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Mitchell

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(54) **INTEGRATED CIRCUIT WITH EMBEDDED EMULATOR AND EMULATION SYSTEM FOR USE WITH SUCH AN INTEGRATED CIRCUIT**

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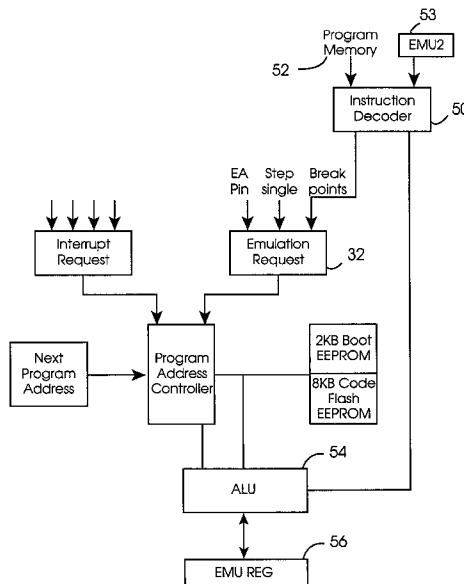
Assistant Examiner—Douglas W. Sergent

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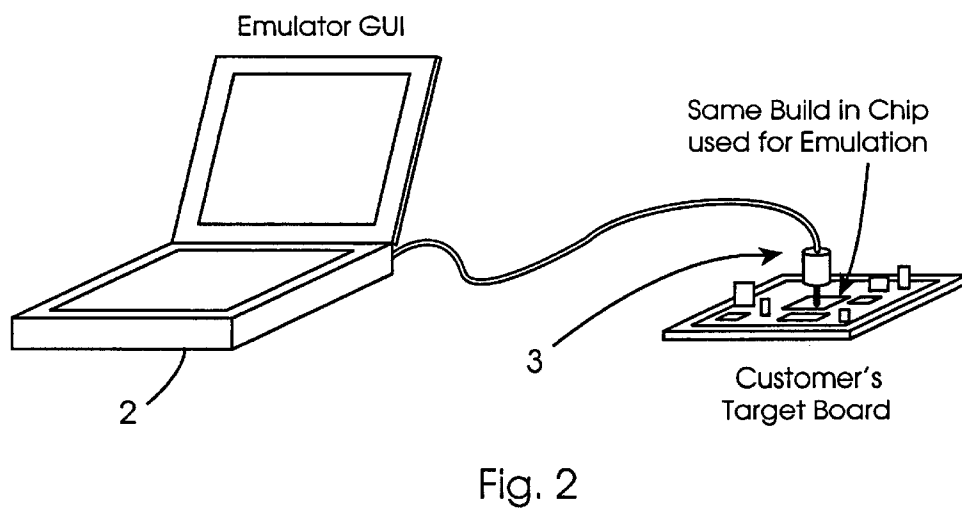
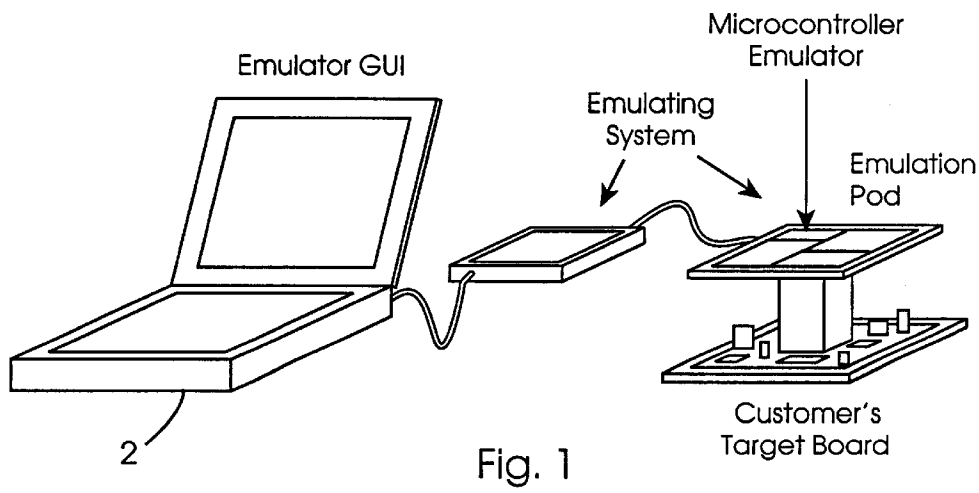
(57) **ABSTRACT**

A data processor is provided in which an embedded emulator communicates with a control emulation system using a serial communications link involving one pin of the data processor package.

