Driving a DSP Underground.

R.M. Gooch, T.A. Clarke, D.D.A. Pushpakumara & T.J. Ellis.

Centre for Digital Image Measurement and Analysis
School of Engineering, City University
LONDON EC1V 0HB

Tel: +171 477 8000 Ext 3871
Fax: +171 477 8568
Email: r.gooch@city.ac.uk

Abstract

This paper describes a general purpose digital signal processing architecture for embedded systems. The core hardware modules furnish high price/performance ratio DSP platforms on a compact footprint. Expansion and peripheral boards provide interface, communications and data acquisition subsystems, which may be attached to the DSP modules via a standardised expansion bus. Modular libraries of C and assembly code provide the final ingredient for plug-together embedded DSP solutions. This paper describes the development of several illustrative applications, including a magnetic 3-d positioning system, a centrifuge monitoring system, a 3-d optical measurement system, a tunnel profiling device and an underground vehicle for remote pipe inspection.

1. DSP-90

The DSP hardware is based on the Analog Devices ADSP-21xx family of processors. Currently ADSP-2105 and ADSP-2101 devices are supported, and development of 2181 based hardware has been initiated. 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. Conceptually, the approach is similar to that of the PC/104 standard. This is acknowledged in the name assigned to the DSP system: *DSP-90*. (However the '90' refers to the board dimension in millimetres rather than the number of pins in the edge connector). DSP-90 boards are designed on a circular format, but are provided with snap-off 'ears' to enhance the mounting options: Fig. 1(a) shows a 2105 board with the mounting lugs in place, and fig. 2(b) illustrates 2101 board with the lugs removed for mounting in a tubular instrumentation pod.

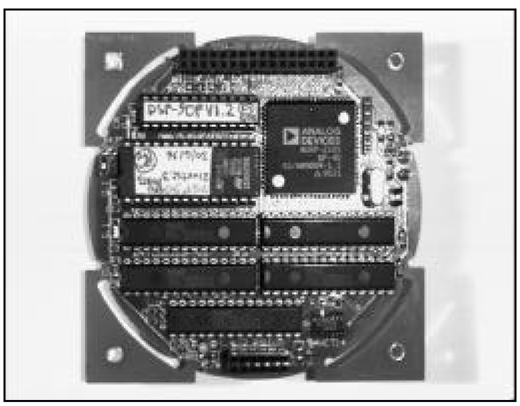

Fig. 1(a) ADSP-2105 based DSP-90 Processor Board

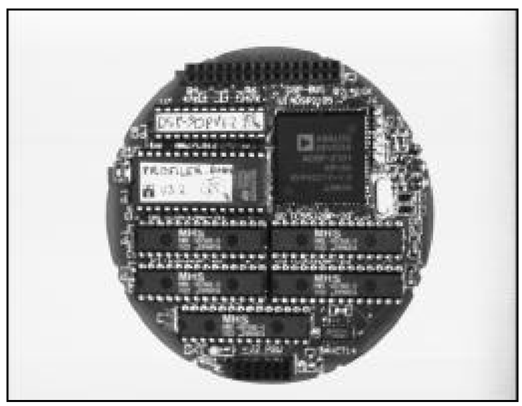

Fig. 1(b) ADSP-2101 based DSP-90 Processor Board

In addition to the internal processor memory maps, external boot memory (BM), program memory (PM) and paged data memory (DM) are provided, the latter taking full advantage of paging facilities provided by Analog Devices' programming tools. For enhanced flexibility in tailoring lower cost vs. higher performance solutions, all memory devices are socketed. Surface mount construction is used elsewhere for compactness. Programmable logic decodes the memory map and also provides the page latch and a number of control signals to the expansion bus for addressing memory mapped expansion and peripheral boards. Fig. 2 shows a DSP-90 system comprising a DSP processor board, a general purpose I/O (GPIO) board and an ethernet board. In this case, stand-offs have been fitted to facilitate mounting on a chassis plate (not shown).

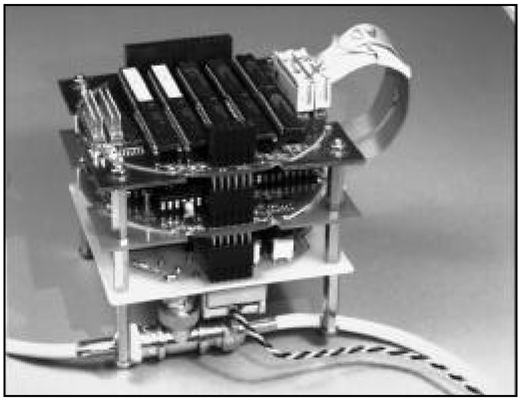

Fig. 2 DSP-90 System on an Ethernet Node

The system illustrated in fig. 2 utilises a ribbon cable connection between the GPIO board (top) and external peripheral devices controlled via the GPIO board. This need not be the case, however. More commonly, a reversed stackthrough connector scheme provides for stacking of multiple peripheral boards on top of the GPIO board.

