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MICROGRAVITY SCIENCE REQUIREMENTS AND THE NEED FOR DATA COMPRESSION

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Abstract. The Microgravity Science and Applications Division (MSAD) of the NASA Office of Space Science and Applications (OSSA) is responsible for encouraging and directing the research of a wide range of physical phenomena in reduced gravity. Under MSAD's direction the NASA Lewis Research Center is presently developing the concept of a multi-user facility which will perform combustion science experiments in space. This facility, known as the Combustion Experiments Module (CEM), will be located in either the Shuttle Spacelab or the Space Station *Freedom* laboratory and will be operational by mid-1997. CEM shall be used to investigate the behavior of a wide range of combustion processes in the microgravity environment which exists in near Earth orbit.

In addition to standard instrumentation to measure temperature, pressure and acceleration, CEM shall employ a variety of imaging and optical diagnostic techniques. Images shall be the primary source of experimental data. Some preliminary experiment requirements indicate the facility may require up to five electronic cameras simultaneously generating images at 30 frames per second. Typically, each image will consist of 512 pixels by 480 pixels with 8 - 12 bits per pixel. In most cases the maximum experiment duration is on the order of 2 minutes. However, one experiment, investigating smoldering combustion, shall last up to one hour.

These images create an enormous amount of data which must be archived on orbit for later analysis. Additionally, ground based investigators will require enough data from the orbiting facility to determine if the experimental parameters need modification before proceeding with the next run. The storage and transmission of this data present a major challenge to the CEM design. Data compression will play an important role in the design of the CEM diagnostics system.

1. Introduction

This paper discusses the science data requirements for the Combustion Experiments Module. This set of requirements serves as an example of data required for microgravity experiments to be conducted upon either the Spacelab or Space Station *Freedom* in near-Earth orbit. Microgravity science research depends increasingly on full-field data which is captured in images. This is particularly true of the diagnostics proposed for combustion science research. In addition to images; instrumentation measurements, such as temperatures, pressures, and accelerations, must be recorded. Scientists require the entire data set to be recorded in the module on-orbit, and they also desire to have the entire data set downlinked. Still, the downlinked data should accommodate at least a "Quick Look" as a subset of the data between experiment runs. This capability is part of a concept known as telescience. In this concept, the principal investigator can interact with the experiment from a ground facility. The investigator will observe the experiment and its data, and he can communicate with mission specialists to modify experiment parameters.

The module will generate a great amount data. Also, the operation of the module, including telescience, will increase the downlink data rate. Limitations in data storage and in downlink capacity suggest a need for both lossless (for recording) and lossy (for downlinking) data compression. This paper identifies critical image and data parameters which must be maintained when considering lossy compression.

NASA's Office of Space Science and Applications (OSSA) funds research by university, industry, and government investigators in ground-based and space-flight facilities. This includes basic research in physical, chemical, and biological processes in a reduced-gravity environment. Investigators also perform basic and applied research on fluid dynamics, transport phenomena, and the processing of many materials and substances. OSSA's Microgravity Science and Applications Division (MSAD) develops space-flight payloads for the Shuttle, Spacelab and Space Station *Freedom*. Currently, payloads are developed to address the science requirements of a single investigator's experiment. However, MSAD's new focus is to develop payloads which are configured (or reconfigured) to accommodate multiple experiments. The Combustion Experiments Module is an example of this new payload. This move towards "laboratory" facilities occurs as increasingly sophisticated and complex diagnostics are being developed. Both of these lend to increased science data.

These orbiting facilities will permit investigators to conduct experiments in reduced gravity for long periods of time. This time period ranges for one minute to approximately one hour for proposed experiments in the Combustion Experiments Module. Current research in drop towers and aircraft limits experiments to two to ten seconds of microgravity. Also, the quality and level of the reduced gravity varies, somewhat unpredictably; especially in the case of aircraft experiments. Still, these platforms provide much information which leads to research conducted in near-Earth orbit.

MSAD payloads permit investigators to study physical phenomena, without buoyant flows, which can modify, mask or dominate a phenomenon in Earth's gravity. Investigators can also study and compare phenomena in Earth's and reduced gravity. Experimental data gathered in these payloads aid the development and verification of practical mathematical models. Some of the proposed MSAD modules are the Microscope, Containerless Processing, the Glovebox for small, self-contained packages, the Combustion Experiments Module, the Furnace Facility, the X-ray System, the Advanced Fluids Modules, Bio-technology, and Advanced Protein Crystal Growth. These modules cover a wide area of science and have a broad range of image and data requirements. The requirements of each module is unique to its science; yet, they have many similarities across disciplines.

2. The Modules and Why: An Example is the Combustion Experiments Module

As an example, this discussion focusses on the Combustion Experiments Module (CEM). The science data requirements for this module highlight a paradox: facilities in near-Earth orbit give longer time periods for the experiment and improved diagnostic capabilities yield large amounts of data; however, carriers such as Shuttle Spacelab and Space Station *Freedom* have limited downlink capacity and a data storage problem.