30 Claims, 7 Drawing Sheets



Prior Art



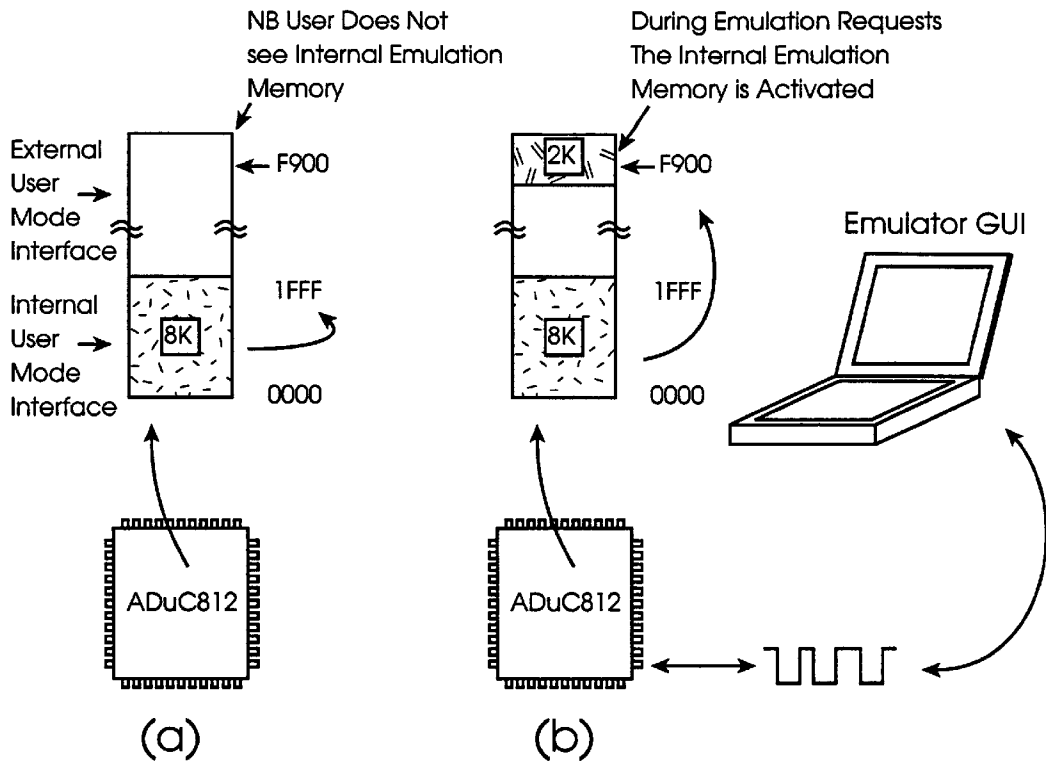


Fig. 3

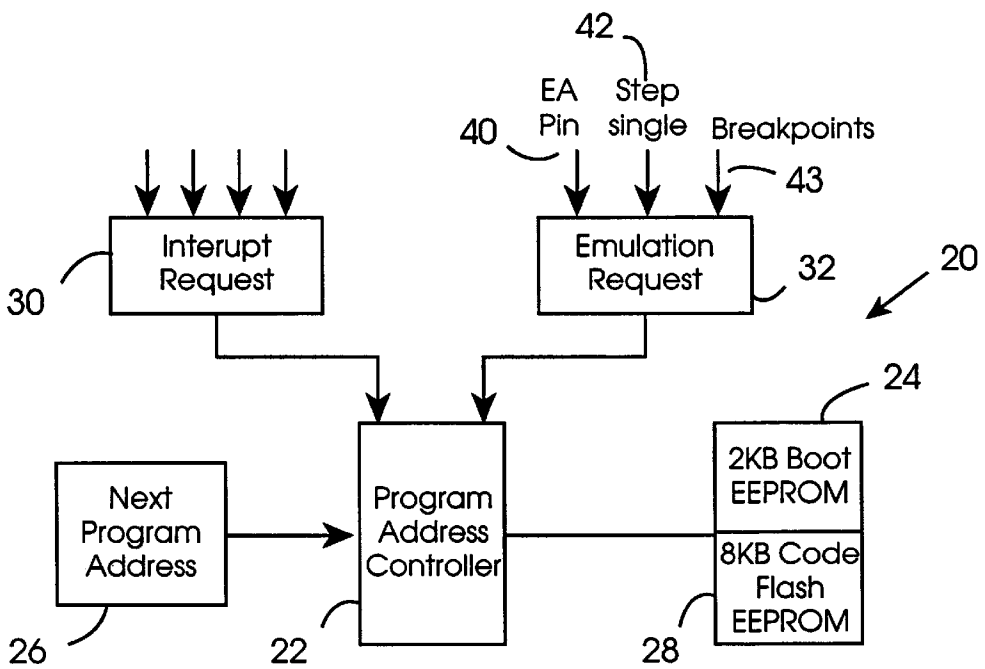


Fig. 4

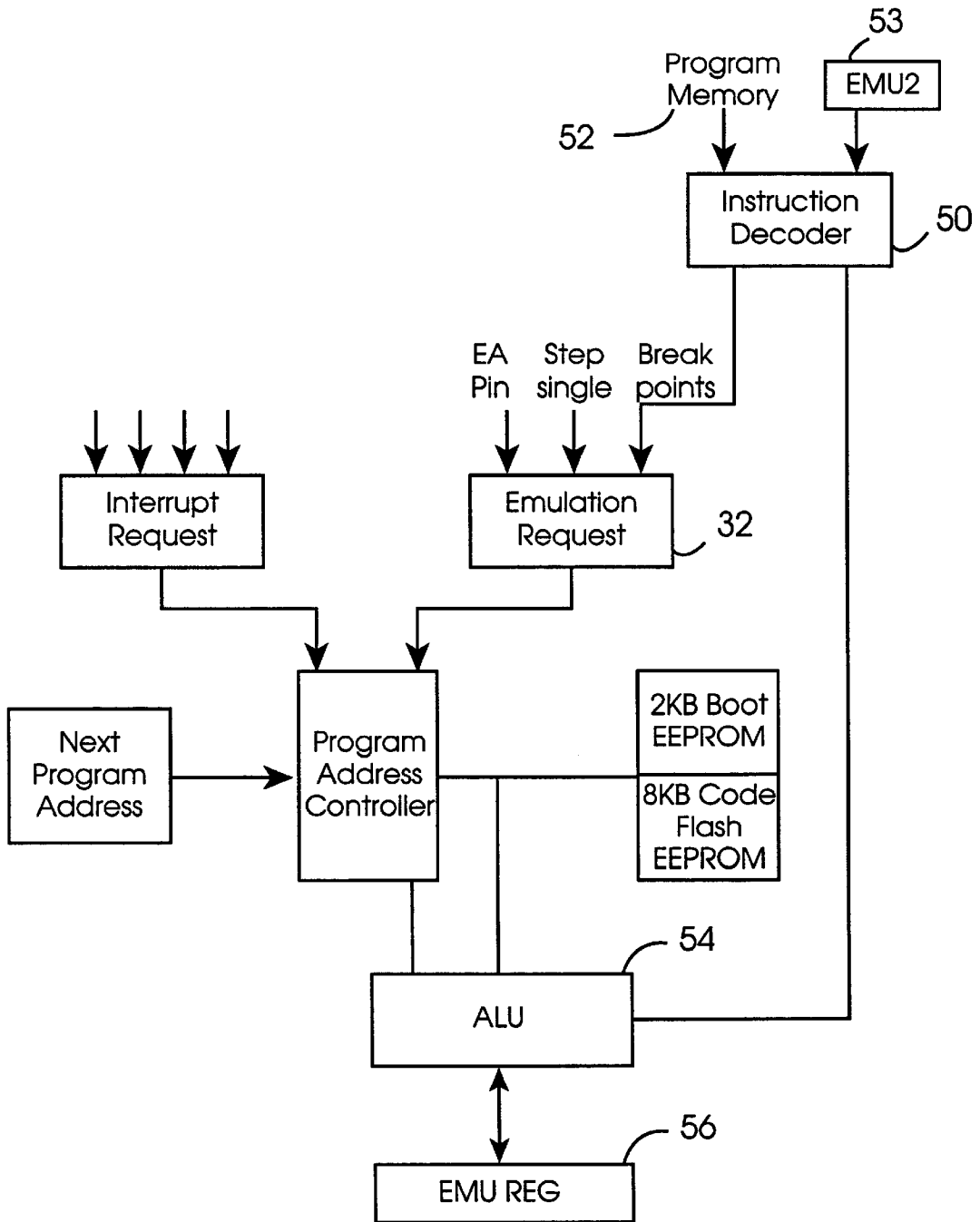


Fig. 5