The GPIO board furnishes two independent 16 bit FIFO input buffers, and four programmable bi-directional 8-bit parallel ports. Although many of the applications that DSP-90 is targeted for involve strict real-time, the FIFO buffers provide some latitude in the allocation of processing resources between data acquisition, processing, and despatching of results (either to controlled devices or over the ethernet). FIFO devices with up to 8k words capacity may be fitted in the sockets provided on the GPIO board. The current ethernet board is designed around a highly integrated SEEQ chipset, and an NE2000 compatible board (based on a National Semiconductor chipset) is at the prototyping stage.

2. Applications

A schematic illustrating a typical deployment of a stack of DSP-90 boards is given below in fig. 3. Here the application is in 2-d profiling. The instrument shown is a pipe profiler, however similar instruments are planned and under development for tunnel profiling and for navigation in autonomous guided vehicles (AGV's). In the AGV application the instrument will be mounted to rotate about a vertical axis, and will provide accurate ranging data for objects in the vehicle environment, which in turn may be used to solve the vehicles position with respect to a known map, or to map an unknown environment. Such methods are further explored in another paper [1].

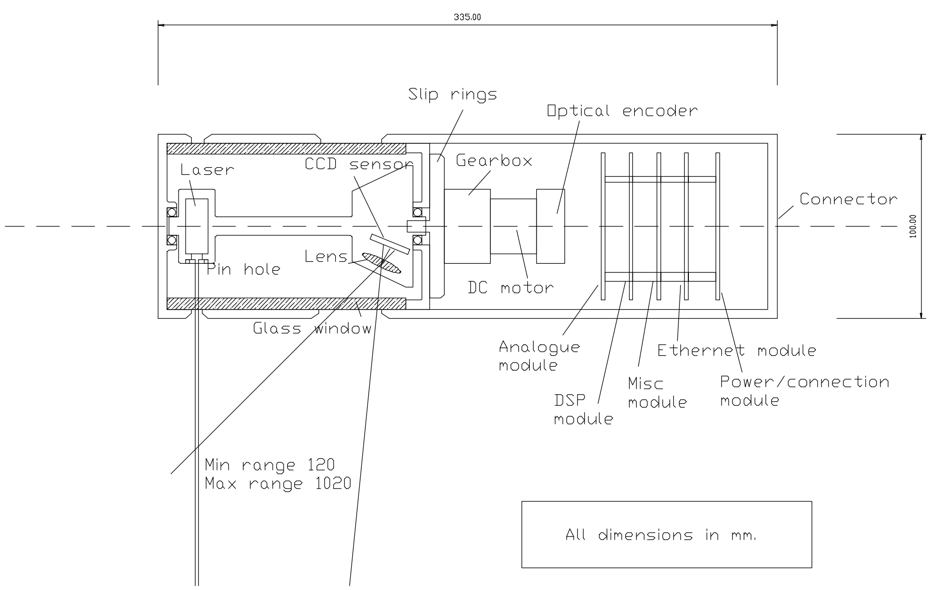

Fig. 3 Schematic of a Cross-Section Measuring Device

The instrument shown in fig. 3 uses a principle of optical triangulation which determines range using the imaged position of a target spot projected by a laser. Here the DSP is used to enhance the ranging accuracy beyond the sensor pixel accuracy, by centroiding the image of the target. Sub-pixel resolutions of the order of one tenth to one twentieth of a pixel may routinely be attained. This impacts on device performance because the technique allows lower pixel-count sensors to be used, and so line data can be clocked off the charge transport faster, and hence data acquisition rates are increased proportionately. Currently a pipe profiling device with a rotational speed of 1000 rpm is under development, with accuracy in the range of tens to hundreds of micron, inside the one metre radius working envelope.

A typical application of the pipe profiler is in sewer inspection. In many ways this application typifies the requirements of an embedded system: The environment is harsh; space in the equipment bay of the instrument pod is extremely limited; power requirements matter; data and control signals must be communicated to and from a remote operator; and above all, the system cost, performance gain and functionality must be clearly perceived by a very down-to-earth industry. Fig. 4(a) shows a current pipe profiling instrument. Fig. 4(b) illustrates a typical tractor vehicle used to deploy the instrument in a sewer pipe, and fig. 5 shows a number of faults which the profiler may be used to detect or quantify.

