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Reconfigurable Mechatronic Robotic Plug-and-Play Controller

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1. Introduction

In today's manufacturing community, flexible manufacturing systems (FMS) are becoming important. There is a global trend towards flexible manufacturing systems with an increasing number of countries competing for a share of the world market. FMS are increasingly required for companies to meet the demand for high quality, reasonably priced products. FMS allow a manufacturer to quickly change processes or operations to produce any product, at any time, while striving to keep the processes economical.

To remain competitive companies should be replacing or upgrading old, obsolete methods, processes, and systems with the latest advances in manufacturing technology. This competition within the manufacturing industry has led to a focus on producing high quality parts quickly and accurately. The quality of products, along with the increased productivity necessary to compete globally, has led more and more manufacturers to introduce advanced manufacturing technologies in their factories. In order for these advanced manufacturing technologies to be accepted by manufacturing companies, they need to be able to implement the new technologies and their processes as quickly as possible so as to keep manufacturing down-time to a minimum. This allows the manufacturer to respond quickly and with increased flexibility to market needs. Such is the need for FMS.

Important to FMS is computer-based technology. Since the advent of the microprocessor, computer-based technologies have made it possible to improve productivity, reduce manufacturing costs, and produce better, uniform quality goods. Manufacturers who introduce computer-based technologies into their manufacturing environment are able to increase their productivity and in turn increase their market share.

Many manufacturers have made the change over to either completely or partially automated systems and processes. The development of the microprocessor has seen the use of robots increase in many applications. FMS generally consist of a number of automated machine tools and materials-handling systems. These systems are flexible enough to reconfigure their elements or processes in order to produce a product. Robotics finds itself to be an important part of FMS due to the flexibility of robotic arms (Krar & Arthur, 2003).

The past few decades has seen a large increase of automated machines in the manufacturing environment. It is therefore important to know exactly what a robot is, and what makes it different from other automated machines, as robots come in many shapes and sizes. The word robot comes from the Czech word "robota" meaning work, servitude

or forced labour. The most widely accepted definition of a robot was given by the Robotic Institute of America in 1979:

"A robot is a reprogrammable, multifunctional manipulator designed to move materials, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks."

George C. Devol designed the first programmable robot in 1954. Its first use in a manufacturing industry was in the General Motors plant, in which its function was to extract heated die-castings from die-casting machines and to perform spot welding on car bodies (Robotics Research Group, 2003). Since this first application of robot arms in the American automotive industry, robot arms have improved tremendously and found many more applications. Most modern industrial robot arms are capable of various types of materials handling, manufacturing processes, assembly, sealing and painting. Robot applications are now also found in science, research, engineering, and medicine.

Today, there are many companies manufacturing industrial robot arms. A problem that has arisen from the many available robot arms is a lack of standardisation. There is little or no interoperability between different manufacturers' systems and between the different generations of automated machinery. Most robots and other systems are custom built and difficult and expensive to upgrade. The main disadvantage of robots is therefore that a dedicated controller is required to control the robots actuating systems. This proves costly and usually makes interfacing with the robot complex due to hardware and software conflicts. It also reduces the flexibility of the machine.

Robotics is an interdisciplinary field that ranges in scope from the design of mechanical and electrical components to sensor technology, computer systems and artificial intelligence (Fu et al., 1984). Mechatronics brings together the disciplines of mechanical engineering, electrical and electronics, information technology and software engineering. It involves knowledge of technologies such as sensor and measurement systems, drive and actuation systems, analysis of system behaviour, control systems, and microprocessors (Bolton, 1999). Mechatronics, therefore, encompasses all the areas and skills needed in the field of robotics.

One aspect of mechatronics research is the ability to look for modular, low cost solutions for the control and flexibility of systems. This is an area in which mechatronics is able to aid the field of robotics by an investigation into an adaptive modular robot actuating system. This becomes a logical solution to the problem of interfacing automated machinery at a computer-based level, and is referred to as Computer Integrated Manufacturing (CIM). At the PC level, "plug-and-play" has become the benchmark for devices, allowing ease of use and increased flexibility. Upgrades have simply become a matter of updating software. Another benefit of a modular actuating system is that it becomes easier and quicker to replace parts than to get them repaired. This reduces manufacturing down time. Instead of a manufacturing companies going out and buying a whole new robot system, they may be able to salvage old robot arms that have been out of service simply because they are too expensive to repair.