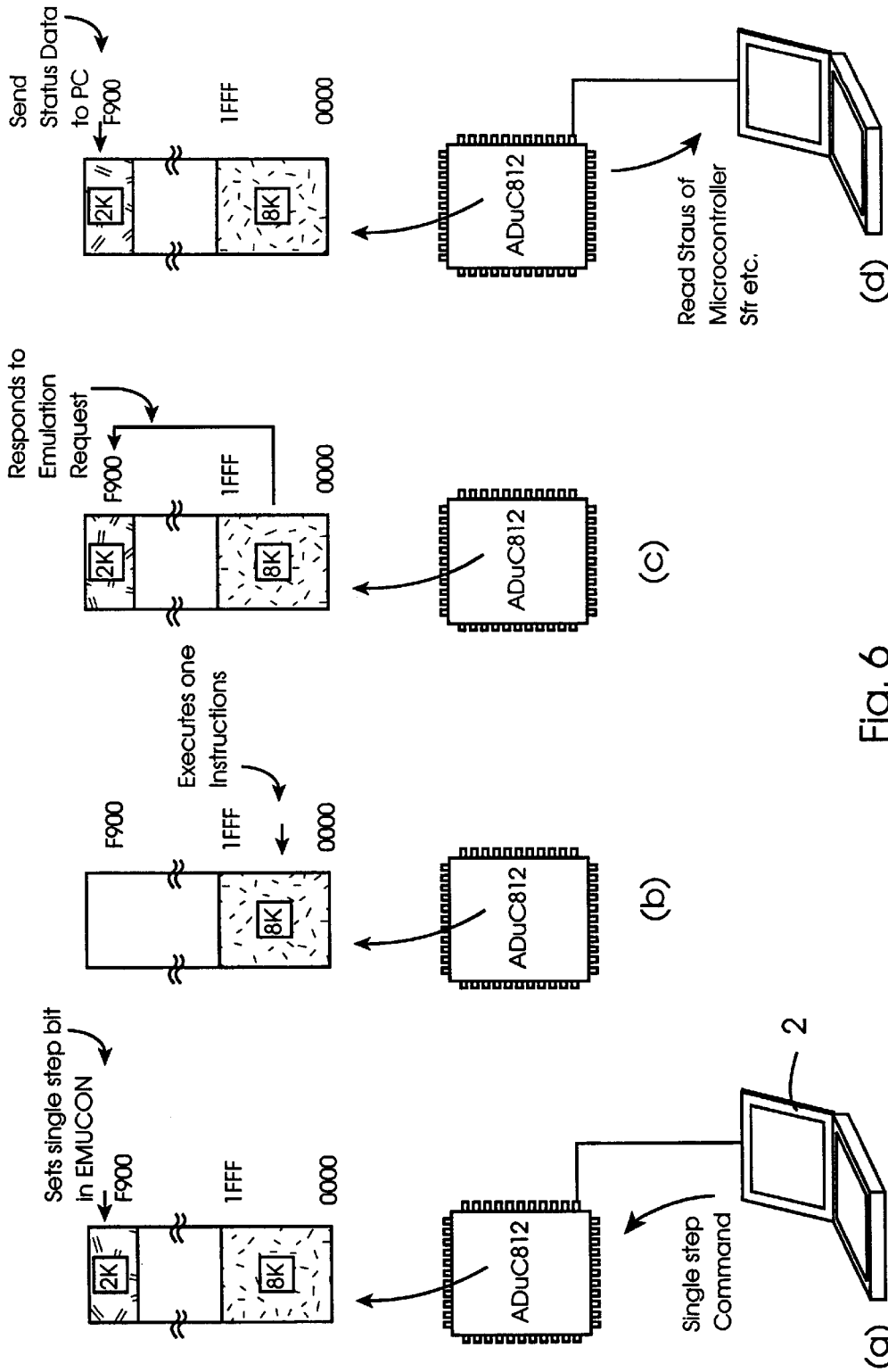


Fig. 6

Breakpoint Using a Special Instruction

Address	OPCode	Breakpoint JMP
0120	CLR A	A 5 ← Emulation Break Instruction
0121	INC A	INC A
0122	DA A	DA A
0123	CLRC	CLRC

