AN IMAGE PROCESSING SYSTEM FOR REAL-TIME 2-D AND 3-D TRACKING OF TLC PARTICLES.

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In recent years, high quality CCD sensors, frame-grabbers and image processing techniques have been applied to flow measurement with considerable success. Such measurement has allowed advanced techniques for visualisation and analysis to be developed. In this paper Themochromic Liquid Crystal (TLC) particles are used to provide simultaneous spatial and temperature measurements for a liquid within a thin rectangular cavity. Such measurements are useful in the study of heat and mass transfer problems in fluid flows. A novel image processing system is described which allows simultaneous capture of particle locations and intensities from the RGB channels of a single CCD camera. This system is based upon a Digital Signal Processor (DSP) which is able to compute and store particle locations in real-time for up to a thousand targets. The eventual aim of the research is the real-time visualisation of temperature, velocity vectors, and spatial distribution of particles.

Keywords: Liquid Crystal, DSP, 3-D, temperature, flow

INTRODUCTION

Particle tracking (both 2-D & 3-D) has become a powerful tool in the analysis of flow. As a result the spatial distribution of velocity vectors can be measured which is particularly useful for turbulence research. In this case the statistical and structural features of turbulent flow can be studied in detail. Several 3-D PTV (or PIV) techniques have been developed and applied to the measurement of various turbulent flow situations. However, there still remain many areas where these techniques can be improved both in terms of spatial resolution, simplification of calibration methods, and application to gaseous flow and temperature fields. The purpose of this paper is to introduce some novel hardware which has been developed for simultaneous PTV measurements using a single RGB camera with extensions to 3-D. This system makes use of sealed and encapsulated liquid crystal tracers as indicators of temperature and velocity. To place this work in context the work of Kowalewski[1], and Stasiek[2][3] is reviewed. The history of these techniques is briefly described along with the principal methods.

TWO AND THREE-DIMENSIONAL PARTICLE TRACKING VELOCIMETRY AND THERMOMETRY

Liquid crystal can be used to make visible the temperature and velocity fields in liquids by the simple expedient of directly mixing the liquid crystal into a liquid in very small quantities. The encapsulated forms of the liquid crystal material (ELC) can be mixed directly into water, glycerol, and silicone oils for use as thermo and hydrodynamic tracers. Very dilute mixtures are recommended, 0.02%, by weight of ELC material in water being sufficient for example. Too much ELC will cause a milky appearance, representing white light scattering from the surfaces of the particles, which dilutes the colour. As opposed to previous researchers who used ELC, Hiller[4] and Stasiek[3] dissolved unencapsulated (unsealed) chiral-nematic material in ether and sprayed the mixture into the air above a free-surface of glycerol. The ether evaporated in mid-air, leaving small drops of liquid crystal material which fell into the glycerol forming an “almost mono-dispersal” suspension of particles approximately 30-100 microns in diameter. The concentration was kept below 0.01% by weight[1][2][5]. Images were taken with the camera perpendicular to the line of the illumination. The specimen was illuminated by using a Xenon flash tube which generated a 2-3 mm. thick sheet of white light which was directed to the area of flow to be monitored. The lamp was controlled by computer or programmable signal generator to flash at specific intervals between flashes (from 1 second to 60 seconds). Two computer aided experimental techniques were used for simultaneous measurement of temperature and velocity fields - analysis of the light colour (hue) which is reflected by the liquid crystal tracers suspended in the flow, and particle tracking velocimetry system based on one, two, three, or more cameras[1][2][6]. The experimental set-up used for measuring temperature and velocity fields is essentially the same as that used by Hiller[7], & Stasiek[3] where flows observed in the X,Y,Z, planes at the vertical and horizontal position of the rectangular cavities (180 mm. long, 60 mm. wide and 30 mm. high)[3].

