDS would see all the features of fire, including size, and dump unless the MVFDS is operating in a system mode. In the system configuration, the second or other detector(s) would see the flame as too small and possibly moving away, thus preventing a suppression dump.

D. EXPERIMENTAL RESULTS

The algorithms described in Section IV C were tested against real fire event data. This section describes the results of implementing them in "C" language and running them on a Sun SPARC computer.

1. Tracking Bright Regions

Figures 9-15 are digitized images from a sequence taken of the HAS JP-4 running fuel fire test at Tyndall AFB in 1985. The camera aperture was improperly adjusted to capture the detailed spectral or texture characteristics of the flame. This sequence can be used, however, to demonstrate the ability of the algorithms developed in this study to locate bright regions and to monitor their growth.

Figure 9 is the first frame in the sequence. A small fire has started in the lower left part of the image (assume at this instant in time that UV/IR detectors have responded, therefore transforming the MVFDS system operation from standard to alert mode). The bright pattern of light entering the hangar through the door on the right side of the image has persisted without growth for a significant amount of time before the UV/IR alert and is not considered to be a threat. The system identifies the bright region in the lower left as a candidate fire region.

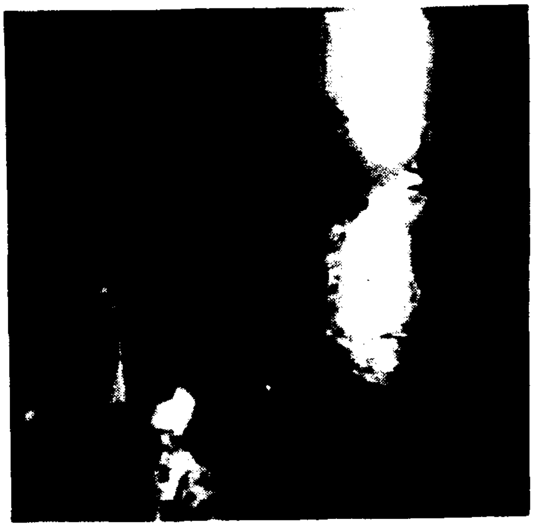


Figure 9. Fire Ignition Time
Frame 1

Figure 10. 0.1 sec Later
Frame 2

[Sequence of Images Beginning with Figure 9 of Running 165 gal JP-4 Fuel Fire During "HAS" Tests at Tyndall AFB, 1985]

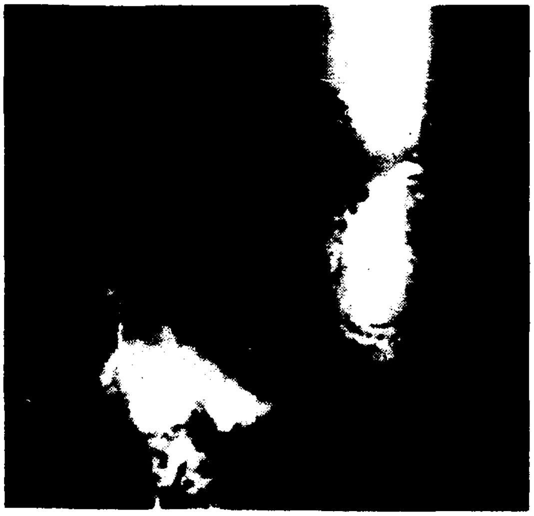


Figure 11. Continued Fire Growth
Frame 3

Figure 12. Continued Fire Growth
Frame 4

Figure 13. Continued Growth - Frame 5

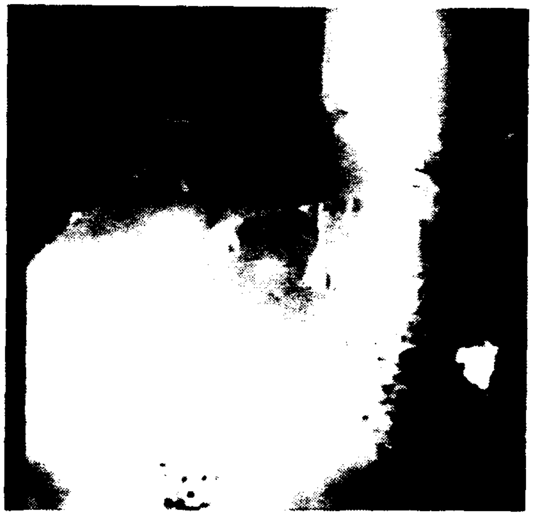


Figure 14. Continued Growth - Frame 6

Figure 15. Continued Growth - Frame 7 (2 sec after start)

Figure 16 indicates the detected growth of the fire between Frames 1 and 2. In Figure 16, a few new bright pixels on the right side of the image are identified. These pixels are due to random fluctuations in the edges surrounding the light passing through the door and can be rejected automatically as threats because of their small "point" size.

Figure 17 indicates the detected growth of the fire between Frames 2 and 3. Since the estimated growth is based only on intensity, a region made up of the reflection of the fire from the airplane is detected as a growth region. Figure 18 tracks the growth of the fire between Frames 3 and 4 and Figure 19 tracks the growth of the fire between Frames 4 and 5. In Frame 6, a second fire starts in the lower right part of the image and its presence along with the continued growth of the first fire are indicated in Figure 20. In Frame 7, Figure 15, the second fire grows and suppressant is dumped from the upper left. These events are detected by the algorithm as indicated in Figure 21.

2. Identifying Fires by Spectral Content

Figures 22-37 illustrate the capability of the algorithm described in Section IV C-6 to locate fire pixels using only their spectral signature. Figures 22, 24, 26, 28, 30, 32, 34, and 36 are eight color frames taken of a growing JP-4 running fuel fire at Tyndall AFB. Each frame contains several bright regions in addition to the fire. Figures 23, 25, 27, 29, 31, 33, 35, and 37 indicate in white the pixels that the algorithm classified as fire using only local single pixel color information. These figures show that this technique is very accurate in identifying only fire pixels in the presence of other bright stimuli. In addition, these figures show that the method can capture fine spatial details in the fire structure.

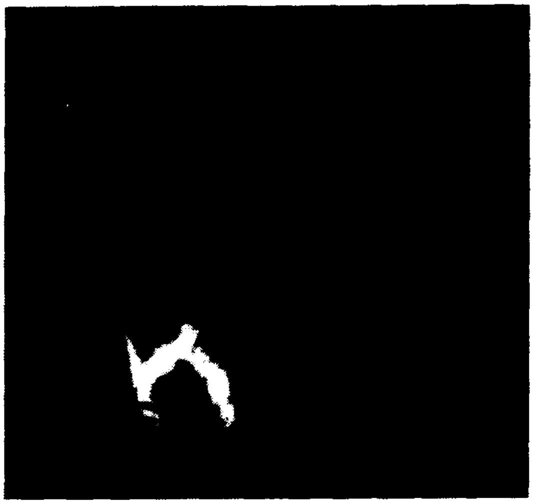


Figure 16. Detected Growth Between Frames 1 and 2

Figure 17. Growth Between Frames 2 and 3

Figure 18. Growth Between Frames 3 and 4

Figure 19. Grwoth Between Frames 4 and 5

Figure 20. Second Fire Ignited in Lower Right

Figure 21. Second Fire Growth in 0.1 sec
(note halon release upper left)

Figure 22. 35mm Color Still Photo at Fire Ignition in "HAS" Test

Figure 23. Result of Classification Algorithm Processing Pixels for "Fire" Signature (note all other bright objects eliminated)