2. Background

2.1 A Brief History of Robotics

During the decade of the 1960s, one of the most important advances in technology that has aided robotics occurred. The first integrated circuits, combining multiple transistors and other components within a single chip, started to appear. Development of electronic

technologies continued throughout the decade (Bradley et al., 2000). The 1970s saw a boom in robot designs mainly due to the increased development of integrated circuit technology. Large scale integration (LSI) was allowing 10,000 components onto a square centimetre of chip. This led to the introduction of the first 8-bit microprocessor. Before this, robots were reprogrammable but blind, deaf, and had no logic. Robot developers were now able to get their robots to perform more difficult tasks such as welding and assembly processes. In 1978, Unimation launched the PUMA which stood for Programmable Universal Machine for Assembly.

The 1980s saw a second generation of robots that had sensing capabilities. This was due to further advances in microchip technology. Intel introduced the 32-bit microprocessor in 1980. In 1981, IBM introduced the first personal computer. Dedicated microprocessors began to be used to control the operation of an increasing range of systems (Bradley et al., 2000).

The 90s built on the advances in electronics and other technologies. Robots were given mobility and autonomy. They were able to make intelligent decisions on their own. Electronics and processing power has led to the development of application specific integrated circuits (ASIC). This has allowed the development of robots that have intelligence and, as a result, have increased the performance and reduced costs of manufacturing (Bradley et al., 2000).

Robotic design has simplified the automation of complex manufacturing processes. There are now many more applications of robots outside the manufacturing industry. Senses such as sight, touch, and hearing have been added to allow robots to perform more complicated and sensitive tasks. With these advances in the state of modern technology, robots now have many applications in science, engineering, space, and medicine.

2.2 PUMA 560 Robot

As a workhorse of the robotic industry, it is useful to have a good knowledge of the original PUMA 560 series robot arm. In the original PUMA 560, each joint is driven by a 40V brushed permanent magnet 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 (waist, shoulder, elbow) are also equipped with a 24V electromagnetic brake which must be released before that joint can operate. These brakes stop the arm from collapsing when the power is removed. All the joint motors were fitted with 250 line sin-cos incremental encoders giving position feedback to the controller.

The controller consisted of a DEC LSI-11/02 computer, and six joint controllers that consisted of a Rockwell 6503 microprocessor, a digital-to-analog converter (DAC), and a current amplifier. The DEC LSI-11/02 computer was used to compute the setpoints that made up the desired robot joint level position. The setpoint was updated by the LSI-11/2 every 28ms. Each update cycle, new setpoints for each joint are transferred from the LSI-11/2 to one of the six Rockwell 6503 microprocessors. The microprocessor received and acknowledged the new setpoint and performed interpolation between the current setpoint value and the new one. This was the computed joint error. Every 0.875ms the microprocessor would read the incremental encoder and then update the error. The error-actuating signal would be converted to a current signal using the DAC, and the resulting current would then be sent to the amplifier to move the joint (Fu et al., 1984).

This control scheme is essentially a PID control loop. One of the main disadvantages of this type of control, as will be noted later on in the discussion section, is that the feedback gains are constant and pre-specified. The feedback gains cannot be updated for varying

payloads. Since inertial loading and the effects of gravity dependant on the position or velocity of the robot arm, the simple PID control scheme does not perform very well (Fu et al., 1984).

The original control system was 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, were transmitted along an 80 core, 5-metre umbilical cable.

The PUMA 560 series robot that was donated for the project came with the entire arm intact. The robot was a six-axis revolute robot arm. It had a complete wiring loom and the 80 core umbilical cable with connectors. However, there was no power supply for the motors, no information as to the workings of the encoder circuits on the motors, and no controller hardware. These essential parts of the project required investigation and development before the control hardware was to be implemented.

3. Hardware Development

From the specifications of the PUMA 560 robot, it was found that a 40V DC power supply was needed to power the motors. The motors were also equipped with 24V electromagnetic brakes, so a 24V DC supply was needed. A 5V logic supply was also necessary to power all the encoder circuits on the motors and the microprocessors used.

3.1 Full-Wave Power Supply

Electrical power in New Zealand is distributed as 50Hz AC with a nominal voltage of 230Vrms. Transformers are used to obtain any other AC voltage. Two circuit diagrams of a full-wave power supplies are shown in the Figure 3.1. Only the secondary coils of the transformers are shown.