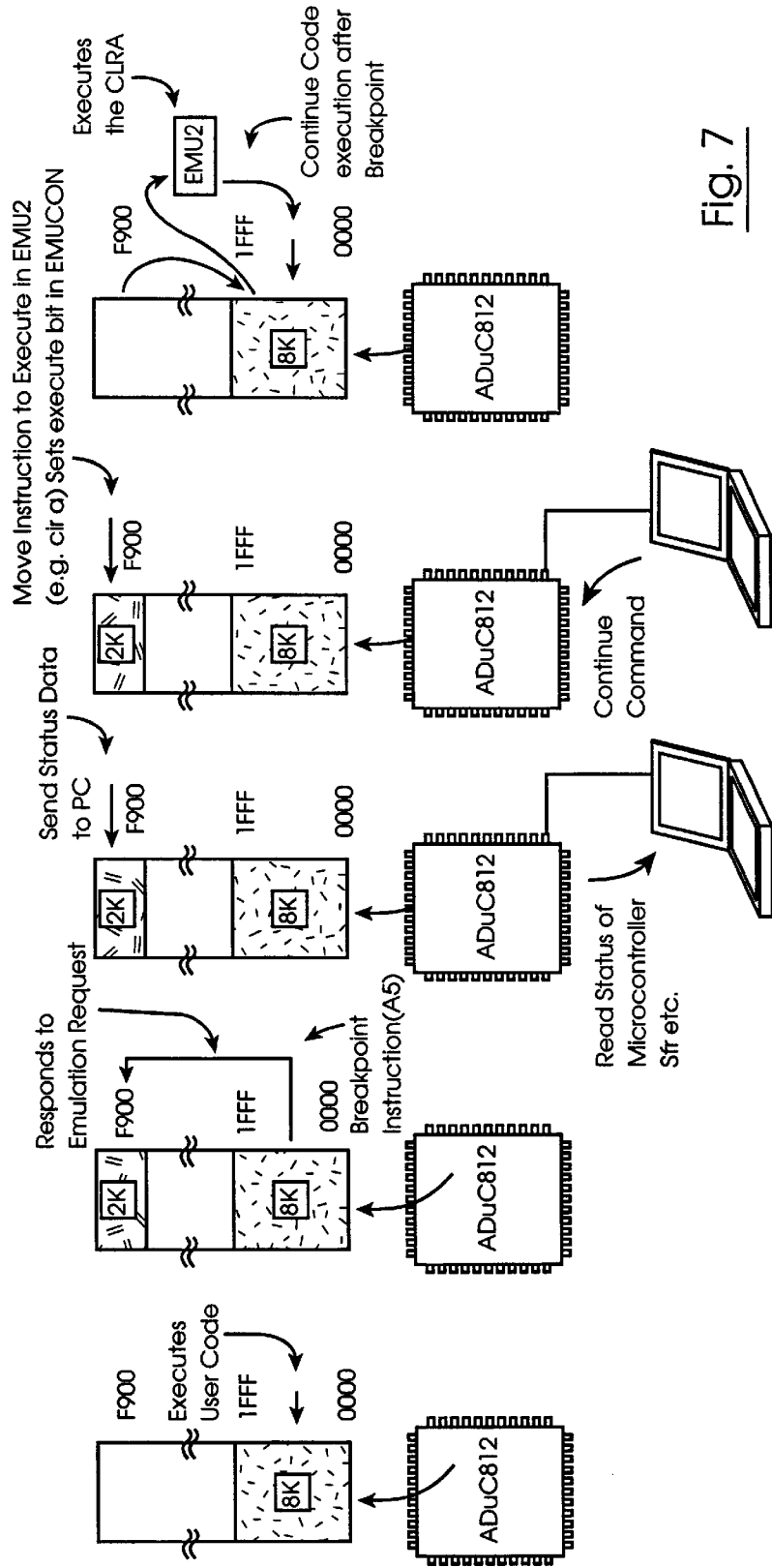


Fig. 7

EMUCON Register (EMUCON)

