Distributed Digital Control of a Robot Arm

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Abstract

Most robot arms use a central control box that contains the power electronics, the motor controllers and the coordinating computer. This paper presents a distributed control network that allows the power electronics and motor controllers to be placed adjacent to the motors. Each controller uses a DSP for all motor control, with the individual controllers communicating with each other and a host computer using a Controller Area Network (CAN). The design eliminates the bulky multi-core cable that is a major source of downtime for robots such as the PUMA 560, while improving controller bandwidth and facilitating greater software control of motor response.

1 Introduction

This paper describes the design of a distributed digital control system in a PUMA 560 six DOF robot arm. The control system presented consists of a controller for each joint networked together with a PC which provides the user interface. Each controller contains a TMS320F241 DSP operating a full bridge power stage to control the voltage applied to the DC motor on each joint, based on position, velocity and armature current measurements. The individual controllers are located physically close to the motor they are controlling, enormously simplifying the wiring harness of the robot down to a pair of power and network cables. Additionally, the abilities of modern DSP devices allow greater capability and flexibility in the control system design.

1.1 PUMA 560 Robot

The PUMA 560 robot arm continues to be used in industrial situations for assembly operations and material handling as it has since 1979. Each joint is driven by a 40V brushed DC motor, with the motors for the bottom three joints rated at around 160W and the motors in the wrist rated at around 80W. Each of the first three joints (JT1: waist, JT2: shoulder, JT3: elbow) are also equipped with a 24V electromagnetic brake which is required to be energised (released) before that joint can operate. These brakes stop the arm collapsing or swinging when the power is removed. All joints are also fitted, on the motor, with 250 line count sin-cos encoders giving position feedback to the controller.

The PUMA 560 has an analog / digital hybrid control system, contained in a large racking box along with a terminal system for operator control and programming of the robot. The motor and brake control signals to the robot arm, and the encoder and potentiometer signals coming back from it, are transmitted along an 80 core, 5 metre wiring bundle. The control system consisted of an analog and a digital control board for each joint. These boards, along with others to supply power, interface to the terminal, and interface to the robot arm, were connected via a custom backplane inside the electronics box. Also housed inside the box were the linear power amplifiers to run the motors on each joint, along with the robot's power supply. Each analog board implemented the inner current loop control of the joint, and provided the signal conditioning between the sin-cos encoders and the digital board. The digital board controlled the outer position loop for the joint, taking its position target commands from the coordinating computer every 28ms. The controller on each joint runs a PD control loop at approximately 1 kHz.

These components have remained fairly consistent over the past twenty years, and although the physical volume of the off-board control box been reduced, the bulky, expensive and unreliable cable remains. The cable is an artifact of a centralised control system. To remove it, a distributed control methodology must be adopted.

1.2 Distributed Control Systems

Research into the area of distributed control systems has largely centred on the networking of 'dumb' sensors and remote input / output modules with a central master controller (such as described in [1]). The inclusion of this type of system into robotic control has only been a recent development, and has not been included into the robot itself. Bezi and Tevesz outline a system developed for control of a PUMA 560 robot arm that uses a i486 master PC to control, via an Ethernet network, six i386 based joint controllers, which controlled a joint each through a servo amplifier, and received the encoder data through I/O cards inside each PC [2]. This system does not eliminate the large, unreliable cable to the robot, and its only development is the change from a backplane to the Ethernet network.

Some more recent work has been done with implementing distributed motor control systems with Digital Signal Processors (DSP). Overmars and Toncich used two networked low power TMS320E14 DSPs (6.4

MIPS), to calculate the response in the PID control loops to run two DC motors [3]. Their application was for use in CNC milling machines, and the network between joints was limited both in speed (115kb/s) and distance (40m).

1.3 Enabling Technologies

The CAN bus is a highly reliable standard developed by Robert Bosch GmbH for use in the automotive environment [4]. It is a multi-master system, with sophisticated error checking and arbitration, so that any high priority message will always get through first without corruption by other messages. All data contained in each packet (up to eight bytes) is also checked with a Cyclic Redundancy Check (CRC) error checking scheme, that can correct up to five random errors, and will be automatically retransmitted if not correct. The error checking capabilities make an extremely reliable and robust network: CAN operating at 500 kbit/sec over standard networking twisted pair cable, at 60% capacity for eight hours per day, 365 days per year, has a of an undetected fault of one bit error per thousand years [5]. The network operates at up to 1 Mbit/sec at up to 30m, or up to a distance of 5km at 10 kbit/sec. The CAN protocol uses an 11 bit node identifier, allowing 2048 joint controllers to be on the network at once.