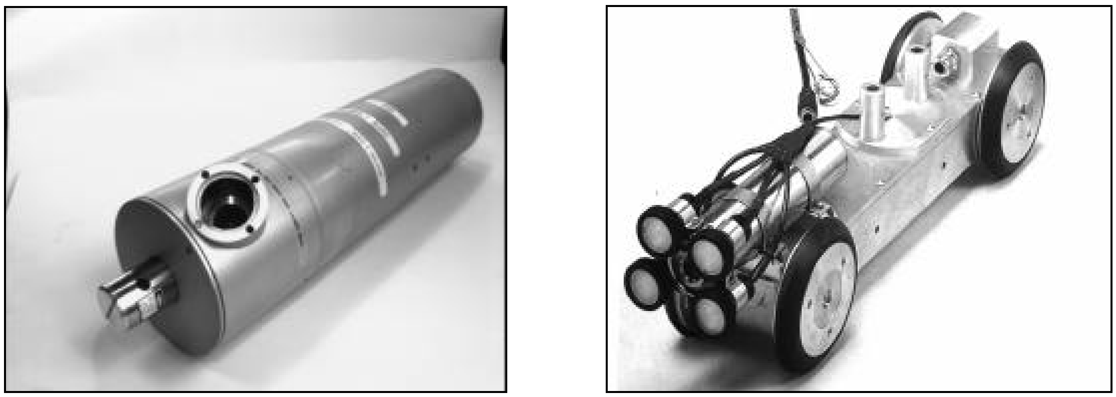

Fig. 4 (a) Pipe Profiling Instrument **(b) Typical Tractor Vehicle**

Fig. 5 (a) Hanging Debris **(b) Cracked Pipes** **(c) Grossly Deformed Pipes** **(d) Blockages**

Assisting an engineer to decide exactly when to repair a given sewer is a task which has cost benefits if pertinent information can be provided. Traditionally CCTV surveys have been used to acquire pipe condition data. But CCTV only facilitates a *subjective* estimation of the degree of degradation. The pipe profiler described above allows cross-sections of sewers to be measured accurately thus enabling the engineer to make objective decisions [2]. But this is only a first step toward a new surveying philosophy. Once a DSP is embedded in the instrumentation system it is possible to process image data by implementing edge detection and Hough transforms [3]. The results may be combined with profile data to form a map of the sewer, which can be indexed with condition classifications derived automatically. Precise information on sewer faults may be archived for further analysis, whilst uninformative data may be eliminated. Fig. 6 illustrates some potential developments.

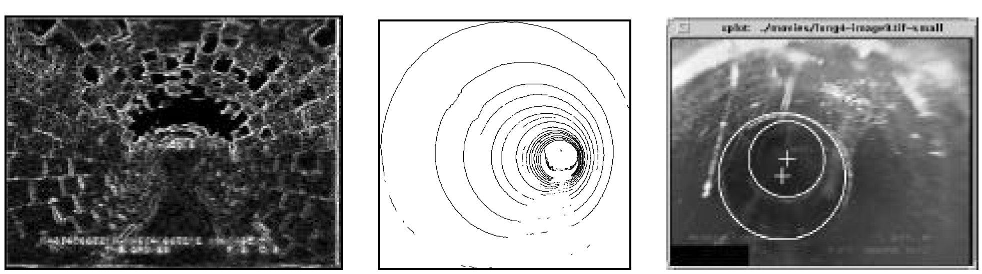

Fig. 6 (a)Sobel Edge Detection **(b) Reconstructed Profile Data** **(c) Pipe Joint Tracking**

Fig. 6(a) shows an edge detection scheme which could be used to enhance video data for locating missing bricks in large sewer pipes. Fig. 6(b) shows a scene reconstructed from a set of profiles obtained with the instrument of fig. 4. Fig. 6(c) shows the detection and tracking of pipe joints based on Hough transform methods. Using DSP-90 hardware and ethernet communications any and all of these techniques may be combined, with the computation distributed between the data acquisition system deployed in the sewer, the operations room in a van at the surface, and on the engineers workstation. This area of research is currently being supported by Thames Water PLC and by Morgan Collis Ltd.