CLKD			EE	EES	ESS	EAIN	EAOUT
0	0	0	1	0	0	0	1
R/W	R/W	R/W	R/W	R/W	R/W	R	R/W

Fig. 8

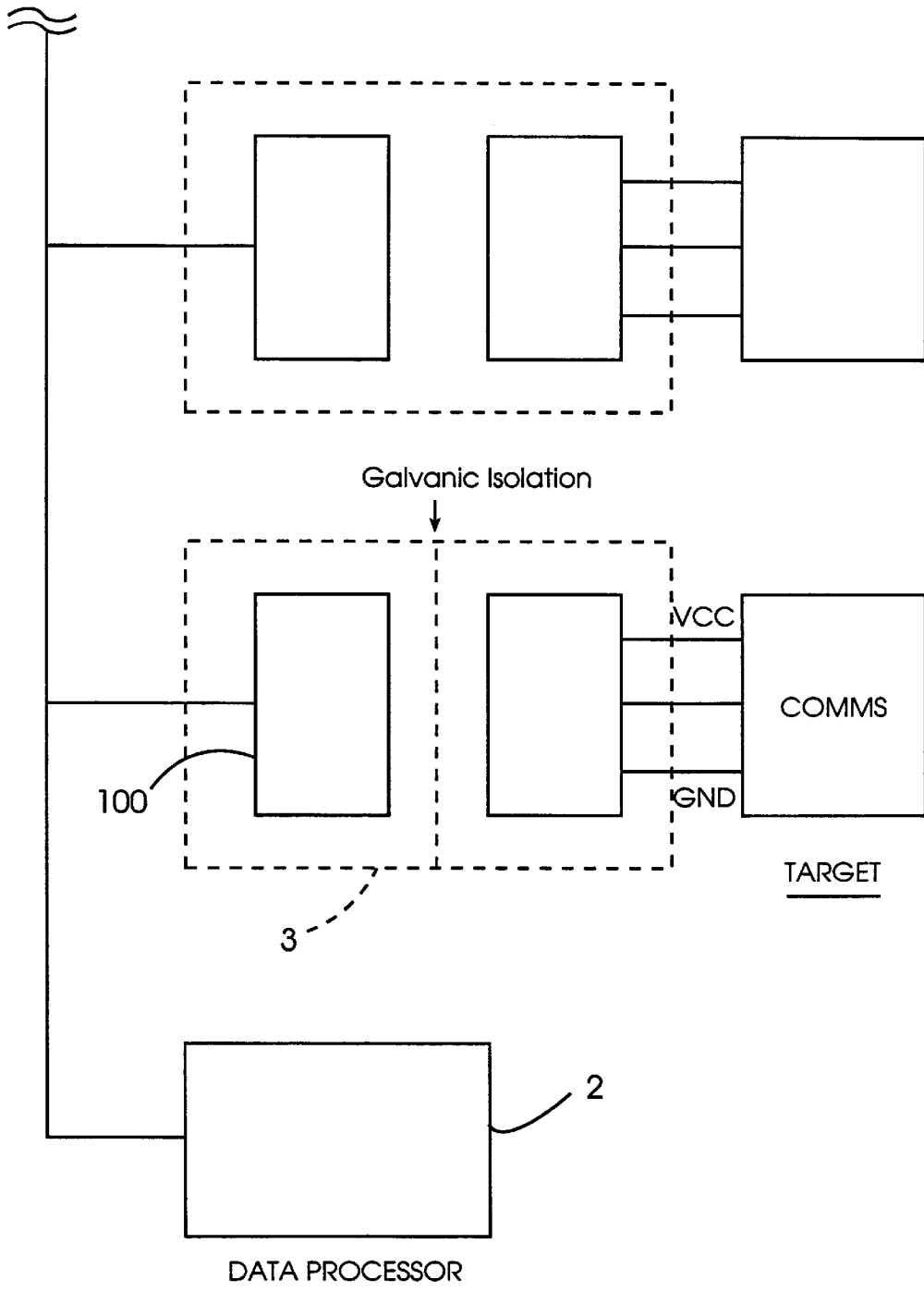


Fig. 9

**INTEGRATED CIRCUIT WITH EMBEDDED
EMULATOR AND EMULATION SYSTEM
FOR USE WITH SUCH AN INTEGRATED
CIRCUIT**

TECHNICAL FIELD

The present invention relates to an integrated circuit having an emulator embedded therein, and to an emulation system for use with such an integrated circuit.

BACKGROUND OF THE INVENTION

Executable code for a data processor such as a microcontroller, requires testing and correction during its development cycle. Software debugging is initially done in a simulator or debugger offline. Once the software is debugged, it is then down loaded into the target system. However, if the software does not work correctly, for example, due to a timing problem it is then necessary to do an "in circuit" examination of the software and the data that it is manipulating. It is known to perform this by removing the target data processor and replacing it with a replica of the data processor which can be probed or interrogated via an emulation pod. The replica data processor emulates the real data processor and this process is called "in circuit emulation".

A disadvantage of known "in circuit" emulators is that the additional sockets, clips, adaptors or pods can induce extra parasitic components into the target system which alter its performance. This usually restricts the emulation to a slow speed in order to avoid timing problems introduced by the parasitic components. The use of such in circuit emulators can cause problems where debugging is to be performed in hybrid digital-analogue systems where analogue accuracy is a critical issue, especially when more than 6 or 7 bit resolution of analogue variables is used.

It was also known, in the case of microcontrollers where the internal address and data busses do not come out to the pins of the data processor, to produce a special "bond-out" version of the circuit. This has to be manufactured into a bigger package to bring these extra signals to the pins so that the emulator can monitor them. The bond-out version is disadvantageous since it requires the chip manufacturer to create a second version of the chip and package, with consequent timing differences from the read chip, increases complexity, and a need to provide an adaptor for connecting the "bond-out" version of the chip to target systems in place of the standard chip package.

It is known to integrate emulation address comparators and emulation break point registers within an integrated circuit and then to perform a hardware compare of the contents of the address register with the emulation break point register in order to determine when to force a break point for emulation purposes. However, the additional registers and comparators are wasteful of space on the silicon die of the integrated circuit, and are inflexible in their operation. An additional register and comparator is required for each break point. Typically a designer may wish to have between eight and sixteen break points available. The addition of sixteen or so additional registers and comparators can add a significant cost to the production cost of the integrated circuit.

SUMMARY OF THE INVENTION

According to a first aspect of the present invention, there is provided a data processor including an emulation con-

troller for causing the data processor to enter an emulation mode, and dedicated registers for use in the emulation mode.

It is thus possible to provide a software driven emulator within a data processor which leaves the registers used by the data processor to execute tasks unaltered during an emulation or debug operation. A software driven emulator is flexible and allows, for practical purposes, for an unlimited number of break points to be implemented.

Preferably the registers dedicated for use by a data processing core (also known as an arithmetic logic unit) of the data processor during emulation can only be altered during emulation.

Advantageously a programme for controlling the operation of the data processing core during emulation is stored in a reserved non-volatile memory area which is hidden from the use of the data processor.

Preferably the emulation controller can operate in a single step mode wherein the register status of the data processor, or other information such as the contents of a stack or memory can be output after executing a single instruction of the user's programme. Additionally or alternatively, the emulation controller is responsive to a single byte instruction placed in the user code in order to initiate the emulation mode. The single byte instruction is, in general written over another instruction in the user's programme. In order to ensure that the user's program performs as intended, the overwritten instruction is held in a special purpose register so that it is executed when the emulation mode is excited. Additionally or alternatively, the data processor may also be responsive to a signal on one of the data processor control pins in order to initiate the emulation mode.

According to a second aspect of the present invention, there is provided a data processor having an emulator embedded therein, and in which the emulator is initiated by a single work instruction.

According to a further aspect of the present invention, there is provided a data processor including an emulator therein arranged to communicate information concerning the internal status of the data processor via a serial communication link.

Preferably the serial data link utilises a pin in the data processor package. Advantageously the pin is multiplexed with a control function of the data processor. For example, some data processors include control pins which are only relevant during the power up initialisation of the data processor. The pin may indicate to the processor whether it is to initially execute instructions from an internal or an external memory. Once this information has been conveyed to the processing core of the data processor the pin becomes effectively redundant. Such a pin may then be used as a communication link between the embedded emulation system within the data processor and an external development system or emulator controller.

Preferably the emulator is responsive to a signal on the pin, such as a voltage transition, in order to activate the emulator.

Preferably the emulator is a software controlled emulator, and comprises emulation instructions held as software within a reserved memory integrated into the data processor. The receipt of the instruction to start emulation, either by a signal on the emulator control pin or via a software instruction within the software being debugged, forces the data processing core of the data processor to suspend execution of the user's programming code and to execute instructions from the emulation instruction code. Preferably the receipt of an instruction to commence emulation causes a high level

non maskable interrupt to be issued to the data processing core of the data processor.

Preferably the data processor executes emulation instructions using reserved emulation registers, thereby leaving the contents of the registers used for programme code execution unaltered, except possibly for the programmed address controller and the stack which may experience some minor and wholly reversible alterations. Advantageously an auxiliary stack and/or auxiliary programme address counters may also be provided solely for use within the emulation routine such that the registers, programme counter and stack used by user executable code may be left entirely unaltered. As an alternative dedicated registers may also be provided for storing the contents of the program address controller. In yet a further alternative, the data processor may be arranged to download the stack and register contents to virtual registers with an emulator control data processor or within an interface element, and to upload the register and stack contents when exiting the emulation mode.