In one of the earliest experiments (Stasiek[1] & Hiller[4]) the flow was observed at the central vertical and horizontal cross-section of the cavity used a light sheet technique and an ordinary camera. The latest 3-D particle tracking over multiple time steps achieves three dimensional particle tracking. In the simplest of 3-D systems two cameras coupled to video recorders are used for post experiment analysis. Computer simulations have been performed to quantitatively evaluate the effectiveness of: particle tracking techniques, temperature measurement, and data reduction speeds. An example of temperature and velocity visualisation in a glycerol filled cavity (vertical position) under free convection, using TLC is shown in figure 1. The subject of the Kowalewski[1] paper was the experimental investigation of the response of an initially isothermal fluid in a cube shaped container to an instantaneous change of the temperature of one of the vertical walls. The temperature and velocity fields were measured by means of liquid crystals suspended as small tracer particles in the liquid. The method applied here for velocity measurement uses two separately captured digital images taken at a constant time interval (typically 5 s) to evaluate the motion of the particles. Each of the images taken shows a relatively dense cloud of single illuminated particles. The magnitude and direction of the velocity vectors were determined using correlation methods. This was achieved by dividing the whole image (512x512) into 64x64 pixel matrices which were spaced every 32 pixels (partly overlapping each other). The correlation of the corresponding matrices of both images allowed the evaluation of the mean translation vector for each group of particles simultaneously detected in both matrices[1].

THE DEVELOPMENT OF A REAL-TIME 2-D PARTICLE TRACKING SYSTEM

The simultaneous collection and processing of RGB images from particle velocity experiments is at the leading edge of what is possible using expensive and highly powerful processors. To make such data collection feasible at an affordable price, and also to solve many other embedded 2-D image analysis problems, a DSP based system has been developed[8]. This system uses state-of-the-art electronics together with a low power DSP and hardware based image processing to provide tracking of several hundred particles in real-time. Storage of information relating to targets is in the form of **x, y** data pairs together with an intensity factor for each colour channel. The hardware is now in a software development and hardware testing stage. For applications which only use the embedded DSP system the hardware has been called *DSP-90* as each board is 90 mm. in diameter. When a the DSP-90 system is combined with a single camera and a network based processor then the system has been called *2D-NET*, and *3D-NET* when this system is used with multiple cameras and processors. Current applications for these systems are in geotechnical centrifuge target tracking, sewer pipe profiling, robot navigation, and real-time 3-D measurement for jigless manufacturing in aerospace applications. The complete *DSP-90* system is modular and in this application requires five modules which are stacked together. These are: power supply, DSP, General purpose I/O, Ethernet, and video feature extractor. Three complete systems are then used to simultaneously collect target location information from the RGB channels independently. Figure 2 is an image of the complete system. The image processing pipe-line is illustrated in figure 3. The initial data rate from each of the RGB channels is relatively high but considerable processing savings are achieved by cutting out the sections of image that are above the selected threshold using a digital comparator to initiate storage of these sections of the image which are then read by the DSP. Each connecting object is constructed and its size and shape checked and if similar to that of a particle the 2-D co-ordinates are passed to any Ethernet based processor which can perform tracking, vector display, and even analysis of the data in real-time with little overhead from the image processing operation. The components of the *2D-Net* system are now briefly described.

At least 90% of the processing which is conventionally performed on images of particles that are well separated from the background is concerned with thresholding the image to find the sections that relate to the particles. The video feature extractor (VFE) uses a hardware based digital comparator to establish whether a particular part of a line of the imagery is over a preset threshold. If it is then hardware counters store the location of this transition together with all values over the threshold. In general there will only be a few values for each particle image. The start of each line is marked with a unique bit in the location data which allows the analysis of the encoded sections of the image as though they were in the complete image. This simple hardware approach is the key to being able to track particles in real-time with a comparatively low powered processor.

Considerable attention was paid to the analogue design of the feature extractor. The input circuitry provides buffering, sync separation and DC restoration. Ultra-wideband amplifiers are used to achieve 10-bit settling times within the order of 15nS for full-power signals. Image thresholding is performed to reset low level background noise to zero, and a variant of run-length coding of the resulting data stream is implemented in hardware. A voltage controlled crystal oscillator circuit was used to provide the absolute minimum of line jitter. A 10 bit analogue to digital converter was used to provide the intensity information which is compared digitally with a threshold set by the DSP. For each target edge segment, the VFE stores in the FIFO buffers the pixel counter value at the first point that is above the threshold followed by the intensity values up to the point at which intensity falls below the threshold. These are all stored as 16-bit values. Figure 4 illustrates a portion of an image and the corresponding edge and intensity data that would be produced by the VFE. The objects shown in the image represent a general situation. In practice the particles are both regular in shape and small. However, other high intensity objects in the image must be distinguished from particles, hence, all possible situations are considered. The beginning of each line of data is identified by a unique number “0” that is placed by the VFE hardware into the appropriate FIFO buffer. One of the high order bits in the data words is used to distinguish between edge and intensity data. A useful feature of the design of the system is the use of two FIFO’s, one for the odd field, and another for the even field. This allows the separate processing of each field which in turn allows the use of short exposure times (which are linked to the fields not frames) to enable distinct capture of the particles at 0.2 ms per field at instants as short as 1/10,000 of a second with a standard CCD camera.