(a) Simple full-wave power supply.   (b) Bridge rectifier full-wave power supply
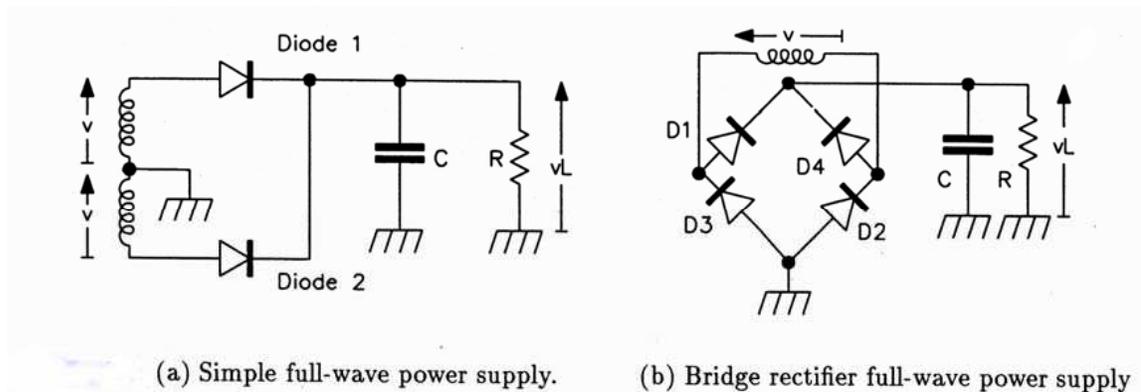
Figure 3.1 Full-Wave Power Supply Circuits (Bold, 2000)

Figure 3.1(a) uses a transformer with a centre-tap that is connected to ground. The other ends of the secondary coil are each connected to a rectifying diode. Both halves of the secondary coil winding have the same voltage across them, but they are opposite in polarity. When the top of the transformer is positive, diode1 conducts to charge the capacitor. When the bottom end of the transformer is positive, diode 2 conducts and also charges the capacitor. Diode 2 can be thought as inverting the negative goes portion of the AC output voltage of the transformer.
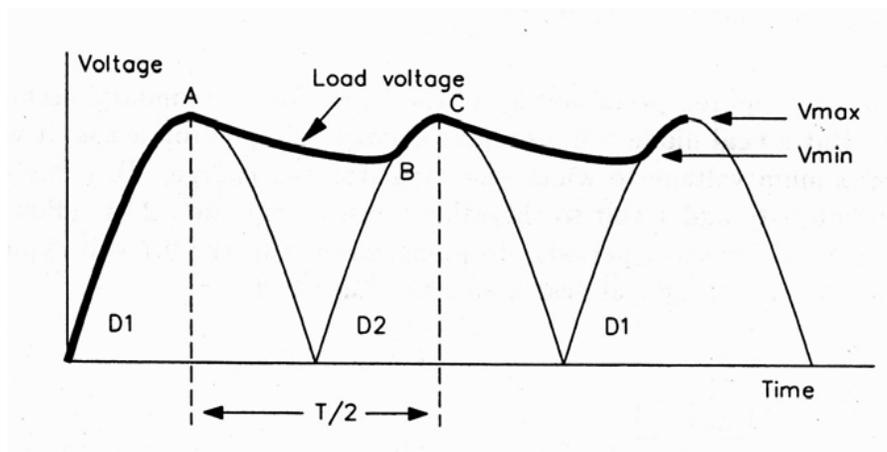
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Figure 3.2 Waveforms observed with full-wave power supplies (Bold, 2000).

Figure 3.2 shows the resulting waveform created by the circuit. Diodes 1 and 2 are active in the portions of the cycles label D1 and D2 and conduct alternately. If the capacitor is initially uncharged and the input voltage goes positive, the capacitor charges up to the peak positive voltage at point A. The transformer drives current into both the load and the capacitor. When the transformer voltage falls below the peak voltage, the capacitor begins to discharge through the load giving the portion of the waveform from A to B. The load voltage falls until point B where it intersects the rising of the waveform again. At this point the capacitor charges again and so the cycle repeats. The voltage drop between point A and point B is known as the ripple voltage. Using a larger rated capacitor can smooth this ripple.

The following equations show how the capacitor and transformer voltage can be calculated.

$$C \approx \frac{I_{DC}}{2 V_R f}$$ (3.1)

$$V_{rms} = \frac{V_{DC} + \frac{V_R}{2} + 1}{\sqrt{2}}$$ (3.2)

Where C is the capacitor value and Vrms is the voltage required from each transformer winding. VR is the ripple voltage, f is the frequency of the waveform (50Hz), and VDC is the required DC voltage. The one added to equation (3.2) is to compensate for the small voltage drop that occurs across the diodes when they each conduct. Generally this drop is 0.7V for most power supply diodes (Bold, 2000).