According to a further aspect of the present invention, there is provided a development system comprising a control data processor for monitoring the status of a target data processor, wherein the target data processor includes an embedded emulator for communicating information concerning the internal status of the target data processor via a serial communications link, the development system including interface element adapted to communicate via the serial communications link.

The interface element may be in the form of a pod providing electrical isolation between the target and control data processor. Advantageously the pod provides bi-directional communication between the target and control data processors and includes a controllable voltage generator for causing a voltage transient on an emulation control pin of the target data processor for forcing it to enter the emulation mode. The voltage generator may also be used to communicate data and instructions to the target data processor.

Advantageously the interface element communicates with the control data processor via a conductive link, such as a cable. Alternatively, the communications pod may communicate with the control data processor over a radio or optical based, such as infra-red, communications link. Advantageously the or each communications pod has a unique identity such that a plurality of pods may be independently addressed by a single emulation control data processor. Thus the emulation control data processor can control and/or debug a plurality of target data processors within a target system.

Advantageously the or each interface element contains a local data processor for handling may timing features or handshaking required to communicate over the data link. The local data processor may contain registers or memory for temporarily storing the register contents of an associated target data processor, or may handle the modification of a block user program code, i.e. changing the code or inserting a break point instruction.

In a preferred embodiment, the or each interface element is a pod having three pins, one for connection to ground, one for connection to the power rail Vcc, and one for connection to the pin on the target data processor for communication therewith.

It is thus possible to integrate emulation and debug features with a data processor, thereby ensuring that emulation has minimal effect on the operation of the target board.

As used herein, "emulation" includes software debugging carried out using the target processor.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will further be described, by way of example, with reference to the accompanying drawings, in which:

FIG. 1 schematically illustrates a prior art emulator arrangement;

FIG. 2 schematically illustrates an emulator constituting an embodiment of the present invention;

FIGS. 3a and 3b schematically illustrate the memory organisation within a data processor constituting an embodiment of the present invention in normal operation and in emulation mode, respectively;

FIG. 4 schematically illustrates the internal layout of a microcontroller constituting an embodiment of the present invention;

FIG. 5 schematically illustrates the internal layout of a microcontroller constituting a further embodiment of the present invention;

FIG. 6a to 6d schematically an emulation in a single step mode;

FIG. 7 schematically illustrates an emulation using a single step break point instruction;

FIG. 8 shows a layout of a special purpose emulation register; and

FIG. 9 schematically illustrates the emulation system.

DESCRIPTION OF THE PREFERRED EMBODIMENT

FIG. 1 schematically illustrates a prior art emulator in which a large emulation pod plugs into the data processor socket on a customer's target board in order to provide interconnection with an emulator system comprising an emulation control processor running an emulator software package which typically displays register contents of the target processor and allows for editing of instructions via a graphical user interface (GUI). The large size of the emulation pod makes it inconvenient to use and also can give rise to subtle changes in operation of the target board due to the extra load and parasitic components introduced by the emulation pod. Furthermore, the known emulation pod uses a different or modified data processor which gives rise to changes in output driving characteristics and loadings which can effect signal timings and degrade analogue performance where analogue circuits or DAC or ADC's are involved.

As shown in FIG. 2, an emulation system comprising a data processor constituting and embodiment of the present invention and an interface card 3 for providing galvanic isolation between the customer's target board and the emulation control data processor 2 provides for a more compact emulation system and, more importantly does not change the operating characteristics of the customer's target board due to the introduction of parasitic components.

The data processor having an emulator according to the present invention performs emulation under software control. In order to achieve this a reserved memory containing emulation instructions is provided as an integral part of the data processor. As shown in FIG. 3a, a data processor may have, for example, a memory space in which addresses 0000H to 1FFFH (where "H" indicates that the addresses are expressed in hexadecimal) are provided for internal user programme code and the addresses 2000H to FFFFH are allocated to external user code space. The emulation memory is placed on another page of memory such that it remains hidden from the user. Thus, for example, external

memory addresses F900H to FFFFH may contain a user programme, whereas internal addresses F900H and above contain the emulation programme.

FIG. 4 schematically illustrates the internal arrangement of a data processor, generally illustrated as 20, whereby a programme address controller 22 holds the address of the next memory location to be read from. This location normally points to a boot strap memory 24 which contains executable code to be used during power up sequences or for data exchange routines, or to a user programme 26 which may be stored in an internal user code memory 28 or in external memory (not shown). The programme address controller 22 is responsive to an interrupt request handler 30 which, as is well known in the art, allows normal execution of a programme to be interrupted in order to respond in a predetermined way to specific events. The data processor is arranged to execute an interrupt routine in response to an interrupt request and then to return to the user code when the interrupt routine has been completed. The data processor constituting an embodiment of the present invention is also provided with an emulation request controller 32 which issues a priority non-maskable interrupt request which takes precedence over all other interrupt functions. The interrupt controller 30 is arranged to buffer incoming interrupts while the programme address controller is responsive to the emulation request controller 32 in order to ensure that interrupt requests are properly serviced upon return from the emulation mode.

The emulation request controller is responsive to three inputs. A first input 40 is responsive to a voltage transition on a single pin of the data processor package. In the preferred embodiment, the pin is a "EA" pin (provided on all ADuC812 data processor) which is used to tell the data processor and it should execute from internal (EA=high) or external (EA=low) memory during the power up. The state of the pin is latched by the data processor at power up or reset and thereafter it can be used as the emulation control pin. The EA pin is also used, when emulation has been initiated, as a bi-directional serial communications pin.

The emulation request controller is also responsive to a single step flag 42 which ensures that an emulation request occurs after execution of a single instruction of the user programme code. Preferably, the emulation controller 32 is responsive to a break point instruction 43 whose occurrence in the user code causes the emulation controller 32 to issue an emulation request.

As shown in FIG. 5, a break point instruction decoder 50 is provided to specifically handle the occurrence of the additional single byte emulation instruction (break point instruction) contained within user programme memory 52, which may be external memory or, more likely, internal memory area 28. Additionally, a special register EMU2 53 is provided to hold the instruction which was overwritten by the emulation request instruction thereby ensuring that the addresses of the remaining programme code are unaltered. As shown in FIG. 5, the processing core 54 (also known as an arithmetic logic unit ALU) has a dedicated set of reserved registers 56, EMUCON, EMU1 and EMU2, for using during emulation. The reserved register set may also include an alternative stack and/or programme counter for use during emulation.