Figure 24. Color Photo 0.3 sec Later

Figure 25. Results of Algorithm Processing

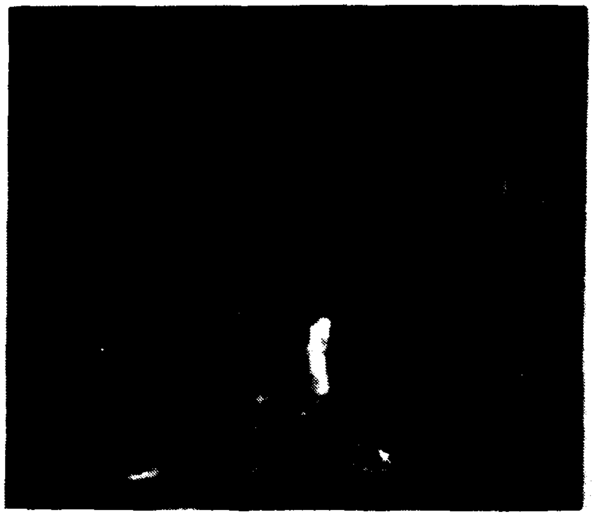


Figure 26. Color Photo of Fire after 0.6 sec

Figure 27. Result of Algorithm Processing for "Fire" Pixels

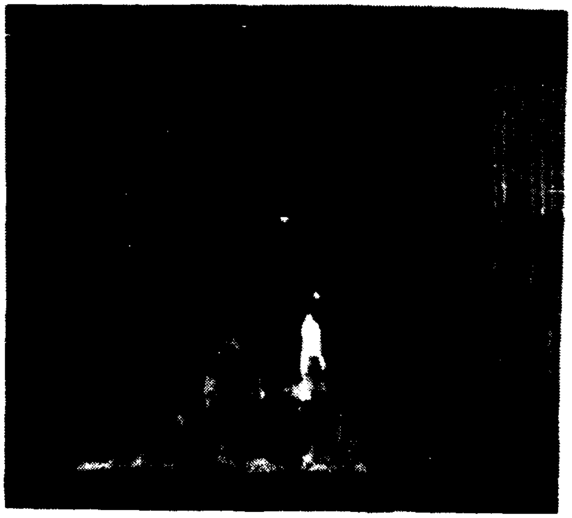


Figure 28. Next Photo 0.9 sec After Fire Start

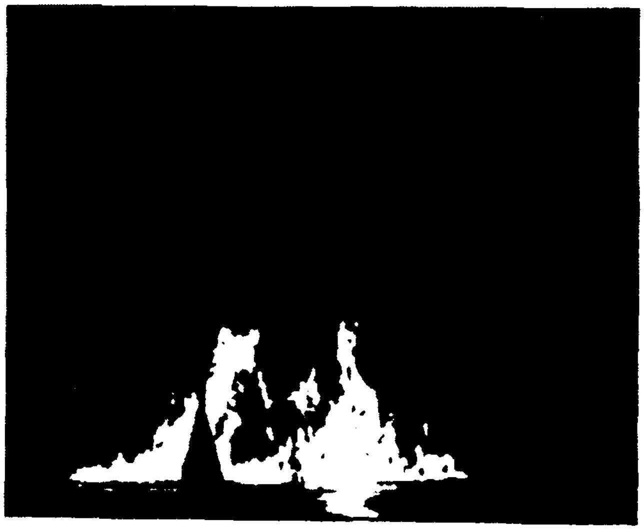


Figure 29. Results of Algorithm Processing of Pixels

Figure 30. Next Color Still Photo 1.2 sec after Fire Start

Figure 31. Result of Algorithm Processing for "Fire" Pixels

Figure 32. Next Color Photo 1.5 sec after Fire Start

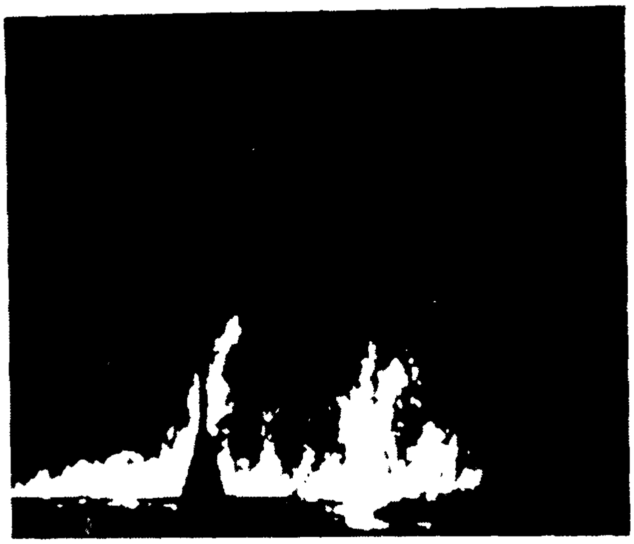


Figure 33. Results of Algorithm Processing of Pixels

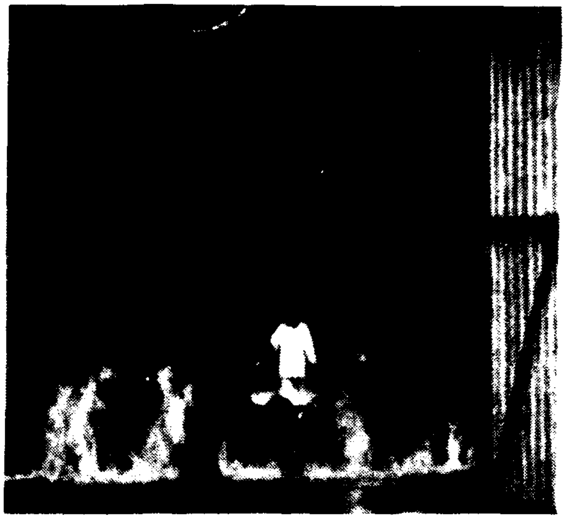


Figure 34. Next Color Still Photo 1.8 sec after Fire Start

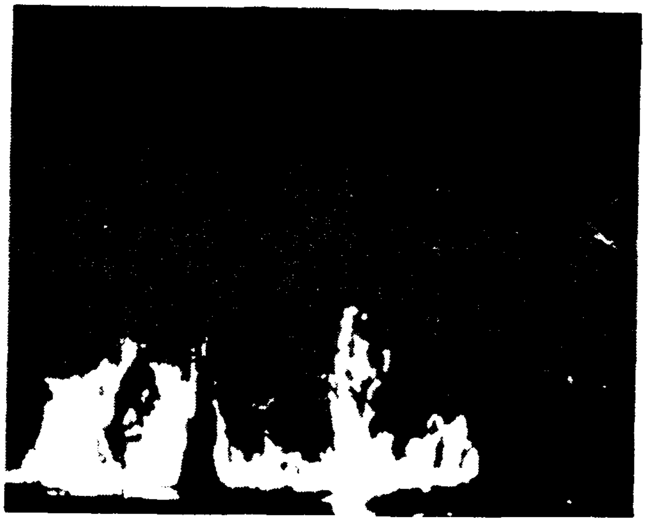


Figure 35. Continued Success of Algorithm Processing for Fire Pixels

Figure 32. Next Color Photo 2.1 sec after Fire Start

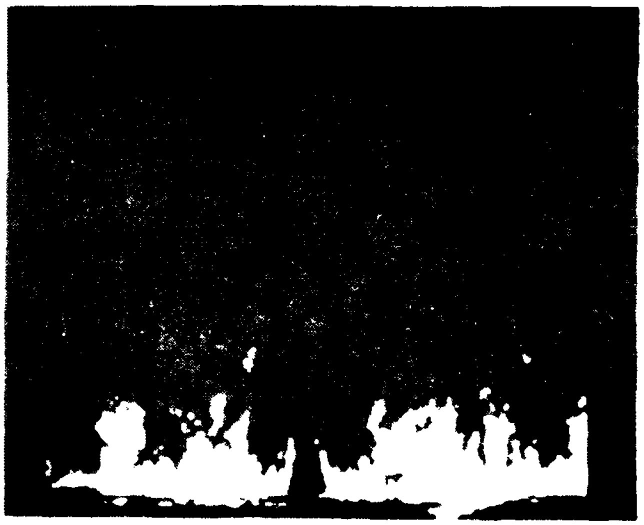


Figure 33. Continued Results of Algorithm Processing

Figures 38-41 further illustrate the ability of the spectral classification algorithm to identify fire regions in the presence of potential false alarm sources. Figures 38 and 40 are frames containing a 7-inch fire at a distance of 50 feet from the camera, a floodlight at 8 feet from the camera, and a highly reflective card containing many bright colors of different patterns intending to confuse the algorithm. Figures 39 and 41 indicate in white the pixels that the algorithm classified as fire using only local single pixel color information. These figures demonstrate that the algorithm can locate small fires in the presence of false-alarm stimuli.

3. Identifying Fires by Spatial Variation

Figures 42 and 43 demonstrate the ability of the algorithm to measure spatial variation (texture) within a single frame of a fire sequence. Figure 42 is an image of a 16-inch pan fire 19-inches from the camera. Intensity and color spatial variation within the fire is clearly evident. Figure 43 indicates in white local image regions that exhibit large spatial variations. These figures demonstrate that spatial variation is a useful cue for fire identification.