Recent improvements in DSP technology have revolutionised the field of embedded motor control. DSPs allow high speed execution of common control schemes such as PID control, and have the processing power to implement more advanced control techniques. Several DSPs have just been released from Analog Devices and Texas Instruments which are designed to perform digital motor control. They are with on-board peripherals such as high speed, multi channel A/D converters, multiple PWM output channels, flexible timers, quadrature encoder inputs, many external interrupts, and network interfaces (CAN, SCI, SPI). For example, the TMS320F241 from Texas Instruments [6], operates at 20MHz, and can read the A/D converter, calculating a PID control law, current limit, and generate the required PWM output, in under 10 µs.

1.4 Desired Benefits

This high speed operation is very important to the tracking accuracy possible with the control system. Tarn et.al [7], [8] describes the effect of four different control algorithms on the accuracy of a PUMA 560 tracking a circular path. While operating with a PD control loop, the maximum position error (while tracking) was 10mm when sampling at 100 Hz, but had dropped to 2mm at 500 Hz. The potential for an accurate control system using the TMS320F241 is very good, with a sampling rate of 20 kHz readily obtainable. Tarn states that:

> "… the tracking performance is highly sensitive to feedback gains. Higher gains can only be used a higher sampling frequencies. Thus a high sampling rate is imperative for good tracking performance." [8]

Since the sampling rate possible with the networked DSP based controller is orders of magnitude higher than those used in Tarn's motor controller system, the DSP should be capable of running an extremely high performance system. The other control schemes used by Tarn employed a mathematical model of the robot to compensate in advance for gravity and dynamic effects. It did not include coriolis and centripetal terms, or compensate for motor stiction or backlash. However, when running on a Silicon Graphics SGI/340 VGX machine, a servo rate of 1000Hz led to a tracking error of 0.7mm. Extrapolating the performance increases of the PD control loop to higher sampling frequencies indicates that it should be possible to obtain even better accuracy *without* using approach to the control system using a high sampling speed and high loop gains instead of model based control.

The whole concept of a model-based controller relies on the accuracy of the model. As reported by Corke and Armstrong-Helouvry [9], there is a considerable variation in the model data available for the PUMA 560. Corke states "the success of the model-based controllers may be interpreted as a demonstration of the robustness of model-based control approaches when applied to the relatively slow and rigid PUMA 560 manipulator." For example, the reported mass of link 2 (upper arm section) varies anywhere between 10.2 and 22.4 kg. The model-based controllers are usually robust enough to tolerate minor changes in the model parameters, however, such a large change as doubling the mass of the arm section would be likely to impair the performance of controller. The model-based type controllers are less stable in other ways, as Tarn [8] notes that when the third-order model control system was modified (to increase the performance) by increasing the position and velocity feedback gains, the model-based controller rapidly became unstable. The PD controller did not exhibit this undesirable effect until much higher gains [7].

2 Control System Hardware Design

Each joint controller system can be separated into several discrete blocks. Their interactions are shown below in Figure 1. Each of these blocks are detailed in the following subsections.

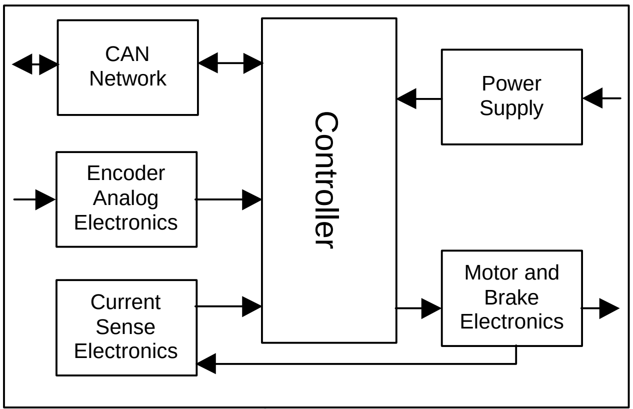

Figure 1: Block diagram of the joint controller system.