As indicated, there is also potential to deploy this technology in profiling larger scale civil engineering structures [4]. The tunnel profiler project applies the principles of optical triangulation to surveying of tunnels of up to 10m diameter. At these extended ranges the accuracy of measurement diminishes even when the largest linescan sensor arrays are employed in the instrument design. Again, DSP-90 based sub-pixel sampling is the enabling technology and experimental trials show that an inexpensive sensor design will be capable of sub-millimetric accuracy in this application. Sample rates of up to 20k measurements per second should be obtainable. A prototype instrument has previously been constructed to demonstrate the soundness of the method, and the current project is advancing the design of the instrument to the stage where full-scale field trials may be undertaken in order to establish a complete methodology for operating the instrument in a variety of applications. It is intended that many measuring tasks currently effected with a theodolite on a point by point basis may be partly automated. For example, the position of the profiling instrument might itself be determined with a theodolite, and then hundreds or thousands of measurements around the tunnel may be gathered by the profiler. A potential application is monitoring of deformation in tunnels being constructed using the NATM technique. The instrument may also find application in long-term monitoring of man-entry sewers and in conducting 'Wriggle-Surveys' of various forms of tunnel construction.

3. Further DSP 90 Applications: 3D-Net

Taking the idea of distributed DSP-90 systems one step further is the concept of 3D-Net. 3D-Net was originally conceived as an extension of traditional photogrammetry, where the term 'network' refers to a geometrical configuration of cameras which are used to photograph an object of interest. The photographic films are analysed, knowing the camera parameters, to yield highly accurate 3-d data for the object [5, 6]. Digital photogrammetry involves the use of CCD cameras as opposed to photographic film, and the conception of 3D-Net was originally as a network of camera stations where each camera contains an embedded DSP-90 system. Thus 3D-Net is a computer network as well as a photogrammetric network. Each camera/DSP-90 station transmits 2-D scene data onto the ethernet, and a central 3-D workstation processes the sets of 2-D data to yield 3-D scene data. Such data may feed into manufacturing process control systems, 3-d imaging systems, or may simply be used to automate traditional applications of photogrammetry. Local processing and intelligent target detection performed at each camera station by the DSP-90 keeps data rates well within the ethernet bandwidth. Two areas that are under current development are jigless manufacturing of advanced aerospace componentry and medical imaging. The former is backed by British Aerospace, with the intention of developing a full demonstrator system geared to jigless wing assembly. The latter is backed by the French *Projet Magellan*, and indirectly by EDF and the École Polytechnique.

Jigless assembly involves a number of measurement cells, each of which has a known absolute position. Within each cell an independent 3D-Net segment tracks the position of componentry such as aileron hinge points. This is achieved using DSP implementations of the traditional photogrammetric methods [7]. A typical camera configuration is shown in fig. 7(a) where the compound curvature of a (marine) propeller is the subject of interest [8]. In fig. 7(b) the view of targets attached to the propeller as seen by one camera station is presented. In fig. 7(c) the rendered CAD model derived from the optical measurement process is shown. Simulation results show that DSP-90 hardware, providing embedded, distributed, numerical processing power, will enable such measurement processes to be carried out in real-time, for up to several hundred targeted locations.

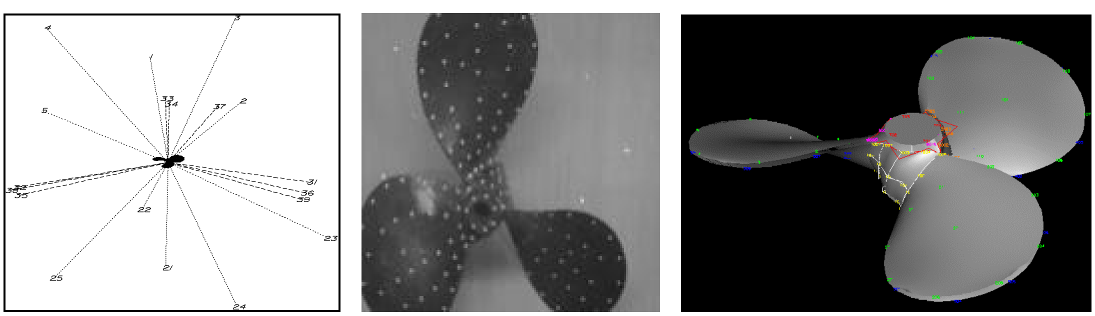

Fig. 7 (a) Nineteen camera stations (b) A View of Targets (c) Reconstructed CAD Model

Magellan [9] involves 3-d measurement on a smaller scale. The idea is to track medical instruments in real-time during the course of an endo-nasal surgical intervention [10]. The position of the patients head is also determined in real-time. Detection currently relies on a magnetic sensor system based on the mutual coupling between sets of orthogonal loop antennae. An inverse solution of the Biot-Savart equations yields position vectors relating the co-ordinates of the sensors in 3-d space. The resulting data is used to drive a computer visualisation system which guides the surgeon. Pre-operative CT scan data is displayed as a backdrop, upon which is superimposed CAD models of the surgical instruments. Positional data ensures accurate registration between the imaged displays and the actual position of the surgical instruments. A typical display as seen by the surgeon, is presented in fig. 8.