4. Identifying Fires by Temporal Variation

The ability of the algorithm of Section IV C-8 to measure temporal variation (flicker) is shown in Figures 44-48. Figures 44-47 are four consecutive frames taken of a 16 inch pan fire 19 inches from the camera. A small rectangle of approximately the same color as the fire has been superimposed near the upper left hand corner of the image.

Figure 48 indicates in white the pixels that exhibit significant temporal flicker. Nearly all the fire pixels that are within the dynamic range of the imaging system are marked. As

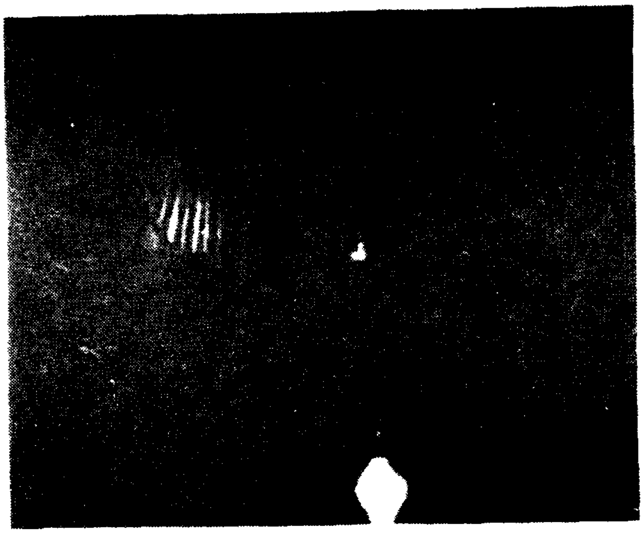


Figure 38. 7-Inch JP-4 Pan Fire with Intense Strobe Light and Color Reflector in Scene

Figure 39. Results of Classifying Pixels with Algorithm to Discriminate False Alarm Sources

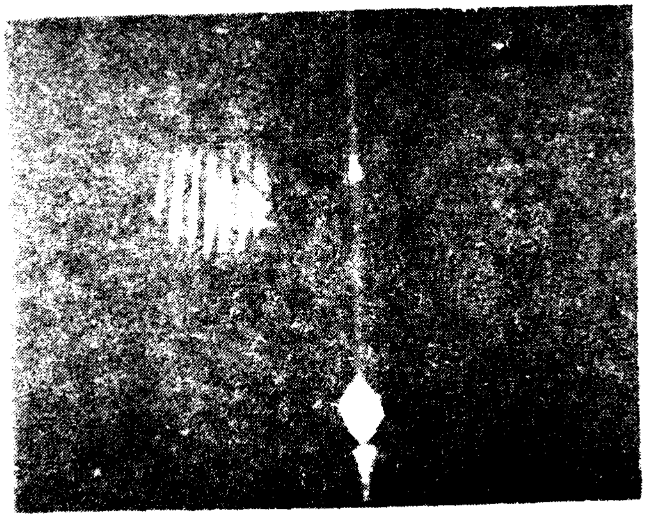


Figure 40. 7-inch JP-4 Pan Fire with Moving Bright Xenon Light and Reflecting Color Stripes

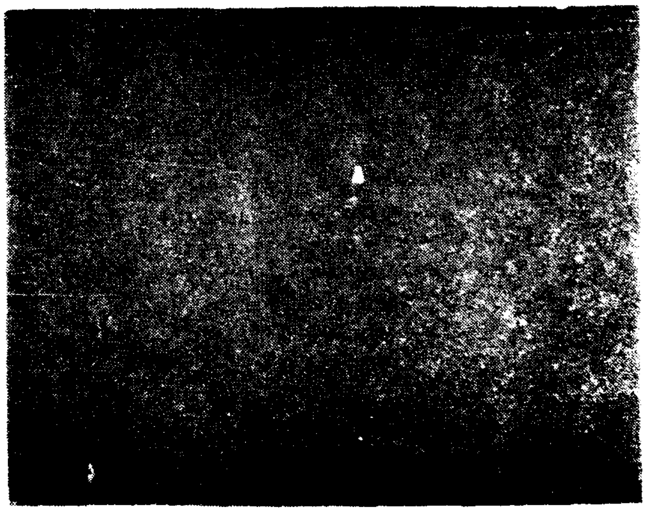


Figure 41. Continued Results of Classifying "Fire" from "Other" Pixels

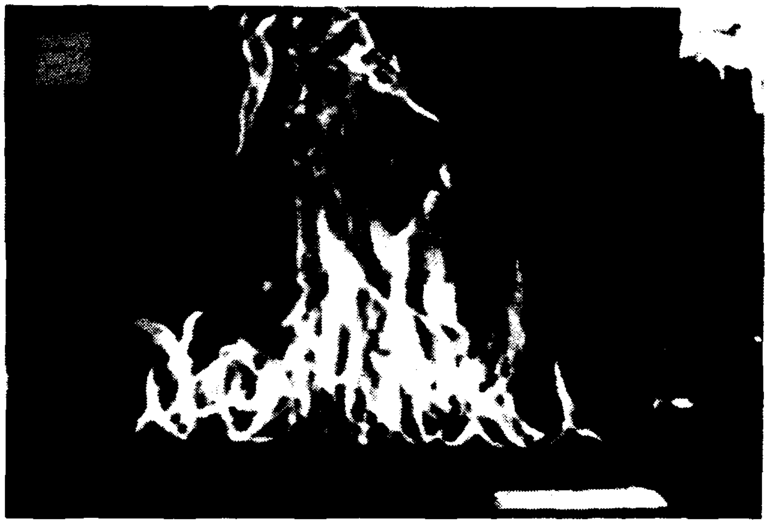


Figure 42. Color Frame of 16-inch JP-4 Pan Fire Showing Detailed Spectral Structure and Variance Pixel-to-Pixel

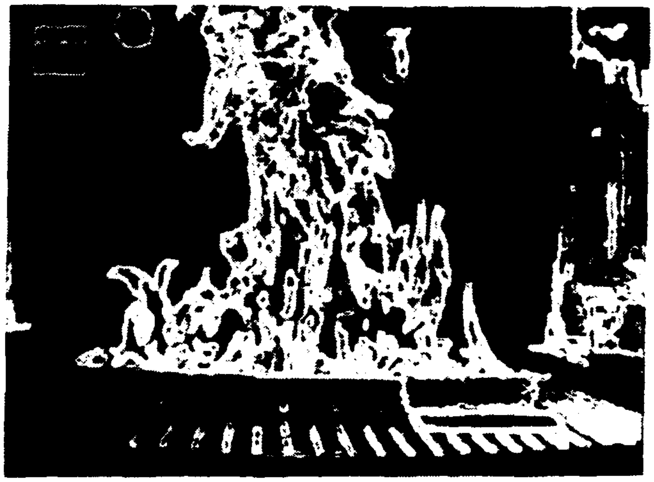


Figure 43. Results of Processing above Digitized Frame for Areas Showing Large Spectral Variations (this demonstrates that spatial variation is a very useful fire discriminator)

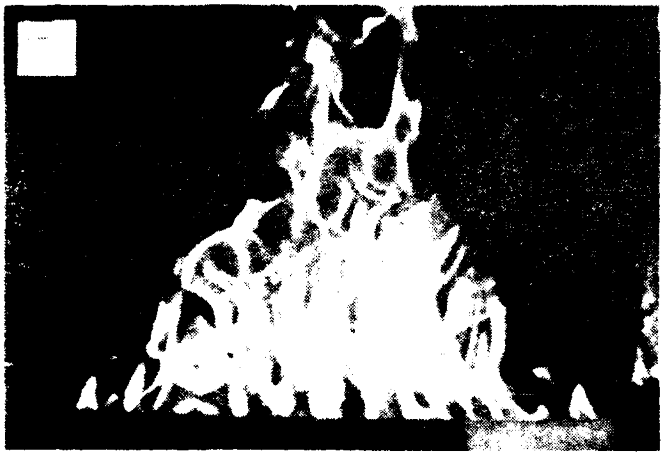


Figure 44. 16-inch JP-4 Pan Fire at 19-inches - Frame 1 of Sequence Taken with CCD Color Camera

Figure 45. Frame 2 1/30 sec after Frame 1

Figure 46. Frame 3 1/30 sec after Frame 2

Figure 47. Frame 4 1/30 sec after Frame 3

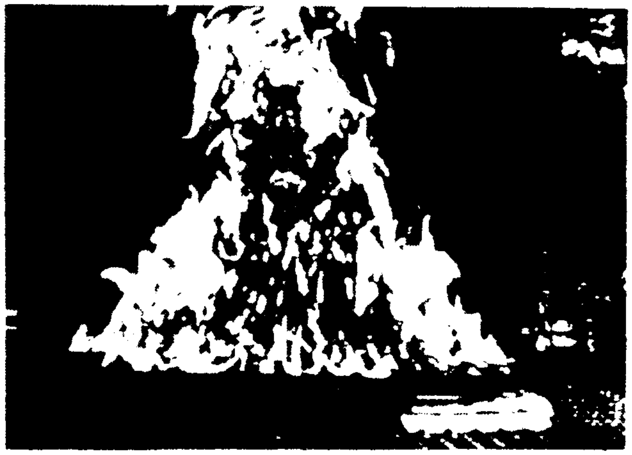


Figure 48. Results of Algorithm Processing to Exhibit Pixels with Large Temporal Spectral Variations

expected, it can be concluded that temporal variation is an important fire characteristic that can be used for discrimination.