The Combustion Experiments Module (CEM) is a multi-user, modular facility which will accommodate several different experiments, each having numerous runs, during one Spacelab mission or one Space Station utilization cycle. Experiment hardware can be changed out during a mission. After a mission, the module can be reconfigured to run another set of experiments.

The design of the facility will also permit the on orbit changing of diagnostic instruments, optics, and cameras. Extensive diagnostic capabilities provide mapping of temperatures, velocities, and species concentrations. Many of these mappings result from images. Consequently, the CEM is a heavy user of video images, and it relies heavily on the accurate recording and interpretation of these images.

Combustion science differs from other branches of fluid physics because of large temperature variations, 300K to 3000K. Highly localized, highly exothermic heat release from the chemical reactions of the combustion process creates large temperature variations and large density gradients. These potentially lead to the strong currents of buoyant flows. The flows can dominate, modify, or mask the convective transport processes which mix and heat the fuel and oxidant reactants before chemical reactions begin.

Because of this complexity, buoyancy is often omitted from the mathematical analysis of combustion. Complicated two phase flows and surface tension behaviors are also affected by the buoyant flows. Gravity also introduces a degree of asymmetry in an otherwise symmetric phenomena. For example, combustion of a gaseous jet injected normal to the gravity vector quickly loses its axial symmetry as the flame plume gradually tilts "upward". Transport phenomena, feeding the flame, are multidimensional and complex.

The science data requirements for the CEM are provided as an example of the type of data needed in a microgravity experiment. It is also an example of the modular, multi-user facilities being developed by MSAD. While some of the particulars of an experiment or class of science may vary in number, types of measurements, storage, and data rates, the general scope of the experiments is similar.

3. A Summary of Science Data Requirements for the CEM

The particular data requirements discussed here are taken from the seven proposed experiments currently under consideration. Also, the particular diagnostic methods described here may vary as their development and the need for them continues.

CEM scientific data will come from two main sources: instruments and images. Table 1 shows a list of proposed experiments for CEM and the types of diagnostics each might use. The techniques are optical methods currently under investigation for space-flight. Specific diagnostic methods, as well as the experiments, may change by the time of the first launch in 1997. This table also shows an estimate of the type and number of instruments required for each experiment.

Table 1: Video and Instrumentation Requirements for CEM

EXPERIMENT	TECHNIQUE (Optical)					INSTRUMENTS (Quantity)		
	Video (usually 2 views)	IR or UV Detection	Particle/Light Sheet Visualization	Rainbow Schlieren	Light Extinction/Soot Number	Temperature	Pressure	Acceleration
Effects of Buoyancy on Laminar Gas Jet Diffusion Flames	•	•	•	•	•	9	1	3
Fundamental Study of Smoldering Combustion Spread	•	•				8	1	3
Diffusive and Radiative Transport in Fires Experiment	•	•				8	1	3
Studies of Premixed Laminar Flames	•	•	•	•		6	1	3
Ignition and Flame Spread of Liquid Fuel Pools	•	•	•	•		10	1	3
Droplet Combustion Experiment	•	•				1	1	3
Laminar Jet Diffusion Flame	•	•				?	?	?

The operating scenario for CEM calls for data archiving, quick-look, and downlinking capabilities. The investigators require the entire set of scientific data be recorded. For a quick-look, a portion of the data will be downlinked between experiment runs. Investigators can verify the success of experiments and they can see if they are achieving the expected results. Also, even with the best of models and analysis, investigators are often surprised to observe unexpected phenomena during a test run.

With a run length of approximately one minute, most experiments will end before the data subset can be viewed on the ground. Still, a quick-look will enable investigators to vary test parameters before the next run, thus maximizing the science return from an experiment.

The entire set of stored data may be downlinked at a later time when channel capacity is available. This is determined by the duration of the mission and the requirements of other payloads aboard the carrier. Also, data set downlinking will free up storage resources for subsequent CEM experiments. Finally, this capability may be used to guard against the loss of data. After the mission, "hard copies" of the data will be recovered including data storage media, film, videotapes, and experiment samples.

Estimates of the data rate and data storage needed for one CEM experiment challenge the limits of available storage capacities. They also greatly exceed the limits of available downlink capacity. These estimates do not include formatting, data tagging, or other types of headers or annotation which may be required.

The data rate for instrumentation (temperatures, pressures, flows, accelerations) range from 1.0 to 27.2 kilobits per second (Kbps). For images, the data rate varies from 670.0 Mbps (megabits per second) for 3 cameras to 1.0 Gbps (gigabits per second) for 5 cameras. The available downlink data rate aboard the Shuttle Spacelab varies between 1.5 to 48 Mbps. The expected downlink data rate for a Space Station payload is 48 Mbps. Some form of data compression will be necessary to achieve real time or near-real time transmission of on-orbit scientific data.

Estimates of CEM data storage requirements vary from 40 to 67 Gb (gigabits) per experiment. Data storage options, for either carrier, are analog tape and digital storage, possibly to 1.0 terabits. For monochrome images, a Super VHS video cassette (analog tape) will provide sufficient resolution and signal-to-noise ratio for many applications. In optical diagnostic methods where 24 bit, true color images are required, this type of analog recording may not be adequate. These images may require storage as digital images. The effects on data fidelity of recording these color images on a Super VHS machine requires additional study.