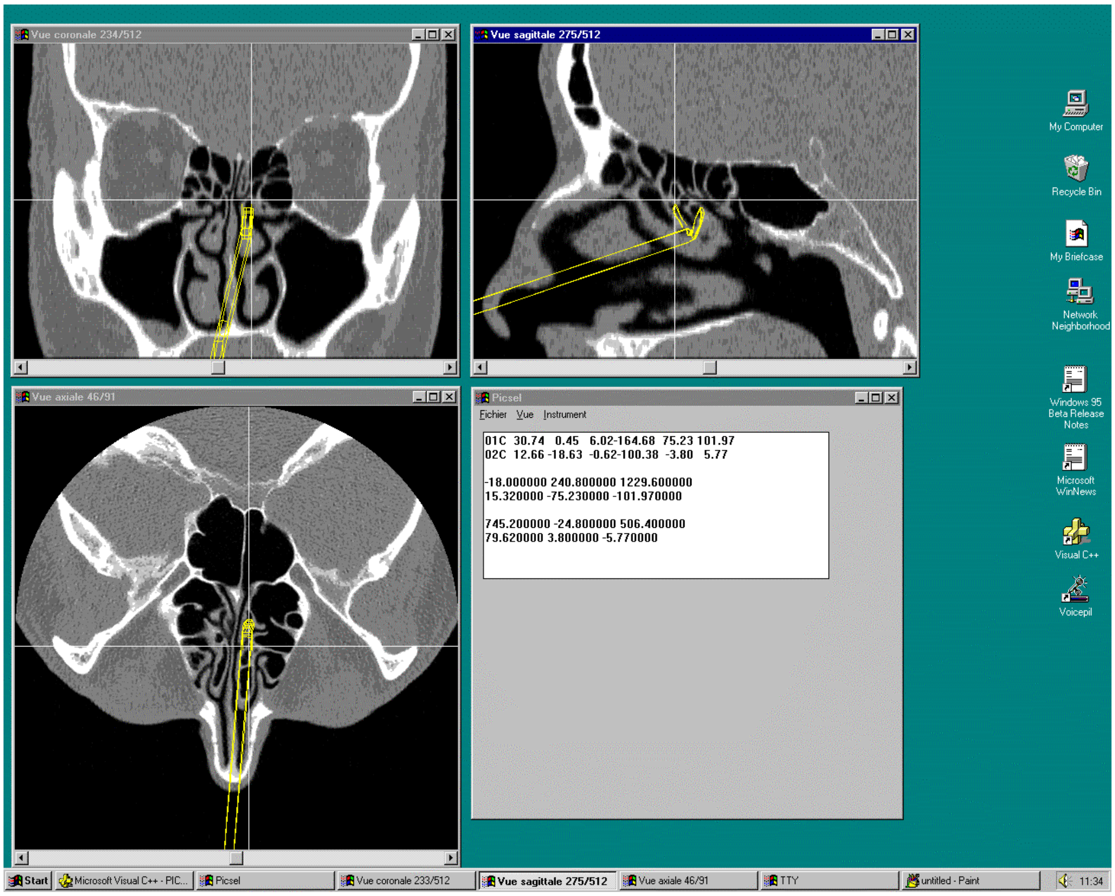

Fig. 8 Typical Magellan Display showing cuts through 3-d volume model, with superimposed instrument.

The previous Magellan sensor system relied on a closely coupled mesh of transputers to solve the co-ordinates of multiple instruments plus the position of the patients head. Currently DSP-90 and 3D-Net hardware is being developed to replace the transputer system with a distributed solution. Each surgical instrument will be permanently assigned its own DSP-90 system, which in turn will be calibrated for that instrument. If the surgeon requires additional instruments during the intervention, these may simply be connected to the ethernet, as and when required. One or several Magellan workstations may also be connected to the 3D-Net to receive positional data on the net and produce the corresponding visualisation. A schematic is shown in fig. 9. The distributed DSP-90 3D-Net solution has the added advantage of inherent reliability. If one node fails, then the rest of the system should be unaffected.