2.1 Performance Specifications

The new control system was specified with three main criteria:

- It should exceed or at least equal the performance of the old system.
- It should eliminate any complex wiring harness.
- It should be as simple, reliable and low cost as

possible, but still have the flexibility to allow for future control technique experimentation.

To be able to obtain these three specifications, the new electronics hardware must have several major differences when compared to the old system used previously. To give the required high performance motion control, and to keep the design simple, a highly integrated controller containing sufficient processing power and the required peripherals on chip is necessary. This processor needs to be able to efficiently interface to many subsystems in the robot environment. These include the motor driver, brake driver, current sensing, quadrature encoder, potentiometer input, emergency shutdown circuitry, communications, and self monitoring. To adhere to the low cost, the processor should have internal non-volatile memory, that can be reprogrammed without expensive equipment – preferably without removing the IC from the board.

To eliminate the complex wiring harness of over 80 cores in the existing robot, the control of each joint would have to be done with individual control modules, and the control modules would need to fit *inside* the robot, with each controller next to the motor/joint that it was controlling. This leads to a further requirement in the joint control modules of a high speed, highly robust network interface between joints and to the host controller.

2.2 DSP Considerations

The TMS320F24x series is a 32 bit DSP designed for motor control. The availability of the Control Area Network (CAN) module in this series, along with bootloader programmable internal Flash memory makes the device particularly attractive for this application. Furthermore the device features 8k words of internal flash memory, 8 PWM channels with deadband generation, quadrature input circuitry, an 8 channel 10 bit analog to digital converter with a conversion time of 800ns, a power drive protection external interrupt, and a 50ns instruction time.

2.3 Power Electronics

The two choices for the motor drive electronics were either a linear amplifier similar to the original PUMA output stage, or a modern design using a switchmode (Class D) power amplifier in a H-Bridge configuration. The switchmode power stage was the obvious choice for this application, as it needs only a single supply rail and it has a high efficiency of over 96%. This efficiency results in several advantages over the linear amplifier such as small size, lower cost power devices, no heatsink, and the elimination of extra analog circuitry needed for biasing and removing crossover distortion. The individual devices in the H-Bridge can be driven from separate PWM outputs of the DSP, allowing the deadband features of the PWM peripheral to be used, along with the immediate (<12ns) shutdown of these pins in the event of a fault which triggers the Power Drive Protect Interrupt (PDPInt) pin on the DSP.

A semi-discrete solution was chosen for this design. This allows the choice of low on-resistance and fast switching MOSFETs, to give maximum efficiency and best control. To switch the high side MOSFETs in the H-Bridge, a bootstrapped driver chip is required. This is because to switch an N-Channel MOSFET on, a voltage of around 8 – 12V is required on the gate, relative to the source. Since the source of the high side MOSFET could be at any voltage up to 40V, at least 48-52V is required to apply to the gate. The Harris Semiconductor HIP4081A driver has a voltage rating of 80V, giving a wide safety factor, and also very high speed switching times of 45ns for the lower device, and 60ns for the upper device. Another useful feature, not found on any other drivers, was the addition of a charge pump circuit to keep the bootstrap capacitor charged if the high side was switched on for a long time, such as running at 100% duty cycle. For the power devices, IRF520 N-Channel MOSFETS were selected, for their fast switching time of 9ns, continuous current rating of 9A, peak current of 37A, on-resistance of 0.25Ω, breakdown voltage of 100V and low cost.

The electromagnetic brakes (1.2H, 160Ω) on Joints 1,2 & 3 need 24V to operate, although a much lower voltage than this is required to hold them on. A logic level MOSFET is used to modulate the 40V from the main bus to maintain the current through the brakes. This allows an intelligent approach to give fast brake turn on (release to allow robot movement) and cooler operation, by applying 40V across the brake inductor initially, then reducing to a PWM value required to maintain the brakes in their on state, thus reducing power dissipation in the windings compared to if a constant 24V was used.