4. A Need for Data Compression while Preserving Data Fidelity

Use of sophisticated diagnostics, like the ones listed in Table 1, generate a large number of images in addition to more conventional instrumentation like thermocouples, pressure transducers, accelerometers, etc. This reflects the investigator's desire for field type measurements as well as point measurements. The science requires the correlation and annotation of data from these varied sources.

Lossless compression is preferred, and in some cases required, for data storage. Still, some lossy compression might be considered if storage capacity and data rates dictate the need for it. Greater compression, which is required for the Quick-Look in telescience, requires full motion in order to observe the phenomena of the experiment. In this case, the unexpected must be captured, so a technique which severely compresses the inter-frame motion is undesirable.

However, more central than the question of lossless or lossy compression is the question of the impact compression has on the fidelity of the data derived from the images. As suggested earlier, some signal reduction or degradation may have little impact on the accuracy of the final data analysis. This entire question requires further investigation. Most importantly, implementations of compression must preserve critical characteristics of the image. This may be to increase the intensity of a weak signal; for example, so that a dim flame can be distinguished from its background. When determining soot number, small changes in the intensity of a light beam passing through a flame are directly related to the amount of soot produced in the reaction. In many experiments' images, the high spatial frequency information associated with edges needs to be preserved. In true color, 24-bit images, the transformation of color coordinates can permit significant compression. In all cases, images will benefit from processing and compression methods which minimize noise and increase or preserve the dynamic range. They require robust algorithms which protect images from over-optimization. This is true, especially when the images will be further processed in the downlink. It is possible to compress an image to the point where a transmission error is fatal to the transmission of an entire image or series of images.

In combustion science, one class of experiments investigates phenomena resulting in very faint, low luminosity flames. Compression or processing would be desired which can help extract this faint signal from the background. This increased intensity or dynamic range should be done without increasing the noise level of the recording medium. This is the current problem when motion picture film is push processed to reveal faint flames. Also in slow flows, techniques are needed which help to discriminate particles over time. Quite often, these small particles, which are used to indicate the velocity of flows, become difficult to distinguish from the "background" of the fluid in which they are moving.

Techniques which help to preserve and discriminate edges are useful in the analysis of flame front propagation. This is a critical parameter in the study of solid smoldering and combustion. These techniques will also help measure the change in diameter in burning fuel droplets.

Color is another important characteristic of images to preserve. Natural, high fidelity color indicates much about the type of combustion and chemical reactions occurring. The accurate determination of hue with reference to a calibrated reference is critical for diagnostic methods such as rainbow schlieren deflectometry. In this technique, the RGB (red-green-blue) camera signal is converted to an HSI (hue-saturation-intensity) signal. The hue is of primary importance. In this case, a 24-bit, true color, RGB image can be significantly reduced to an 8-bit hue signal with fewer than 8 bits each for the saturation and the intensity signals.

The rainbow schlieren technique indicates how preprocessing of data might be used to reduce the number of bits per pixel. The hue in the resulting image is compared to a reference image. The corresponding hue indicates the amount of deflection of the light beam due to changes in the index of refraction along the beam's path. This information is used to determine temperature and density variations across the field of the light beam. However, this type of preprocessing is unique to a particular technique and is different from a general compression strategy. The hardware associated with this type of technique and its preprocessing is inserted in the signal stream before data storage or downlinking. It affects the initial data; and therefore, pre-processing on orbit may not be desired.

Compression algorithms require implementations which are efficient with short processing times. The limitations of volume and power in orbiting facilities such as CEM indicate the need for routines which efficiently run with minimum memory and low electrical power. Hardware implementations, although lacking in flexibility and requiring development time, provide speed and efficiency in a low power package. Often the memory is integrated with other processing elements into the package.

5. Conclusions

The science requirements for CEM serve as an example of the data required for MSAD's near-Earth, reduced gravity experiments. Although the particulars of an area of scientific research may differ, the general data handling problems are the same across modules. Often as scientific research progresses, diagnostic methods become more sophisticated with more steps in the analysis of the data. In many instances, these techniques involve video images. All of the modules have requirements for image recording and transmission. The increasing use of electronic cameras and image analysis amplifies this problem.

This discussion indicates the need for further research into the applications of image compression and processing within the orbiting module. One issue is to assess the impact of recording, compression, and processing on the fidelity of data for full field measurements. Likewise, one needs a means to assess the effects of these processes on image quality. Compression and processing of images must preserve important features such as edges, color and intensity. These processes need to preserve dynamic range and to maintain or increase signal to noise ratios. These factors will help to preserve image quality and data fidelity.

The concept of telescience, which enables the scientist to observe and conduct the experiment from the ground, will require some type of data compression for the downlink. Experiment automation and telescience also make increasing use of electronic imaging and image analysis. Future experimental scenarios, and the weight and volume constraints on the amount of film or videotape carried to spaceflight, increase the need for downlinking and recording of data off of the carrier. Data compression, if properly applied, can provide a solution to the data storage and transmission problems of on-orbit experiment facilities such as CEM.