The DSP processor system consists of a general purpose I/O (GPIO) board and the DSP processor board itself. The system is bus-based for expandability, and uses stack-through connectors which eliminate the need for card guides and cages in multi-board applications. The GPIO board has four 8-bit programmable bi-directional I/O ports, one of which is used for setting the threshold of the edge detection comparator. In addition, a pair of 16-bit FIFO buffers are provided for storing the edge and intensity data and to de-couple the image data analysis from the collection process. The processor board uses an Analog Devices ADSP2101 fixed point processor operating at 20 MHz. DSP’s are capable of multiple instructions and complex operations such as multiply and accumulate in one clock cycle. The multiply and accumulate process occurs many times in a centroiding operation. These features mean that these apparently slow processors (measured by a clock cycle of 20 MHz) can perform certain tasks as quickly as high-end processors. The processor has 16K words (16-bit) of data and 16K words (24-bit) of program memory, of which 2K words of data memory and 1K words of program memory are on-chip. 128 words of the external data memory space is used for memory-mapped I/O ports. The rest of the external data and program memory spaces are filled with 30nS SRAM. The 16K words (24-bit) of boot memory space is occupied by a 70nS EPROM. In operation the processor reads edge data from FIFO buffers and carries out the object reconstruction, recognition, and location. In addition, the processor controls particle location, data transmission, and data reception via the Ethernet link.

The target location algorithm[9][10] is optimised for use with real-time processes in that it only requires target edge and intensity data belonging to two consecutive lines of the image to carry out processing. It reconstructs, recognises, and calculates the centroid of targets in a progressive manner as each line of data becomes available. The algorithm considers all objects of all possible shapes to ensure reliable operation and isolation of good target candidates. For connectivity determination purposes, the objects encountered can be categorised into five groups: new, finished, continuing, splitting, and merging. The algorithm uses a number of logical tests to ascertain the connectivity of object segments found in the current line with those in the previous line. These tests are sufficient to guarantee that any object encountered in this line by line fashion is completely charted regardless of complexity. These tests are simple to apply and for most objects, which do no split or merge, the operations are quick to perform. One of the significant benefits of this technique is that for the objects which are above the threshold the objects are effectively filled which avoids the problem of overlapping square windows which can be encountered with other methods.

In operation a stack is maintained for object labelling purposes. When a new object is encountered a unique identity number is popped from the stack. The algorithm maintains a pair of buffers for storing the identity numbers of the objects in the current and previous lines which are used for connectivity establishment. In addition another buffer is used in which parameters belonging to the objects are stored. For each new object, a number of locations are allocated in the parameter buffer. These are updated until the object is completely reconstructed. One of the parameters is the sum of the product of pixel locations and intensities, another is the sum of intensities. Other parameters such as: the identity number; the peak intensity; the area; the first line number; and the last line number are stored for particle recognition purposes. Parameters for objects that cannot possibly be particles (objects that are large or of irregular shape) are not updated. However, each object is completely traced to retain the integrity of the recognition process. Any parameters pertaining to these objects are discarded when the object is completed. When an object passes the criteria for selection as a particle the identity stack is pushed and grey-scale centroid[11][12] is calculated. The locations in the parameter buffer which are then freed are then made available for a new object. The buffers and stacks require 9K words (16-bit) of RAM and are implemented in the external data memory of the DSP-90 system. An executable version of the algorithm coded in the ADSP2101 assembly language takes 892 words (24-bit) of program memory. The processor takes approximately 67µS per particle to reconstruct, recognise, and compute the centroid of a particle which is assumed to be 5x5 pixels in size.