1.4 Power Supply

One important constraint for the main 40V power supply is that the kinetic energy of the robot can flow back to the voltage bus under certain conditions. This reduces dissipation in the output devices and reduces losses and general power consumption. However the bus must be able to absorb power as well as supply it. A direct mains powered supply would have destructive increases in voltage under these circumstances. Currently the solution to this problem is to use large lead-acid batteries to store regenerated energy, although this does lead to some irregularity in the 40V supply rail as it depends on the charge state of the batteries. Power for the DSP and analog electronics is derived from a 12V supply on the CAN connector.

1.5 CAN Network

The CAN controller peripheral requires minimal external hardware, using only one bus driver chip, containing the power devices to drive the network, and the receiver hardware to read data off it. The CAN network is terminated at either end with 120Ω resistors, to eliminate signal reflections in the wiring. The CAN is a multi-master bus network, with any node being able to transmit a message at any time. To eliminate collisions on the network, a combined hardware/firmware approach is used. The bus is capable of two states: recessive, in which both CAN-H and CAN-L lines are pulled via resistors to 2.5V; and dominant, where CAN-H is driven to 5V, and CAN-L is driven to ground. So this means if two or more nodes try to transmit data at the same time, a node transmitting a dominant state will read back a dominant state, whereas the nodes transmitting a recessive will read back with an error. If two or more bus nodes start their transmission at the very same time after having found the bus to be idle, collision of the messages is avoided by each node monitoring each bit of its unique identifier for errors. Devices detecting a collision (with a non-dominant bit) will drop out.

1.6 Sensor Interfaces

Current sensing is performed in the three base joints by a 0.066Ω resistance in each leg of the H-Bridge; while the wrist motors have a 0.096Ω resistance; each is made up of two 1W resistors in series. The voltage from these sense resistors is amplified by differential amplifiers and measured by the ADC. Current is also checked against a screwdriver adjustable hard limit that is used to trigger the Power Drive Protect interrupt.

The position feedback from the sin-cos encoders provides a count on every edge of both quadrature channels. This provides 1000 counts per motor revolution from the standard 250 line count encoder wheels. Ambitiously, each channel is also interfaced to the DSP's ADC, providing a theoretical 3 micron accuracy at the tool point. While this accuracy is unlikely to be realisable, the extra position sensing ability may prove of benefit in fine motor control.

In addition, the DSP can measure the bus voltage, the position potentiometer sensor, and the temperature of the MOSFETs.

3 Control System Software Design

The software for the DSP on each joint controller has to perform many tasks at high speed. The major functions of the controller are performed in the operation of the joint position control loop, with only the host communications section operating outside this loop. The communications section receives new commands and passes fault and diagnostic information to the host and the other joints. The whole controller is interrupt driven, with most of the execution time spent in a null loop. The different interrupt service routines (ISRs) do the actual work of the controller, and described in the following sections.

3.1 CAN Software

The communications ISR in each DSP is triggered on receiving a packet addressed either to the specific joint or an overall (broadcast) address. As described previously, messages on the CAN bus will be transmitted in order of priority, with the highest priority having the lowest message address value. The robot communications network is configured with Address 0 as a broadcast address, which all joints and the host controller will receive in their second receive mailbox. These data frames are reserved for urgent robot-wide messages such as a request for immediate joint shutdown. Address 1 corresponds to messages specifically for Joint 1, up to address 6 for JT6. This is arranged so that commands to the joints with the largest ranges of movement (and therefore the most dangerous in the event of a delayed packet) will always get through first. Address 7 is for joint to host communication, with the DSP attached to the host PC via its RS-232 serial port listening for data frames with this address.

The advantage of the multi master network configuration is readily apparent in the event of a joint suffering a major fault such as a hardware overcurrent trip or a low (or non-existent) bus voltage. The joint does not have to wait to send a message to the host and then wait for the host to broadcast to the other joints, it can immediately broadcast the message to the other joints *and* the host. This way, the other robot joints will have already begun to shutdown and come to a safe halt by the time the host interface is aware of the problem. Since it is a priority 0 message, it will get transmitted as soon as the current transmission on the network is finished – in the worst case time it will be approximately 0.2ms before each joint begins shutdown.