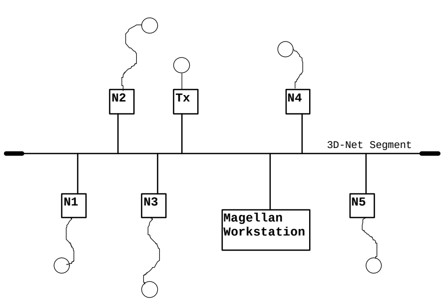

Fig. 9 Schematic of a Magellan Installation Based on 3D-Net.

The 3D-Net segment connects several DSP-90 nodes (N1,...,N5), the sensor system reference transmitter (Tx) and the Magellan Workstation. Each DSP-90 solves the position of one sensor (connected to it by a flexible cable) and thus determines the position of the medical instrument that the sensor is attached to.

As a further extension of this concept, it is currently envisaged that heterogeneous sensor systems may be connected on the same 3D-Net segment. In particular, both optical and magnetic sensor systems could broadcast positional data on the net, and various control or imaging systems could filter out and process data that was addressed to them. For this reason it is intended that evolving standards in this area should eventually be launched as an open system, similar in concept to Devicenet, but in this case oriented toward measurement rather than control applications.

A further measurement project based on embedded DSP-90 hardware involves real-time detection of targets embedded in the surface of a soil sample. This civil engineering project concerns soil deformation under load. The soil sample is accelerated in a centrifuge to in excess of 100g (fig. 10) and resultant deformations are continuously monitored using the targets. The camera will be exposed to high accelerations, but accompanying drive circuits are mounted together with the embedded DSP-90 on the centrifuge axis of rotation and do not experience such high forces. Data will be relayed over the ethernet link, through a set of slip-rings, to a remote monitoring station.

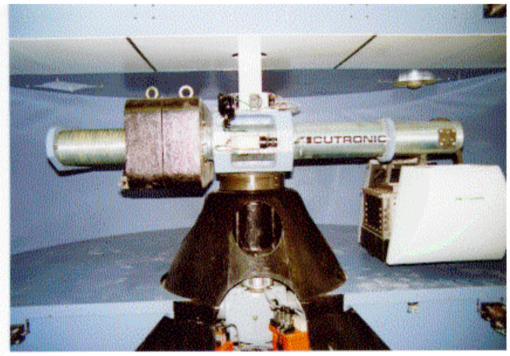

Fig. 10 Measurement of Soil Deformation Under Load in a Centrifuge

4. DSP-90 Standard and Software

In the applications described above, there are several common themes (i) basic requirement for simple processing and control functions; (ii) standard I/O and communications requirement; (iii) the potential for performance increase from signal processing power; (iv) packaging size constraints; (v) cost and development time constraints. Functional requirements are clearly solvable in each case by designing custom hardware, and coding up application software for each solution. However as the production run for each application was not that large, the cost and time constraints precluded development of custom hardware. What was required was a set of building blocks from which solutions could be plugged together. Several candidate solutions did exist, such as stamp format embedded microcontrollers and embedded PC systems. However these systems are at the extremes of simplicity and complexity. Stamp format controllers are typically lacking in power for numerical processing, whilst a fully-fledged personal computer solution, even in an embedded guise, incorporates many components that are surplus to requirements in any given application.

Typically, DSP systems that are currently available are designed for use with a host processor of some kind, which runs the operating system (OS), handles communication and I/O, and schedules numeric processing to the DSP, which in turn is treated as an advanced numerical processor. This scenario is especially true for many compact DSP footprints which are available as TRAMs or TIMs. However in an embedded application where the OS requirements are quite small, the DSP idle time may well amount to unused processing capability in excess of that employed by the host processor in running the OS and handling I/O.

In response to the above scenario, DSP-90 was developed to satisfy the requirements for processing and control functions, I/O and signal processing capability. DSP-90 was designed to satisfy size and cost constraints, and therefore required a DSP with low overheads in terms of support hardware, but which offered the possibility to transfer software investment across several upgradeable hardware options. In addition a rich language and a good set of development tools was a factor since an OS was to be coded for the DSP in addition to the simpler numerical software. Analog Devices' ADSP-21xx family was chosen after a reasonably comprehensive selection procedure, and DSP-90 was initially designed around the 2101 and 2105. The full details of the DSP-90 standard are currently available as a technical report [11], but a few salient details are considered here.

Cards are circular with 90mm diameter, but have auxiliary snap-off mounting lugs. Two types of cards are defined depending on the expansion connector configuration. Type 1 (processor format) cards carry the expansion bus connector and the PSU connector. Type 2 (interface format) cards carry I/O connectors, the PSU connector and may optionally carry the expansion connector. The pinout of the expansion connector is given in fig. 11, and the system memory map derived from control signals on the expansion bus is given in fig. 12.