E. MVFDS SYSTEM HARDWARE

The system consists of discrete UV and IR detectors, video cameras, real time video image digitizing interfaces, a microcomputer image processor, and outputs to initiate alarms and suppressant activations. Figure 49 is a block diagram of a prototype hardware configuration.

One or more color video cameras are used for the videoimaging fire detectors. The camera's RGB (red,green,blue) analog output signals are converted into digital computer data that is stored in video memory to accumulate a complete picture or frame. Each "frame" can be captured upon command and transferred into the microcomputer using a high speed real-time video processor commonly known as a frame grabber card (FGC). The camera video output is connected to a FGC which is plugged into an expansion connector slot on the microcomputer main printed circuit board. The microcomputer processes the spatial and spectral information obtained from fire emissions with the color video cameras to effectively discriminate from nonfire or benign fire emission sources.

The following description of the system's functions is based upon currently available commercial hardware. Video cameras, frame grabber cards, and microcomputer hardware are identified plus the essential operating software required to develop, refine, and implement the computerized machine vision fire detection technology.

1. Color Video Camera

The primary detector used in the system is a standard

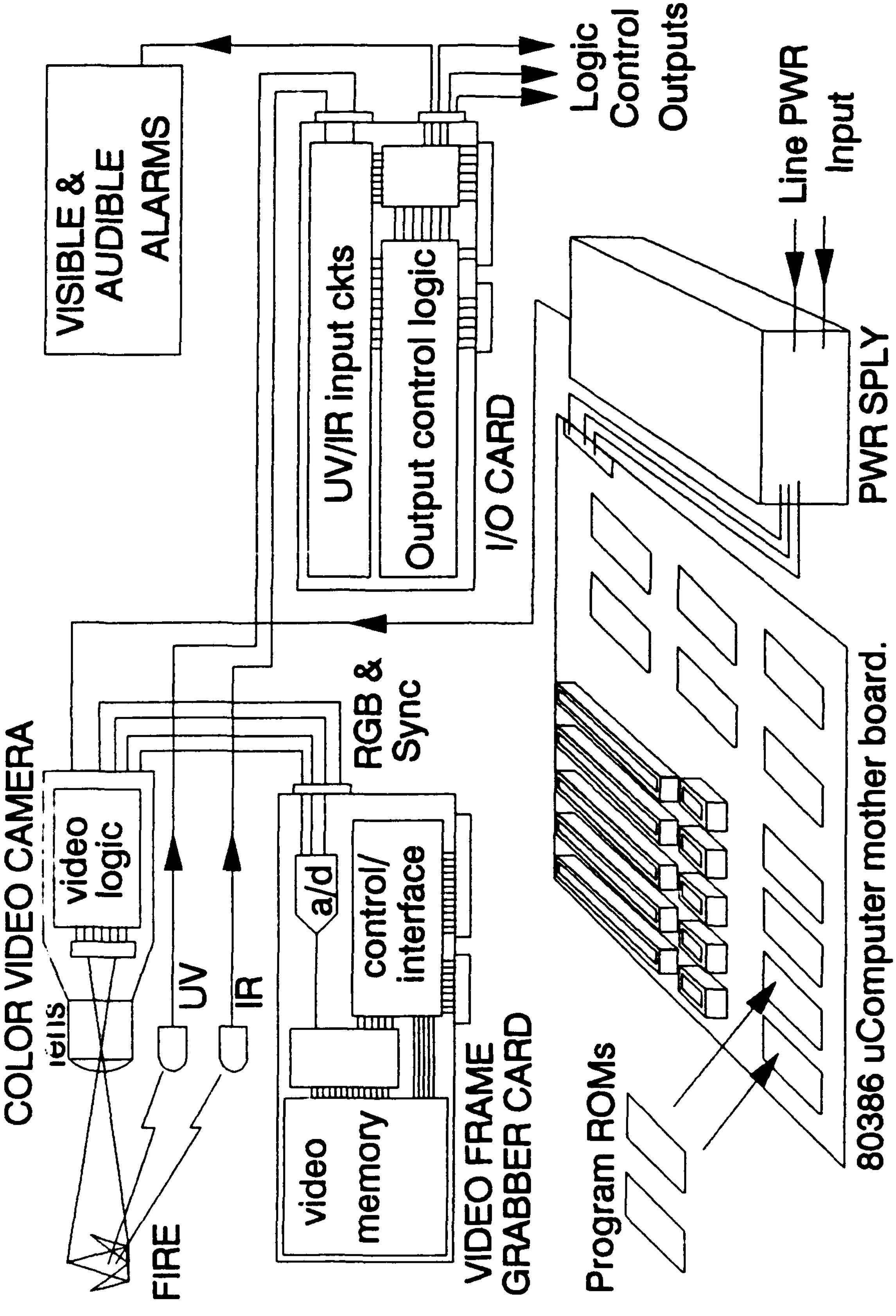
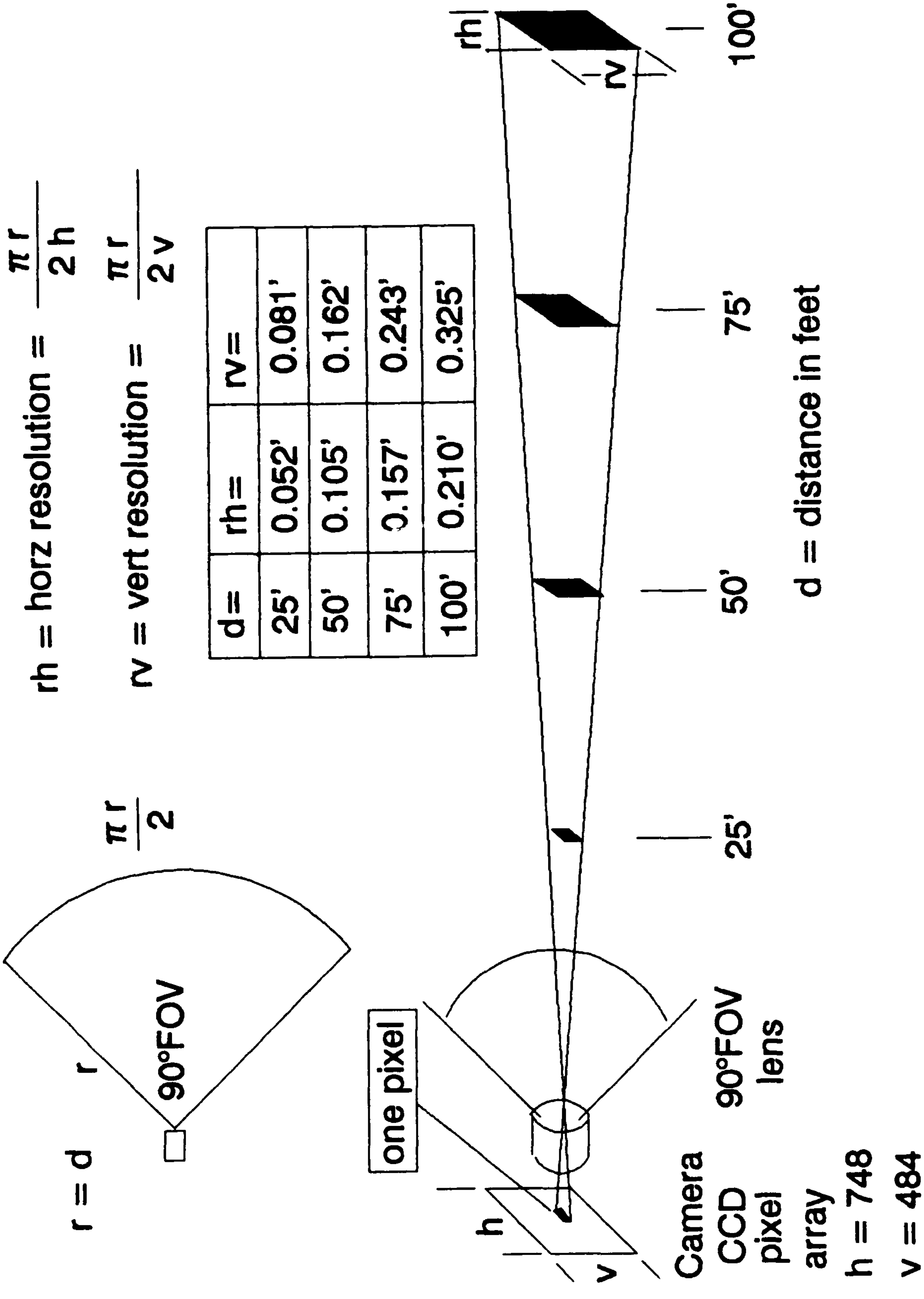