The Ethernet module is based on the National Semiconductors DP83901 Network Interface Controller (NIC). The activities of the network are de-coupled from the DSP-90 bus using a 16-bit bi-directional I/O port. The I/O port based architecture together with a local packet buffer avoids the maximum bus latency requirements of the NIC. Packet transfers to and from the module are via this μ

provide useful feedback on the experimental process itself where adjustments can be made on-line. This option will be especially valuable if the visualisation process is further advanced to provide on-line numerical computation using the real-time data. This work has been placed in context of other work in this field.

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FIGURE 1. TEMPERATURE AND VELOCITY VISUALISATION IN GLYCEROL-FILLED CAVITY UNDER FREE CONVECTION USING TLC - VERTICAL POSITION. Ra = 1.2×10^4, Pr = 12.5×10^3, $\Delta T = 10K$.

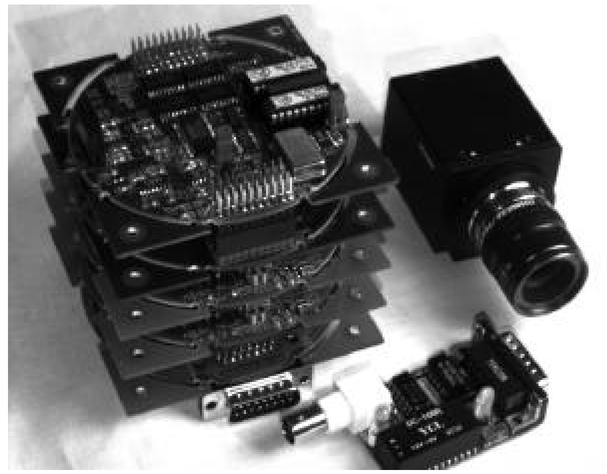

FIGURE 2. IMAGE OF A COMPLETE CHANNEL OF THE EMBEDDED PROCESSING SYSTEM.

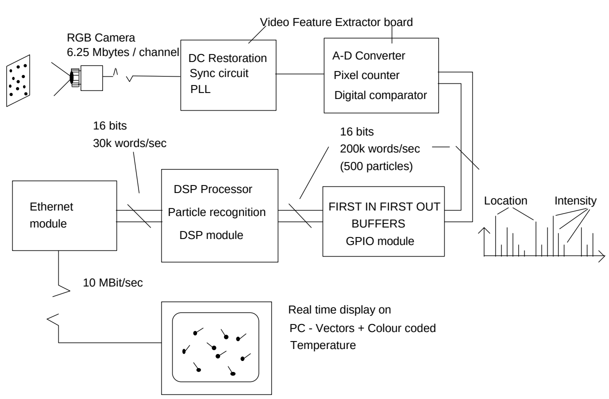

FIGURE 3. THE ARCHITECTURE OF THE *2D-NET* SYSTEM.

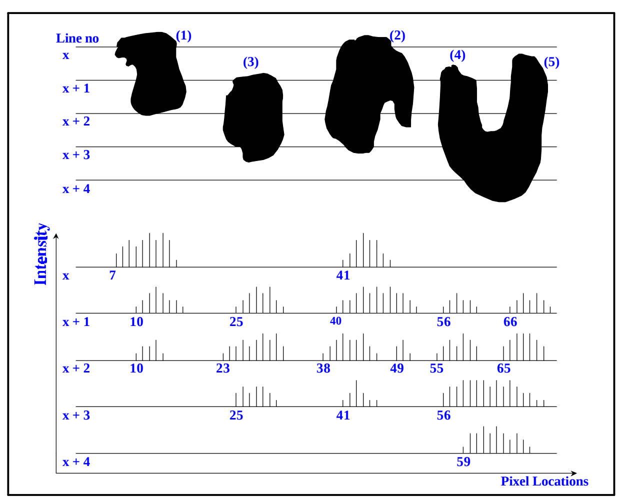

FIGURE 4. OBJECTS AND CORRESPONDING EDGE AND INTENSITY DATA.