FIG. 8 illustrates the emulation control register, EMUCON, provided within a data processor including an embedded software controlled emulator. Workings from the left to right, the first three bits of the register form a control word which causes internal timers and clocks of the data

processor to be disabled if the correct code, in this example 101, is written into these bits of this function register. This enables the emulator to halt internal timers and interrupts when executing an emulation function. The fourth bit is an emulation enable bit, EE, which is placed in the enable condition by default and enables emulation to be started when an appropriate emulation request is received by the emulation request controller. The fifth bit enables execution of the contents of the special function register EMU2. When an emulation routine is started by the occurrence of the emulation break point in the user programme code, this EES register is inspected in order to determine whether the break point instruction should actually be executed. If the contents of this register are not set, then the emulation will be performed. When the emulation routine is completed, the address pointer points to the address of the break point. As mentioned earlier, the original instruction which was overwritten by the break point is loaded into the EMU2 special function register and the bit EES is cleared. As the emulation programme returns control to user code, it sets the EES bit. The address programme counter will return control at the address of the break point instruction. However, this time the EES bit is set and instead of re-executing the emulation routine, the processing core of the data processor is caused to execute the instruction held in the EMU2 special function register. The EES bit is then toggled once the instruction in the EMU2 register is executed, thereby ensuring that the next occurrence of the break point instruction will cause the emulation routine to be re-entered.

The sixth bit is an emulation single step, ESS bit which causes the data processor to only execute single instructions between emulator programme operations.

The final two bits EA-in and EA-out enable the status of the EA pin to be read and written to respectively.

FIGS. 6a to 6d schematically illustrate operation of the emulator in a single step code execution mode. The emulation routine takes advantage of the fact that the emulation interrupt will not respond until at least one instruction of the user code has been executed. Thus once control has been passed from the emulator to the user code, the emulator issues, via a hardware resource, a highest priority non-maskable interrupt that ensures that programme execution is immediately returned to the emulator, irrespective of what instruction was being performed.

Thus as shown in FIG. 6a, the emulation control data processor is arranged to issue an emulation request via the EA pin which causes a jump to the emulation memory. This initially allows communication between the emulation control data processor 2 and the emulator in order that new instructions can be set in the emulator, such as changing one or more of the flags in the EMUCON register, in this example, the control data processor sets the single step instruction, ESS, flag in the EMUCON register. Once the emulation control data processor has indicated that it does not wish to set any further instruction changes, control is relinquished from the emulation code and the user code is executed. However, since the EMUCON register was set with the single step enabled, and interrupt request is issued via the emulation controller 32 thereby causing control to be returned to the emulation code after a single instruction of the user code has been executed as shown in FIG. 6c. The emulation code then down loads data to the emulation control data processor 2 via the EA pin. Down loaded data may include the status of the internal registers of the data processor, but may also, depending on instructions received from the emulation control data processor, include the contents of the stack and also the contents of selected areas internal or external memory, or the contents of an internal cache.

FIG. 7 illustrates an example of an emulation request initiated via the break point instruction.

The data processor has a data processing core supporting the 8051 instruction set. The 8051 instruction set has a unused instruction code of **A5**. The **A5** instruction has been implemented as the break point instruction.

It is known to initiate a software emulation or debug by including a jump instruction to the emulation code. However there is a significant problem with this approach since the jump instruction is a 3 byte instruction and if this was inserted at address **0120**, as shown in FIG. 7 then the **inc A** and **DAA** instructions at addresses **0121** and **0122**, respectively, would be overwritten by the jump instruction. Thus it would be necessary to change the addresses of the subsequent steps in order to incorporate the addition of this jump driven emulation instruction. Secondly, in order to use this approach, the emulation memory/programme must be visible for the jump to work and consequently the incorporation of the emulation code within the data processor would limit the user's programming options. A third problem is that, if the addresses of all the remaining code was not changed, it would result in the instructions at **0121** and **0122** being lost, and also an additional break point could not be inserted at the overwritten addresses.

By adding a single byte break point instruction, only one address of programme is over written. Thus in the example in FIG. 7 only the "clear A" instruction at **0120** is overwritten by the inclusion of the software driven emulation break point instruction. However, the clear A instruction is written into the EMU2 register in order to ensure that it is executed as if the break point instruction were not there. If a break point instruction is to be written into the user code for debugging/development purposes, the emulator reads out a block of memory containing the program code containing the address of the instruction to be changed. An internal memory controller then erases the block of memory, and in co-operation with the emulation control data processor, re-programs the block of memory adding the break point instruction. The precise memory control strategies for performing the modification of internal memory within the data processor, i.e. within a single chip package, are not critical to the present invention, but a suitable memory and memory controller is described within a co-pending application filed by Analog Devices, and titled "A MEMORY AND A DATE PROCESSOR INCLUDING A MEMORY". The interface element **3** may provide a local buffer such that as the block of program code (usually two rows on the internal non-volatile reprogrammable user code memory of the data processor), is buffered in the interface element and the local data processor modifies the data to change instructions or insert the break point, and then re-presents the data to the target data processor in order that it can rewrite the data into its internal memory.

During execution of the user programme, the programme counter will eventually point to the address **0120** which has the **A5** emulation break point instruction written therein in place of the "clear A" instruction. The instruction decoder of the data processor decodes the break point instruction and causes the emulation request controller **32** to issue a priority interrupt. Thus the data processing core **54** discontinues execution of the user's programme and starts executing instructions from the emulation memory provided that the EES bit in the EMUCON register cleared. Assuming that the EES bit is cleared, the data processing core executes the emulation instructions using the reserved EMU1 register, and outputs data concerning the status of the various programme registers to the emulation data processor **2**. Once

the data has been sent to the emulation data processor, the emulation data processor toggles the EES bit and issues a command causing the emulation to continue. The emulator then returns control to the user programme. Because the break point instruction is interrupt driven, the control is returned to address **0120** which holds the **A5** break point instruction. This time the EES bit indicates that emulation should not be recommenced, but in fact that the instruction in the EMU2 register should be executed. The data processing core executes the instruction in the EMU2 register and returns control to the user programme at the address following the break point instruction.