Figure 49. Machine Vision Fire Detection System Block Diagram

solid state Charge Coupled Device (CCD) color video camera that produces three primary color signal outputs, red, green, and blue (RGB), which can be recombined in a display device to recreate the multitude of original colors in the image. Only cameras with rugged solid state silicon CCD imaging devices are considered to meet the reasonably high levels of shock and vibration that occur in military operational environments. The CCD imaging device consists of a rectangular solid state light detector array composed of individual picture elements called pixels. Each pixel has a defined horizontal (HORZ) column and vertical (VERT) row coordinate (address) in the array by which it can be accessed.

The color image focused upon the detector surface is separated into three primary colors, red, green, and blue, by vertical RGB color stripe filters placed over each set of three horizontally adjacent pixels. The impinging light level/color information acquired by all the array pixels is scanned sequentially by the camera internal electronics to produce serial video analog voltage output signals for each of the three primary colors, RGB. Presently available CCD color cameras have very good low light level resolution, contrast, and wide dynamic range which is necessary in applications having highly variable lighting conditions (such as aircraft shelters). The CCD camera's high performance and very small size are very important factors in configuring the MVFDS.

The CCD cameras are available in a variety of cost effective horizontal and vertical pixel array resolutions from a low resolution 128- x 128-pixel array, to a 512- x 512-pixel medium resolution, and a 748- x 484-pixel medium high resolution. As shown in Figure 50, with the latter resolution of 748- x 484-pixel array, and a 90-degree field-of-view lens, fires near 1 ft^2 in size at about 100 feet distance can be resolved (it requires at least 9 contiguous pixels to be able to perform the all the



$\frac{\pi r}{2}$

rh = horz resolution = $\frac{\pi r}{2h}$

rv = vert resolution = $\frac{\pi r}{2v}$

d=	rh=	rv=
25'	0.052'	0.081'
50'	0.105'	0.162'
75'	0.157'	0.243'
100'	0.210'	0.325'

Figure 50. MVFDS Single Pixel Resolution vs. Distance

discrimination functions).

In Figure 49 the image of a fire, represented by the triangle, is focused by the camera lens upon the CCD imaging device pixel array which translates the light level at each pixel into an analog voltage. The camera electronics provides precision clock controlled timing and sweep drive for HORZ and VERT scanning of the CCD pixel array. This produces a serial stream of pixel data for each of the three colors. Precise horizontal and vertical synchronization (HORZ SYNC and VERT SYNC) are outputted to define the format of each complete frame. Each complete video frame is outputted at the standard 60 noninterlaced frames per second (two interlaced frames in 1/30 second). The electronics also provides control of exposure integration time to accommodate for varying lighting conditions. The scanning process is described in Figure 51.

The VERT SYNC pulse signals the beginning of scanning one video frame starting at the top left corner of the image captured on the CCD pixel array. The HORZ SYNC pulse initiates the scan from the right across the top row of pixels and, when it reaches the right side, another HORZ SYNC pulse is produced which starts the next scan line. This is repeated, each time incrementing to the next line below, until it reaches the bottom of the frame, at which time another VERT SYNC pulse returns the scan to the top of the screen to begin the next video frame. This new frame is interlaced, starting at the middle of the top line.

The color camera produces the video industry standard three primary color analog outputs (RGB). It also outputs horizontal and vertical synchronization (SYNC) signals which output separately or combined in the industry standard NTSC or Y-C formatted video output signal. The three primary color RGB levels when recombined in triad combinations can recreate all the colors. Figure 52 shows the color cube domain.