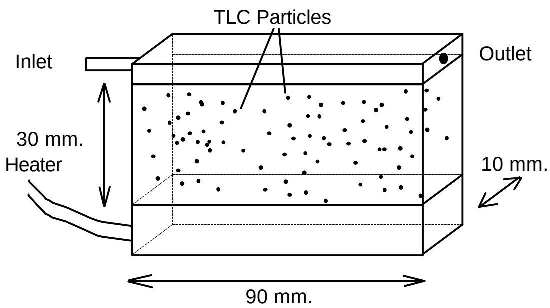

FIGURE 5. APPARATUS USED FOR FEASIBILITY EXPERIMENTS.

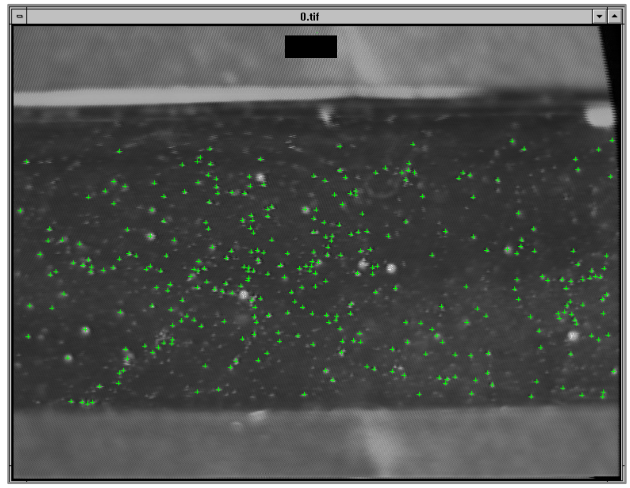

FIGURE 6. TLC PARTICLE DENSITY AND PARTICLE RECOGNITION

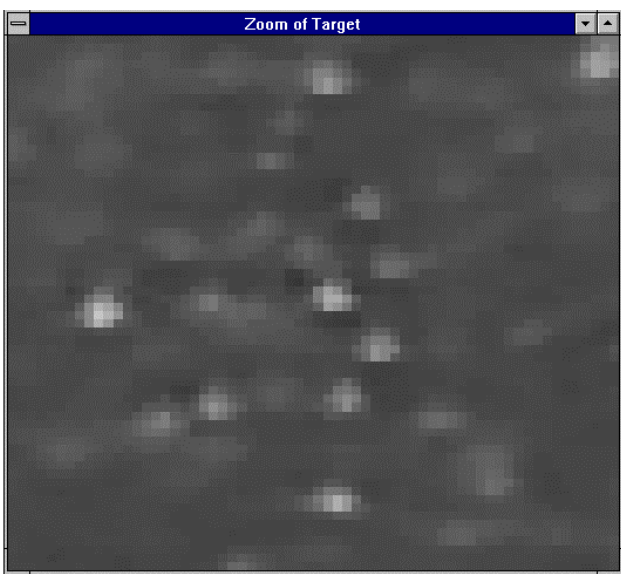

FIGURE 7. AN ENLARGED SECTION OF FIGURE 6.

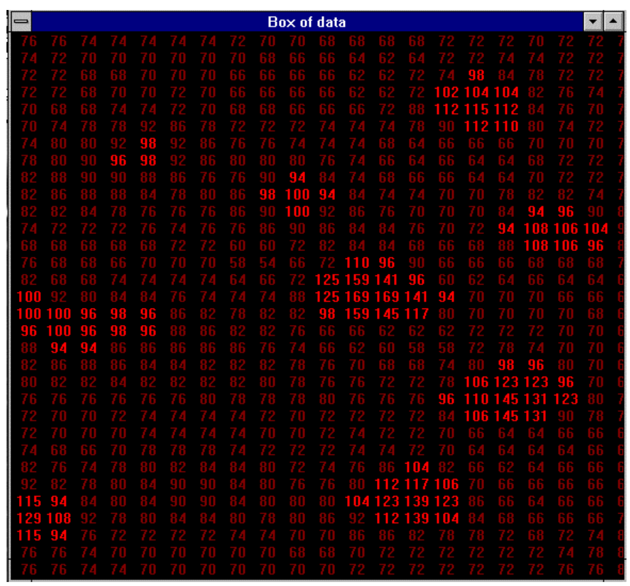

FIGURE 8. INTENSITY VALUES FOR THE ENLARGED SECTION FROM FIGURE 6.

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