FIG. 9 schematically illustrates a multi-target development system in which a single control data processor **2** communicates with a plurality of target data processors via a plurality of interface elements **3**, each of which contain a local data processor **100** which reduces the computational load on the control data processor by performing the communications protocols and also buffers and modified data in the target data processors in response to commands from the emulation control data processor **2**.

It is thus possible to provide a data processor having a software driven emulator embedded therein which uses dedicated registers, thereby ensuring that registers used in execution of a user's programme do not become altered once the emulation mode is commenced. It is also possible to provide a development system for use with such a micro-processor in order that the internal registers may be inspected, or blocks of memory may be inspected and analysis performed thereon. For example, a block of memory may hold values resulting from analogue to digital conversions. The values may be displayed by the emulation control data processor in order to form an oscilloscope trace of the analogue value, or additionally or alternatively may be Fourier transformed in order to perform frequency domain analysis. The emulator may be used to perform a software controlled series of Analogue to Digital conversion, and to send these to the emulator control processor which can then display a graph or trace of the converted variable. The emulator **2** may display a plurality of windows, with each displaying the status of and/or controlling the function of a respective target data processor within a multi-processor target board. Thus the operation of master and slave processors may be analysed, possibly on a single step basis, in order to check their data exchange operations and mutual performance.

The emulator has authority to modify the internal memory contents of program and data memory within the target data processor. Thus the target data processor may be re-programmed whilst it is in situ in the target board. Similarly calibration coefficients in digital or hybrid digital-analogue systems can be modified. It is also possible, when the interface element communicates using a radiative link, to leave the interface element attached to the target board permanently, thereby allowing for the target data processor to be re-programmed even after it has been installed in a working environment. The provision of an emulator as an integral part of the target data processor has the additional advantage that the board and processor being debugged/developed are identical to the final system. This contrasts with prior art emulators of the type shown in FIG. 1 whereby the data processor on the emulation pod synthesises the functions of the target data processor but in often a physically different type of processor which may have additional hardware attached thereto to simulate the ports of the target data processor.

What is claimed is:

1. A data processor including an emulator, wherein the emulator is arranged to perform bi-directional communication with an external development system via only a single terminal.
2. A data processor as claimed in claim 1, in which said single terminal is a control pin of said data processor, said pin only controlling said data processor during a predetermined operation.
3. A data processor as claimed in claim 2, in which said predetermined operation is an initialisation sequence.
4. A development system for use with a target data processor including an emulator, wherein bi-directional communication between said development system and the target data processor occurs via a serial data link utilising only a single pin of the data processor, said development system comprising a control data processor and at least on interface element each providing an interface between the control data processor and a respective target data processor.
5. A development system as claimed in claim 4, in which said at least one interface element provides electrical isolation between the target data processor and the control data processor.
6. A development system as claimed in claim 4, in which the at least one interface element contains means for causing a transition on the data link in order to cause the target data processor to enter an emulation mode.
7. A development system as claimed in claim 6, in which said transition causing means is controllable to transmit instructions to the target data processor.
8. A development system as claimed in claim 4, further comprising a plurality of interface elements, wherein each interface element is individually addressable by the control data processor.
9. A development system as claimed in claim 4, wherein bi-directional communication between the at least one interface element and the control data processor is via a radiative data link.
10. A development system as claimed in claim 9, in which the radiative data link is an infra-red data link.
11. A development system as claimed in claim 4, wherein the status and register contents of the registers of the target data processor used for program code execution are retrieved and stored during emulation.
12. A development system as claimed in claim 11, wherein the status and register contents of the target data processor are returned to the target data processor before recommencing execution of a user program.
13. A development system as claimed in claim 11, wherein the status and register contents of the target data processor are stored in an associated interface element.
14. A development system as claimed in claim 4, wherein the development system is arranged to read a block of program code from an area of EEPROM within the data processor, to modify the program code and to re-present the modified code to the EEPROM of the target data processor.
15. A development system as claimed in claim 14, in which the program code is modified by the insertion of a break point instruction at a chosen location so as to overwrite an instruction in the program code without changing the length of the program code.

16. A development system as claimed in claim 4, in which the interface element automatically detects the data transmission rate of an associated target data processor operating in an emulation mode.
17. A development system as claimed in claim 4, in which the interface element performs handshaking and data exchange with the target data processor.
18. A development system as claimed in claim 4, in which the interface element performs handshaking and data exchange with the control data processor.
19. A development system as claimed in claim 4, in which the interface element moves control and data information between the target and control data processors.
20. A development system as claimed in claim 4, in which the interface element communicates with the target data processor via a serial communications link.
21. A development system as claimed in claim 4, and arranged to communicate with a target data processor such that a program code stored in an EEPROM of the target data processor can be programmed in situ.
22. A development system as claimed in claim 4, in which the development system can modify programme instructions stored in an EEPROM within the target data processor and also modify data.
23. A development system as claimed in claim 22, wherein said data includes calibration coefficients.
24. A development system as claimed in claim 4, wherein the development system interfaces simultaneously with a plurality of target data processors.
25. A development system as claimed in claim 4, wherein the development system is arranged to retrieve data from at least one target data processor and display the data in a graphical form.
26. A development system as claimed in claim 25, where in graphical form is an oscilloscope trace.
27. A development system as claimed in claim 4, wherein the development system is arranged to retrieve data from the at least one target data processor and to perform frequency domain analysis of the data said target data processor being a production version of the data processor and not a special emulation version.
28. An interface member for performing serial communication with a target data processor and for communicating with an emulation control data processor, said target data processor including an emulator, wherein bi-directional communication between said development system and the data processor occurs via a serial data link utilising a only single pin of the target data processor.
29. A development system as claimed in claim 4, in which the interface member is left permanently connected to the target data processor and communicates with the control data processor via a radiative communications link.
30. An interface member as claimed in claim 28, in which the interface member includes local memory such that the interface member can read a block of program code from EEPROM of the target data processor, modify the contents of the block of program code and rewrite it to the target data processor.

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