When each joint controller receives a data frame which is addressed to it specifically, it will contain the full 8 bytes of data possible in the packet. The first word is used for defining the command to the joint. Although a whole word is not necessary to define the messages, it makes the subsequent coding much easier, and ensures that the network will run satisfactorily at the slowest data rate possible. The individual joint controllers can also send status information to the host controller (address 7) of their own accord. The first byte contains the address of the joint sending the packet. The second contains the message type number, and the rest of the data frame contains any more relevant information, depending on the message.

3.2 Control Loop

The CAN packets deliver commands from the host to the controller as desired joint angles along with maximum velocity and acceleration for the move. The host may also specify other parameters such as the maximum current permissible during a move. This primitive scheme has been implemented as a starting point for the progressive development of the arm software.

A 20 kHz timer ISR implements the main functionality of the joint controller. The controller generates a trapezoidal velocity profile to move from the current position to the desired position. The desired velocity is compared to the setpoint velocity from the profile generator, and compensated using a PI controller. Once the profile has been completed, the control loop runs a PI compensator based on the position rather than the velocity. This serves to further reduce steady state error at the path endpoints, and increases tolerance to disturbance forces.

Whenever a desired PWM is calculated, it is checked against the 'soft' over-current limit. If there was a higher motor current than the limit last PWM cycle, it reduces the calculated PWM by a proportional amount, K_{oc}, to limit the motor current on the next cycle.

3.3 Safety

As soon as the overcurrent detection circuitry triggers the active low PDPINT pin, the six full compare outputs change to a high impedance state. A selection of pull up and pull down resistors brings each line to the appropriate inactive level. In the software, the next interrupt scheduled is the PDP ISR – the only higher priority interrupt is the Reset signal or the NMI (Non Maskable Interrupt). The PDP ISR broadcasts a message on CAN address 0 to all joints and the host to begin an immediate shutdown sequence. The program halts at this point and will not restart until a complete system reset is performed by cycling the power to the robot.

The NMI routine is triggered if the DSP tries to access an illegal address location or tries to execute an illegal opcode. It immediately shuts down the PWM outputs and broadcasts a message on address 0 of the CAN network. The response of the rest of the robot to this message is the same as to the PDP ISR message – immediate shutdown.

4 Results

Preliminary testing of the arm has been used to evaluate the system response of some of the joints. The velocity control loop and profiler described above has been implemented on joints 1, 2 and 3.

4.1 Open Loop Response

Several measurements of system response to a step input have been measured with the new hardware. Naturally the step response of the joints will vary depending on the arm configuration. Figure 2 shows a sample response from a 7V step input to the motor of joint 3 (the elbow). The elbow was configured vertically upwards so that the response would be minimally assisted by gravity.

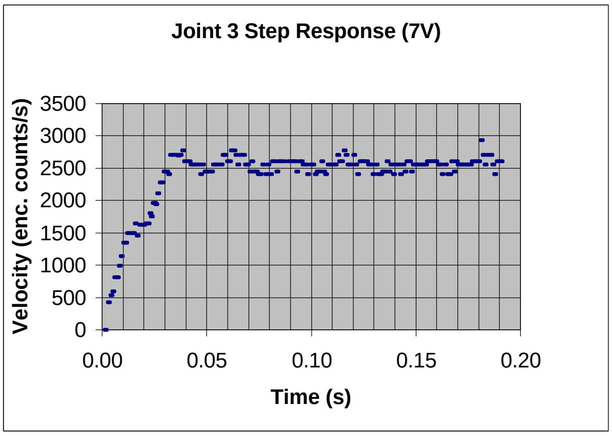

Figure 2: The step response of joint 3 from a vertical position using a 7V input.

Table 1 summarises the first order approximations made of the voltage to velocity transfer function for joints 1 and 3 three joints in various configurations. In all cases, non-activated joints had their brakes locked. Further results are presently being gathered to better characterise the system.

Joint	Configuration	DC Gain (RPM/V)	τ (ms)
1	2 & 3 vertical	0.48	24.3
1	2 & 3 horizontal	0.48	48.5
2	2 & 3 horizontal, up	0.47	49.1
2	2 & 3 horizontal, down	0.78	51.2
3	2 & 3 vertical	2.23	19.2

Table 1: First order approximation results for a step input to some of the joints.