1	D8	2	D9
3	D10	4	D11
5	D12	6	D13
7	D14	8	D15
9	D16	10	D17
11	D18	12	D19
13	D20	14	D21
15	D22	16	D23
17	!IRQ2	18	!RES
19	A0	20	A1
21	A2	22	A3
13	A4	24	CK
25	!WE	26	!RD
27	!ETHER	28	!GPIO
29	!AUX1	30	!AUX2
31	!ACTRL	32	!IORST

Fig.11 DSP-90 Expansion Connector

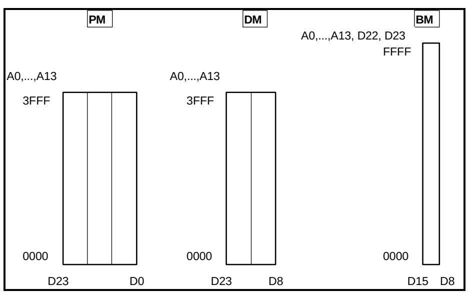

Fig.12(a) DSP-90 Memory Maps

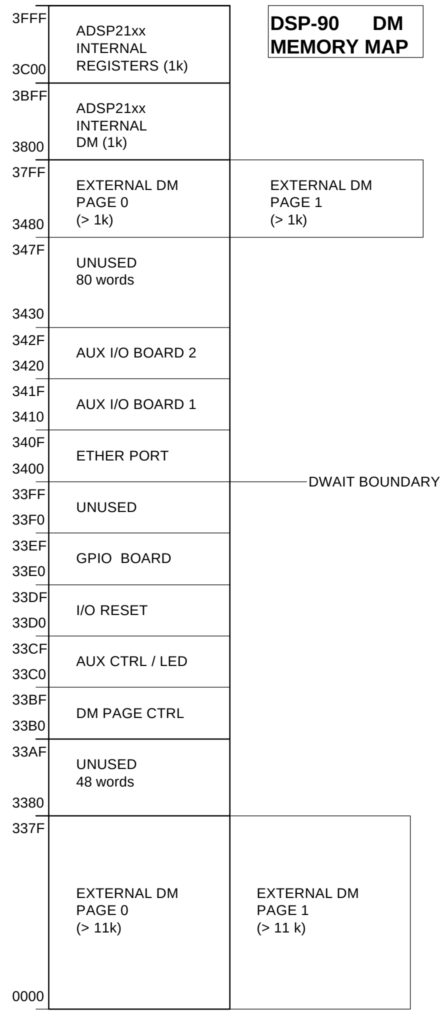

Fig.12(b) DSP-90 Data Memory (DM) Map

Fig. 12(a) shows the basic ADSP-2101 and 2105 memory configuration, which is given in more detail in the Analog Devices Literature [e.g. 12]. Fig. 12(b) gives the DSP-90 DM configuration showing memory mapped expansion boards and registers. Within the scheme of Fig. 12(b), the expansion and I/O addresses lie across a DWAIT boundary of the ADSP-21xx DM. This provides for the future addition of auxiliary boards having slower bus cycles, without slowing down all the existing expansion boards. Further, the ACTRL signal provides a latched signal for controlling access cycles to lower speed peripherals if necessary, and this will typically be used in conjunction with data buffered through a latch on an expansion I/O board. The boards below 0x3400 should operate with zero wait state bus cycles. Those above 0x3400 may utilise wait states. If expansion boards requiring different numbers of wait states are to be used in the same segment of DM, then the ADSP wait state register may be dynamically reprogrammed.

DSP-90 is equipped with monitor software which is compliant with the Analog Devices EZ-Kit Lite Host Program [13]. This facilitates the user programs developed using Analog Decives' C and Assembler Cross Development Tools to be downloaded and run over an RS-232 data link. In addition a real-time operating system based on TERSE [14] is nearing completion. The OS incorporates a bootstrap loader utilising the ethernet link. Libraries of routines for signal processing, as well as device drivers for the expansion hardware have been developed. There is also a suite of EPROM based test routines which exercise various features of the hardware.

5. Conclusion

Low-cost, high price/performance DSP devices are serving to advance DSP technology into a broadening range of applications. In order to expedite this process, DSP-90 has been designed as a general purpose platform for embedded DSP applications. The objectives in designing DSP-90 have been to produce modular componentry with which a given requirement can be fulfilled with little additional investment in hardware design or in programming. DSP-90 systems have already been incorporated into a diverse range of embedded system solutions, thus providing an endorsement of the original conception. A summary of the current DSP-90 solutions is given in table 1.