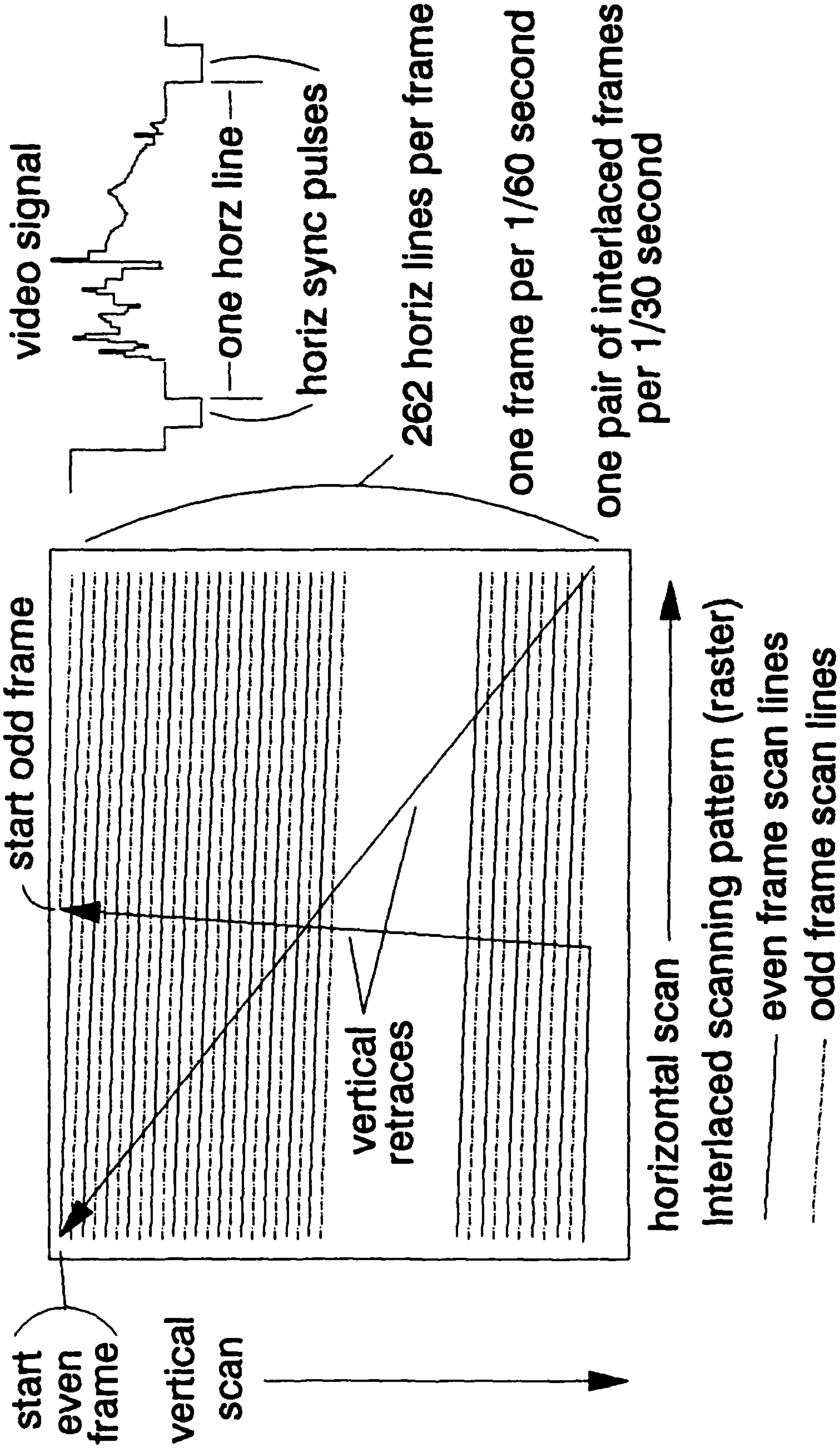
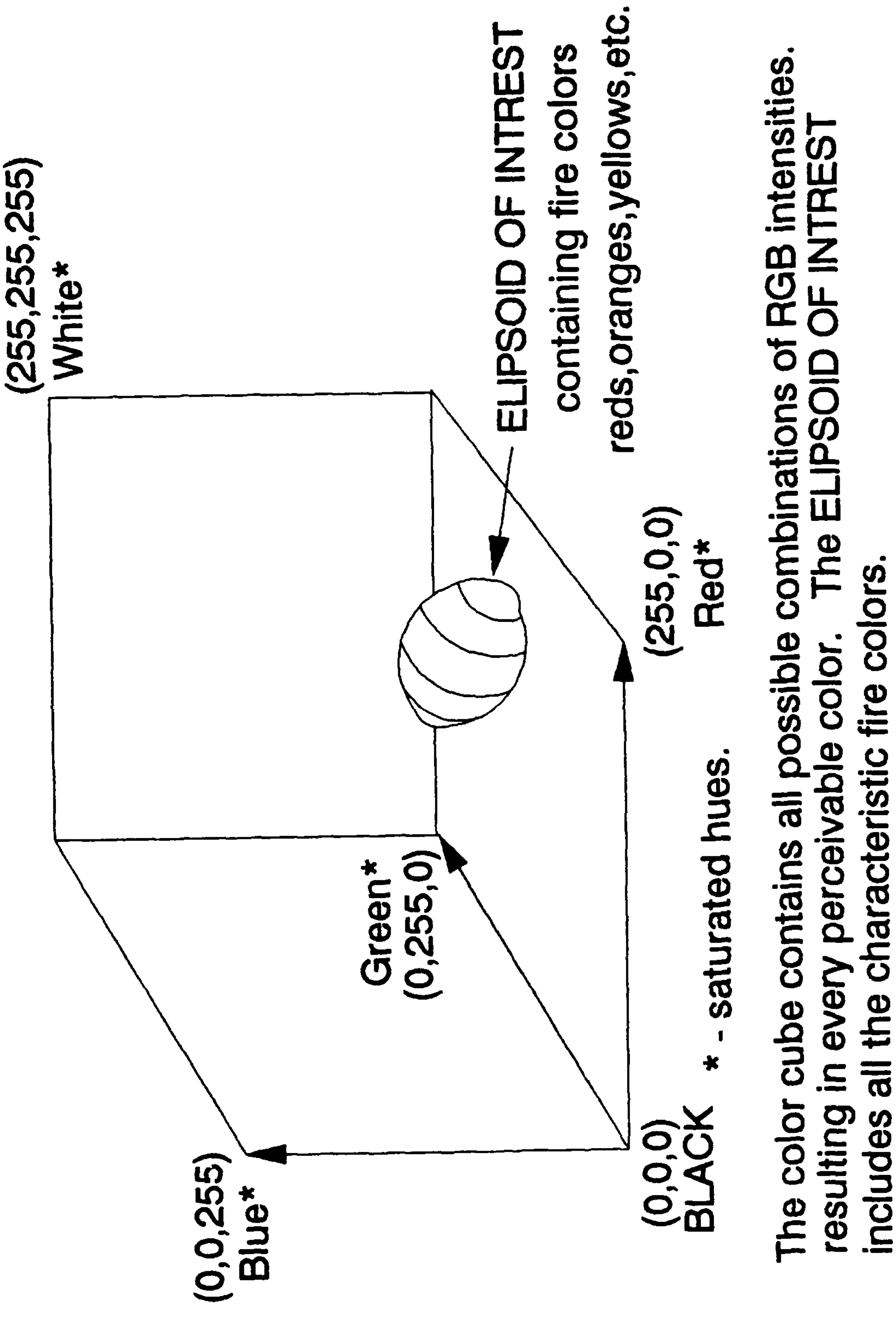


Figure 51. NTSC Scanning and Timing Drawings



The color cube contains all possible combinations of RGB intensities resulting in every perceivable color. The ELIPSOID OF INTREST includes all the characteristic fire colors.

Figure 52. RGB Color Cube Domain

2. UV and IR Detectors

In addition to the primary color camera, discrete UV and IR detectors operating outside the visible spectrum are used to provide early warning of significant fire emission spectral attributes. These have been discussed previously herein. However, these are operated at high sensitivity. When both have registered the presence of radiation, the MVFDS is switched from standby processing to a fast event processing mode. These detectors are available from several sources and are inexpensive (typically less that $100) compared to the cost of complete UV/IR commercial fire/flame detector units (typically $1,500-$2,000).

3. Computer Image Processor Components

a. Video Frame Grabber Card

The FGC is the key interface to translate the color video camera analog RGB output signals into digitized data. The microcomputer can instruct the FGC to capture a video frame output from the video camera, digitize, and store the frame in the high speed video memory. The digitally stored frame image is then accessible to the computer for processing via the I/O Bus interface connector. The microcomputer can capture frames at 30 or so frames per second. Tests performed during this study with an R&D system on scenes from video taped fire tests performed in a hangar environment suggests that frame capturing and processing once every 0.1 seconds, or 10 frames per second, is sufficient to follow a fire growth and determine other features. Preliminary development indicates that all the essential algorithms can be processed at this rate.

b. Microcomputer Mother Board

The MVFDS main control 80386 type microcomputer is on the mother board which has a set of several expansion I/O Bus connector slots. The connectors accept the FGC and I/O card to interface with the detectors and provide output to activate alarms and suppressors through a fire control panel, if desired.

c. Software/Firmware

The hardware requires a software program to operate the microcomputer and control the system. The microcomputer requires operating system software that initiates operation of the microcomputer using a "Basic Input Output System" (BIOS) low-level machine language permanently stored in a "Read Only Memory" (ROM) integrated circuit. The software performs microcomputer and system initialization, progresses to a self testing procedure, and begins running the Fire Detection Program (FDP) with periodic self test procedures run to determine operational status. The majority of the FDP will be programmed in a high level language (such as "C") except for any speed sensitive subroutine that will be written in high speed machine language. The machine level language FDP program will be stored in ROM.

4. Output Devices

The input and output (I/O) activity of the microcomputer operating under control of the FDP uses the I/O card to accept the UV and IR detector outputs and send the data to the microcomputer for action. Fire alarm and suppressor activation decisions from the microcomputer are conditioned to interface with the alarm and suppressor power drivers and activation devices, usually found in the fire control panel.

Alarm driver outputs and alarm status signals to facility alarms and to the local fire authority, and high power drivers to suppressant systems (or controller panels), can be provided on the I/O card. They can also be provided in a separate enclosure, as direct interfaces to existing communications control panels.

5. Power Supply

Highly regulated low voltages are required for the following system components: the microcomputer, expansion boards, camera electronics, and output driver power. These are provided by a high efficiency switching power supply operating off local power mains, or by an uninterruptable power supply (UPS) as required.

6. Enclosure and Connectors

The whole MVFDS system can be packaged in a single enclosure sealed from the environment with sealed connectors/cables provided for power and I/O's. The I/O would also provide for multiple secondary camera detector units to be placed strategically in large hangar applications or other facility application that would benefit from more than one detector unit coverage.

7. Summary

The hardware necessary to implement the MVFDS exists in suitable low cost, low power, small size and reliable components available to package in a single unit for R&D, field testing, an operational installation in fixed ground based environments. Further refinement and simplification of the hardware/software system can reduce size, power and ruggedness for future production systems and broader applications.

The miniaturized camera sizes are indicated by the outline of the Cohu model 6815 camera. The control box electronics of the camera contain much more electronics than needed, such as NTSC encoding, auto exposure lens control, power regulators, etc. These can be eliminated. Therefore, its size can be reduced to about one fourth of the present size. The FGC cards for IBM compatible computers are generally implemented on the 5-inch high by 13-inch long AT (Advanced Technology) card formats. They too have much more circuitry than necessary, namely NTSC encoders/decoders, special effects, genlock, etc. Eliminating these unnecessary circuits can reduce the size by a minimum of one half. The proliferation of low cost PC-AT miniaturized computer mother boards using VLSI chip sets with sizes only one fourth of the 11-inch x 13-inch standard size boards, along with reduced size peripheral boards and power supplies, will yield a very small MVFDS system footprint.