4.2 Velocity Control

The velocity controller outlined in section 3.2 has only been recently completed. Quantitative data is yet to be gathered to show the tracking capabilities, the accuracy and resistance to disturbance of the control system. The controller has been implemented on the first three joints with hand chosen PI values for both position and velocity control. Qualitatively, the arm is able to move swiftly from set-point to set-point and readily holds the set-point angle against disturbances. The effect of the soft current limit can be felt in testing of disturbance response. When the current limit is kept low, the robot becomes torque limited in its response and exhibits a degree of compliance in its movement.

5 Discussion

From initial testing performed on the entire robot as a system, the new type of controller has the capacity to exceed the performance of the original system in accuracy, speed, efficiency and reliability. Also, with the major reduction in the complexity of the wiring harness, and with the new compact, efficient electronics, the overall system cost is substantially cheaper than the old system, both to construct and operate.

The cost for components, connectors, printed circuit board, and DSP for each joint controller is under $180. The cost of the wiring harness is negligible, at approximately $10. The total prototype system cost was $1200 in parts on a “one-off” basis. The labour of wiring the old complex harness has been saved, and the new boards are simple to construct, resulting in a substantial saving in manufacturing time compared to the original system.

Another feature of the new system is that it is cheaper to operate than the old controller. There are no cooling fans or other moving parts to wear, and the power drive electronics are highly efficient, at approximately 96 percent. The linear amplifiers (Class A-B) used in the old system have a maximum theoretical efficiency of 78 percent, but are probably substantially lower (<70%) due to the inductive nature of the motor and brake loads. For a robot working continuously at 500W - approximately 75% of maximum power - this efficiency gain results in a reduction in load of about 195W. Over a year of operation, this will save over 1200 kWh of electricity.

With a small amount of control system development, and a better user interface, this control system has the potential for widespread use in the industrial robotic environment. The nature of the CAN bus used does not limit the use of the robot in large installations, because in expanded mode, over 536 million different nodes can be addressed on the network. Also, the workload on the host controller is very low, consisting only of transmitting position commands to the joints. Many robots could be run from the one host, resulting in another substantial cost and complexity reduction.

6 Conclusions and Future Work

The first stage of this project was entirely successful in its aim of producing the hardware for a modern distributed control system for the PUMA 560 industrial robot. More work is needed on the software before the robot is complete and the full extent of the new electronic design can be tested.

Currently work is under way to develop improved control strategies for the robot allowing trade-off between position, velocity tracking and force control. In parallel, a portable robot programming environment is being developed that can take advantage of the capabilities of the distributed control system. With these modules in place, the robot will used to explore new application domains for the PUMA 560.

References

[1] Parkin, R, *Distributed control systems within a mechatronic environment*, Mechatronics. The Basis for New Industrial Development. 1994; 825 pp. p.521-6, Comput. Mech. Publications, Southampton, UK.

[2] Bezi, I, Tevesz, G, *PC Based Robot Controller for Advanced Control Algorithm*s, Mechatronics. The Basis for New Industrial Development. 1994; 825 pp. p.743-8, Comput. Mech. Publications, Southampton, UK.

[3] Overmars, A.H, Toncich, D.J, *Application of DSP Technology to Closed-position-loop Servo Drive System*s, Int J Adv Manuf Technol, 11:p27-33, 1996.

[4] ISO 11898 (1993): Road vehicles - Interchange of digital information –Controller area network (CAN) for high-speed communication.

[5] CAN in Automation Working Group, *CAN Data Link Layer*, http://www.can-cia.de/ , 1999

[6] Irfan Ahmed, DSP Products Group, Texas Instruments, *Implementation of PID and Deadbeat controllers with the TMS320 Famil*y, Texas Instruments Literature SPRA083, 1997.

[7] Tarn, T.J., et.al., *Effect of Motor Dynamics on Nonlinear Feedback Robot Arm Control,* IEEE Transactions on Robotics and Automation, Vol 7. No. 1, February 1991.

[8] Tarn, T.J. et.al, *Performance Comparison of Four Manipulator Servo Schemes,* IEEE Control Systems Journal, 1993.

[9] Corke P.I., Armstrong-Helouvry B, *A Meta-study of PUMA 560 Dynamics: A critical appraisal of literature data,* Robotica,