Application	Area	Components					Features
		Ethernet	Camera	I/O	DSP	Motor/ Encoder	
Centrifuge	Civil Eng.	✓	✓	✓	✓		200g
3D-Net	Aerospace	✓	✓	✓	✓	Optional	Real-time
Magellan	Medical	✓		✓	✓		Magnetic
Vehicle	Robotics	✓		✓	✓	✓	Control
Pipe profiling	Surveying	✓	✓	✓	✓	✓	Harsh Environment
Tunnel profiling	Surveying	Optional	✓	✓	✓	✓	Interactive Operation

Table 1 DSP-90 Configurations

Acknowledgement: Development of a high performance pipe profiling instrument is being financially supported by EPSRC under grant number GR/H41898, by Morgan Collis Ltd and by Thames Water PLC. The technical collaboration of Magellan in developing a medical positioning system is gratefully acknowledged.

References

[1] R.M Gooch & T.A. Clarke, 'A Semi-Autonomous Sewer Surveillance and Inspection Vehicle' To Appear in Proc. Intelligent Vehicles '96, Tokyo Japan.

[2] T.A. Clarke, 'The Development of an Optical Triangulation Pipe Profiling Instrument'

[3] X. Pan, T.J. Ellis & T.A. Clarke, 'Robust Tracking of Circular Features' BMVC'95 Proc. British Machine Vision Conference, Vol.2, pp 553-562, 1995.

[4] T.A. Clarke, 'Internal Profiling of Industrial Structures' New Developments in Transducers Colloquium, March 1993.

[5] P. Wolf, "Elements of Photogrammetry", 2nd Edition, Pub. Mc Graw Hill Book Co, U.S.A., 1993

[6] C.C. Slama, "The manual of Photogrammetry", 4th Edition, Falls Church, American Society of Photogrammetry, 1056 pages, 1980.

[7] X. Wang, 'An Algorithmic Method for Real-Time 3-D Measurement' To Appear ISPRS Conference, Vienna 1996.

[8] T.A. Clarke, T.J. Ellis, & S. Robson, 'High Accuracy 3-d Measurement Using Multiple Camera Views' IEE Colloquium Digest No. 1994/054.

[9] P. Collet, R.M. Gooch & F. Allouche 'Magellan: Medical version of PICSEL' To Appear CAR'96 10th Symposium on Computer Aided Radioscopy, Elsevier Publishers, Paris, 1996.

[10] P. Collet, R.M. Gooch & F. Allouche 'PICSEL: Computer Aided Surgery' In 'Computer Simulated Radioscopy' Proc. CAR'95 Conference on Computer Assisted Radioscopy, Berlin, Springer Verlag, 1995.

[11] R.M. Gooch, T.A. Clarke & D.A. Pushpakumara 'DSP-90: General Purpose Embedded Digital Signal Processing Systems' CDIMA TR, City University, London, 1996.

[12] Analog Devices 'ADSP-2100 Family Users Manual' (third Edition), Analog Devices Inc., 1995.

[13] Analog Devices 'ADSP-2100 Family EZ-KIT Lite Reference Manual' Analog Devices Inc., 1995.

[14] B. Kauler, 'TERSE: A Tiny Real-Time Operating System' Dr. Dobb's Journal, Dec. 1995, pp 72-80.

About the Centre for Digital Image Measurement & Analysis: In 1984 City University formed a multi-disciplinary centre comprising experts from Machine Vision, Electro-optics, and Photogrammetry. In addition to academic research and teaching programmes CDIMA undertakes external project work for industry and government research bodies. This centre is believed to be unique in the UK and had current interests in all aspects of high precision measurement where the primary information source is image data.

About Richard Gooch: Richard Gooch is a research fellow and an Honarary Visiting Lecturer at City University. He trained as a technician at British Telecom Research Laboratories, Martlesham UK, gained an MEng degree in Electrical Systems Engineering at Kingston Polytechnic, and a PhD in Artificial Intelligence at Bristol University under Professor J.F. Baldwin in the department of Engineering Mathematics. He has experience in artificial intelligence applied to pattern recognition and machine learning, as well as in hardware design and consultancy in industrial robotics, signal processing and smart sensors. He has published research papers in the areas of soft computing, signal processing and medical electronics. Dr Gooch is currently working on autonomous and tele-operated robotic instrumentation systems.

PAPER REFERENCE

Gooch, R.M. Clarke, Pushpakumara, D.D.A., & Ellis, T.J., 1996. Driving a DSP underground. Proc DSP 96 Scandanavia. Copenhagen, Denmark, pp. 159-168.