The extremely large numbers of systems in use, and the manufacturers that produce them, dictate using main stream technology to guarantee a no-risk MVFDS with increasing hardware reliability and increasing capability and versatility for systems with future expansion and upgrades.

The primary MVFDS system with one set of sensors, frame grabber, computer, I/O, and power supply, can be engineered to fit within the estimated envelope shown in Figure 53.

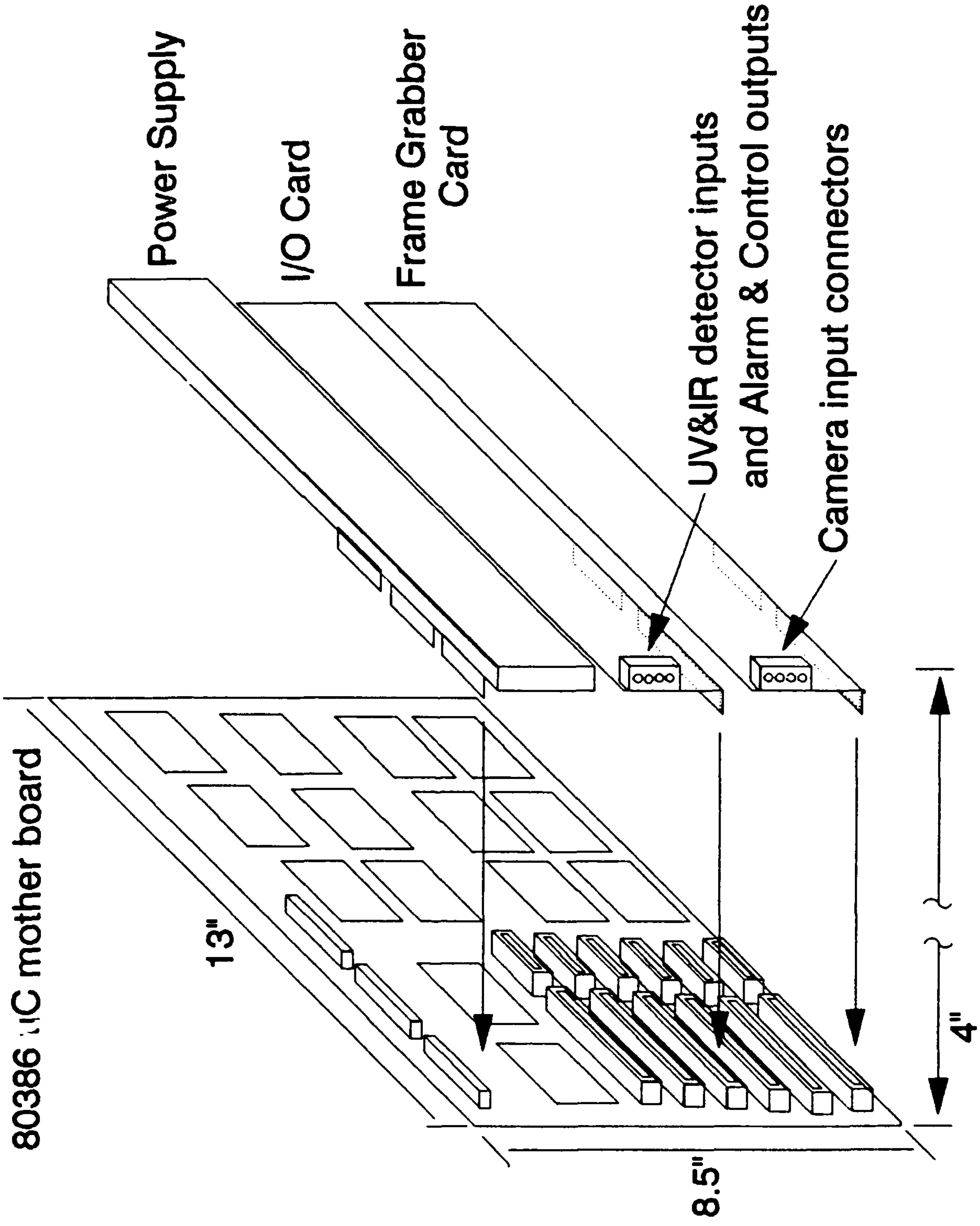


Figure 53. MVFDS R&D Prototype (not production scale)

SECTION V

UTILIZATION AND APPLICATIONS OF MVFDS

A. COMPARISON OF MVFDS WITH CONVENTIONAL FIRE/FLAME DETECTORS

The basic difference between conventional detectors (CDs) and the MVFDS is in the quantity and quality of the information generated by each. In the case of the CD, the only information obtained is intensity levels of UV and/or IR radiation at some specific wavelength regions. The detector does not know the direction, distance, location, size or nature of the source of the radiation. It only knows that it is present. On the other hand, the MVFDS operates in the visible region (like a human being), and knows the source of the light, location, size, distance, spectral color features, movement, association to other objects and, of most importance, <u>that the nature of the light emitting object/phenomena is indeed a fire.</u> CDs cannot accomplish any of the former and are unsure of the precise nature of the emitting object. There are, therefore, major difference between the two detection concepts.

One characteristic of some UV/IR detectors that utilize fast response UV vacuum tubes and IR detectors such as PbSe, is their ability to detect the presence of very small levels of UV and IR within specific wavelength regions (e.g. 190 - 300 nanometers, and 4.3 micrometers). This sensitivity allows them to respond very rapidly, almost instantaneously, to fire ignition. However, this ability is also a detriment to reliable operation because the detector becomes more susceptible to false alarming to the presence of other UV/IR source(s). However, in conjunction with the MVFDS visible intelligence, machine vision operation, the presence of very small quantities of UV and IR can be used advantageously as a "switch" to transfer the MVFDS from standby mode to fast "alert" processing mode, and as an "AND" in the logic decision process of fire determination. The MVFDS can either use its own very sensitive UV/IR detectors (which are inexpensive and simple compared to CDs), or use the outputs of existing, already installed UV/IR detectors for these purposes.

Some specific differences between CDs and the MVFDS are as discussed below:

1. Fire Detection

Both detect fires but by different techniques. The CD relies on an indirect technique whereby measurement of UV/IR above a certain preset threshold intensity level is equated with a fire of some predetermined/calibrated size at some maximum distance, although the CD does not know anything about the nature and/or properties of the emitting source(s). The MVFDS uses UV/IR to "suggest" the presence of fire and then uses visible light input and computer processing to reach an "intelligent decision, just as a human being uses his eyes as input and his brain as the information processor. The former CD technique can be labeled "indirect" as opposed to the MVFDS direct technique.

2. Fire Location

CDs cannot determine where the emitting source is located while the MVFDS knows its distance, size, and position relative to other objects within the field-of-view.

3. Fire Size

As stated above, CDs only know that some threshold intensity level of UV/IR has been detected. They are either preset in the factory or calibrated at installation to be able to detect a fire of some size at some distance. Usually a pan fire of some size, say 10-foot x 10-foot, is set at some distance, say 100 feet, and the detector electronics adjusted until it detects the fire within some maximum time period (usually 5 seconds or so, where time zero occurs when the detector is exposed to an already burning 10-foot x 10-foot pan fire). This only assures that a CD will see this level of intensity of UV/IR. A small fire, however, of less distance away from the detector, will be interpreted as being a large fire at some greater distance. This is because of the $1/R^2$ dependence and that the source is omnidirectional.

The MVFDS, however, knows the distance of the source, the number of pixels occupied by the source, the size of these pixels, and, therefore the actual size of the fire event. It can monitor the fire's growth until it reaches a size requiring an alarm and/or an automatic release of suppressant. This provides for instantaneous action instead of 3-5 seconds or so delayed action as required of CDs today.

4. Time Required to Identify Fire Event

As inferred above, CDs can detect UV/IR from a fire instantaneously. But to reduce false alarm problems, they are usually set to respond in 3-5 seconds after the fire reaches the threshold size for detection (which can be 10-foot x 10-foot size at 150 feet distance). CDs normally operate in this 3-5 seconds range and are, therefore, not reliable to detect small fires in very short times (tradeoff of fire sensitivity to false alarm susceptibility). The MVFDS uses the UV/IR to instantly detect "possible" fire presence and then uses the visible to locate and then analyze all the characteristics of the suspect event/object before making a fire decision. From the tests made in this study, it appears that the MVFDS can identify/discriminate a fire of about 1-2 ft^2 in size at a distance of 100 feet, and that 4 or 5 frames of processing is all that is required to determine all the characteristics of the fire event, including its size and location.

At one frame every 100 milliseconds, this time period would be about 0.4 to 0.5 seconds.

5. Immunity to False Alarms

CDs respond to all sources of UV and/or IR radiation that are within the wavelength sensitivities of the detector. CDs are thus susceptible to false alarming to the presence of one or more of the following type of objects/phenomena: lights of many varieties, heaters, aircraft ground equipments (AGE), tools, electric discharges, lightning, welding, aircraft engines from start through afterburner, heat from engine exhausts, x-rays, and many other items discussed in detail in Reference 1. Although not a UV or IR source, X-ray machines (NDI tools) can set off any UV vacuum tube detector because it operates as an ionization chamber such as a Geiger Mueller Counter. There is some evidence, also, that such NDI devices produce high levels of EMI, thus affecting the electronics of CDs that are not EMI proof.

Although the MVFDS may be set to be very sensitive to UV and IR, it does not respond to them as fire sources. It discriminates fire from possible false alarm objects in the visible by discerning their spatial, temporal and spectral variations, as well as other features that are unique to fire and not associated with others or combination of sources so far identified.

6. Physical Features

The MVFDS detector units are smaller than those of CDs and can be mounted in the same manner and configuration. The first generation MVFDS engineering model will probably be about 13-inch x 8 1/2-inch x 4-inch, with the capability of multiple detector unit inputs. The first production model would be smaller (about 6-inch x 8-inch x 4-inch).

The MVFDS can come in two configurations: a single detector unit with computer electronics in one container, and multiple detector units feeding into one computer electronics box, thus enabling small area fire surveillance as well as large hangar surveillance such as B-2 hangars. The number of CDs required to perform a system application such as a hangar is larger than that required by the MVFDS.

Although CDs are not designed to meet stringent military design and performance standards, they can be designed to do so. There may, however, be some costs associated with such redesign and testing efforts. The MVFDS, as a new device, should be designed initially to withstand the environments specified in Mil-Std-810D and Mil-Std-461/462, and have the necessary MTBF and system reliability to assure adequate fire protection of mission essential weapon systems and other assets.

7. Producibility/Technical Risk

CDs are obviously being manufactured and their use has been accepted for many types of fire detection applications. They are designed for commercial applications and there is no technical risk in the component technology or technical approach employed. Like CDs, every component required in the MVFDS is now being manufactured and is available within the framework of the video camera and PC computer industry. There exist a multitude of manufacturers of these and related hardware items and the technology is being advanced daily while the costs continually decrease.

B. COMPATIBILITY WITH CURRENTLY INSTALLED FIRE PROTECTION SYSTEMS

Many new fire protection systems have been installed, either in new construction or as replacements/upgrades to old, less capable technology. The detection units, although they are much more reliable than older single channel detectors, still experience false alarms and false activations. These installed fire protection systems could be made more effective and certainly more reliable if the MVFDS was integrated into their configurations. CDs with dual UV/IR detectors could be used as input signals to the MVFDS if they were set at very sensitive levels to act as alert switches to the MVFDS camera/computer system to changes from standby mode to fast alert processing mode. For new construction and certain military applications, the MVFDS should be considered on its own merit depending upon the performance requirements and the problems needing solutions.

As a retrofit, the MVFDS would have no problems. It could be easily interfaced with current installed fire control and communication panels. The outputs of the MVFDS could be made to be simple electrical signal inputs to the exiting panels.

There are many advantages of integrating the MVFDS with installed CD systems. This includes, of course, increased coverage of fire sources of all sizes at all locations within very short time periods, accuracy of fire location, size, and threat, and elimination of false alarms and false dumps of suppressant.
Another advantage that may be considered is the replacement of any manned TV monitoring system employed for fire observation. The automated capability of the MVFDS far exceeds the ability of a manned TV monitoring system, saves money, and provides the system reliability and performance levels required to protect valuable assets. This is especially true of those situations where very rapid and reliable fire detection is required to enable suppressant application within seconds. However, if desired, the MVFDS could also act in the automatic and manned TV monitoring mode, as the video output (input to the computer) can also be used for other purposes.

SECTION VI

CONCLUSIONS

The major conclusion of this Phase I study is that it is technically feasible to develop a machine vision fire detector system, in a timely manner, at reasonable cost, and with no technical risk. It has also been demonstrated that there are certain unique characteristics that distinguish fire from possible false alarm sources, that can be accurately, rapidly, and unequivocally determined with the algorithms/software developed in this study and implemented with the computer and camera hardware identified in this study. These MVFDS capabilities provide for major increase in fire detector immunity to false alarms, greater fire protection reliability and, for the first time, very high resolution/identification of small fire events at large distances. The following are supporting conclusions.

1. The presence of UV and IR at wavelengths of 190-300 nanometers and 4.3 micrometers, respectively, might indicate the presence of fire, but not unequivocally. Such precursor information can be used by the MVFDS to "switch" from standard processing mode into a fast "alert mode" and for selective image processing. In addition, the presence of UV and IR can also function as an "AND" in the logic decision tree. As the MVFDS is further developed, the use of this "AND" and precursor signals may prove to be redundant.

2. Bright areas within a scene can be identified, their positions located, and tracked. Further, the bright areas that are present scene to scene when there is no indication of the presence of UV and IR can be eliminated from the stored base scene, thus reducing processing.

3. Bright areas identified when UV and IR are present can be further discriminated by whether their spectral color falls within the selected red, green, and blue color thresholds indicative of fire.

4. Scenes can be captured, digitized, and stored at rates of at least 30 frames per second.

5. The growth and growth rate of a bright area can be determined by frame subtraction of new frames from a base stored frame. Growth is an obvious characteristic of all fire events.

6. The edge profile of bright areas can be determined and measured frame-to-frame for time variations ("flicker"), which is a characteristic of fire.

7. The spectral variations from pixel to pixel in the same image, and the spectral variations of the same pixels frame-to-frame can be determined. The magnitude of these variations have been shown to be unique to fire and not associated with bright light sources, objects, or phenomena that may be classified as potential false alarm sources.

8. The size and position of the bright object, fire event, can be determined either through multiple detector triangulation or because its distance from a single camera unit is known by the line scan number that identifies its base on the floor. Each pixel dimension is then known because the number of pixels in the horizontal and vertical scan planes are known. The MVFDS can, therefore, actually determine fire event size and position in the process of deciding when and if to release suppressant. No other detector technique provides such direct information.

9. The algorithms developed in Phase I have successfully discriminated bright moving lights, colored flickering lights,

rotating color lights, strobe lights, highly reflective striped color reflectors, solar spectral reflection surfaces, and other objects and phenomena from fire events.

10. It was possible to obtain and process the data at 0.1-second intervals using PC types of commercial microcomputer hardware.

11. The camera hardware and computer component hardware required to implement the MVFDS capabilities exists as "off-the-shelf" items. There is no technical risk in the full development of the MVFDS. The small quantity costs for a first generation device are in the same realm as present conventional detectors/logic controllers, and will decrease in time with the advance of technology and larger quantity production runs.

12. The major algorithms for the MVFDS image processing have been defined in the Phase I effort, as well as the fire and false alarm event models. They are ready for refinement, further testing, and coding to run efficiently on the prototype hardware.

13. The concepts developed in this study can make a major contribution to fire protection technology and, when incorporated into the MVFDS, provide the Air Force and other users with a valuable tool for reliable fire detection and other applications.

14. The feasibility of successfully completing a Phase II effort has been thoroughly demonstrated.

SECTION VII

RECOMMENDATIONS

Based upon the conclusions reached in this study, the software and hardware developments accomplished, the apparent benefits of the MVFDS to Air Force and other user needs, and the demonstration and proof of technical and applications feasibility, it is recommended that the Air Force proceed to develop a MVFDS product through a continuing Phase II SBIR program.

It is also recommended that the Air Force consider integrating the MVFDS into installed fire protection systems, thus providing for major increases in system performance, reliability, and immunity to false alarms. In addition, the MVFDS should be considered for new hangar developments, as well as for other applications such as HAS (USAFE and PACAF shelters), large body cargo aircraft (ground operations), and other special fire protection applications. The benefits offered by the MVFDS are greater than those provided by current detection systems, including the involvement of man-in-the-loop TV monitoring.

The types of information generated by the MVFDS should be considered in relation to other subjects of security, assessment, monitoring, and new approaches to fire protection that involve selective use of suppressant in only those areas where the fire is located.

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