Figure 3.1(b) shows the more common bridge rectifier circuit. The secondary voltage is shown in the upper part of the circuit diagram. This circuit does not require a transformer with a centre-tap (which are more expensive). When the transformer secondary voltage is positive to the left, diodes D1 and D2 conduct and charge the capacitor. When the transformer voltage polarity reverses, diodes D3 and D4 conduct using the other half of the AC voltage input waveform. The analysis of the circuit is the same as the first, except that two diodes conduct at once. This means that equation (3.2) needs a two diode drops subtracted from the secondary transformer voltage. This is done by increasing the voltage output from the transformer by two. The new equation becomes:

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$$V_{rms} = \frac{V_{DC} + \frac{V_R}{2} + 1}{\sqrt{2}} \qquad (3.3)$$

To construct the power supply for the PUMA robot required the purchase of a transformer. In the electrical industry transformers are specified by their VA rating. The VA rating is the product of the voltage required on the secondary coil and the current required for the application. An assumption was made about the amount current required for the power supply base on the equation for power and the power rating of the motors. The calculation was as follows:

$$P = VI = I^2 R = \frac{V^2}{R} \qquad (3.4)$$

$$P_{Motor} = 40V \times I$$

$$I = \frac{P_{motor}}{40V} \qquad (3.5)$$

The maximum current necessary for the power supply becomes the sum of currents if all the six motors are going. For the larger 160W motors the current that is drawn at 40V is 4Amp and from the small 80W motors it is 2Amp. This results in a sum of 18Amp for the case where all the motors are drawing their maximum. So for the transformer it was decided to go with the secondary coil rated at 20Amps.

Now the ripple voltage needed to be found so as to work out the equation for the transformer output voltage. The capacitor that was used for the power supply was a 43,000mF electrolytic capacitor, which was salvage from a prevent power supply application. Equation (3.1) is arranged like:

$$C \approx \frac{I_{DC}}{2V_R f}$$

$$V_R = \frac{I_{DC}}{2Cf}$$

$$V_R = \frac{20}{2(43,000 \times 10^{-3})(50)}$$

$$V_R = 4.7 \times 10^{-3} \, V$$

This gives a very small ripple voltage of only 4.7mV and shows that the capacitor does a very good job at smoothing the power supplied.

To work out the AC output voltage of the transformer, equation (3.3) could now be applied.

$$V_{rms} = \frac{V_{DC} + \frac{V_R}{2} + 1}{\sqrt{2}}$$

$$V_{rms} = \frac{40V + \frac{4.7 \times 10^{-3}}{2} + 1}{\sqrt{2}}$$

$$V_{rms} = 29.0V$$

It was found out that in the electrical industry, 230V to 32V transformers are a common standard. So the calculation was reworked to find out how much DC voltage this would supply to the motors. The result was a voltage of approximately 44V DC, which was within the limit of the motors. Thus a transformer with a VA rating of 640 (32V×20A) was ordered.

3.2 Switch Mode Power Supply

The logic power for the encoder circuits and the microprocessors was provided using a computer ATX switch mode power supply unit. These are very cheap (if not free) and can be taken from any old PC just as this one was. This gives a very convenient logic supply as it provides a +5V, -5V, +12V, and –12V. The potential difference between the +12V and –12V rails also supplies the 24V necessary to switch the electromagnetic brakes of the three larger motors.

Four switches were required for test purposes. One was to turn on the 40V DC supply, one to turn on/off the brakes, and also one to turn on the logic supply. Finally, a high-power switch for the emergency stop, which cuts power supplied to the entire system.

3.3 Motors, Encoders, and Potentiometers

The motor, encoder, and potentiometer assembly of each joint did not come with any wiring or circuit diagram. External diagnostic testing of the circuits was not possible as the encoder circuit is very sensitive to incorrect polarity. The assembly was disassembled so as to gain a better understanding of the wiring and physical layout of the assembly. Table 2 lists the wires coming off the motor, encoder, and potentiometer assembly, their colour and corresponding functions.

Wire Number	Wire Colour	Function
1	Violet	+Vpower
2	White	-Vpower
3	Orange	-EncA
4	Green	+EncA
5	Yellow	+EncB
6	Light Blue	-EncB
7	Green	Index
8	Red	+5V encoder/pot
9	Dark Blue	+Vbrake release
10	Gray	Brake return
11	Black	0V ecoder/pot
12	Green/White	Vpot

Table 2. Motor Assembly Wiring

One of the major difficulties in the project had to do with the encoders. Based on an investigation into the workings of incremental encoders, a square wave output was expected from the encoder circuits. However, due to age of the encoders, only a sine wave signal was measured and this output signal was small, at only 30mV. As the sine wave was analogue, the signal required digitisation. This required an analogue-to-digital converter (DAC). However, for the microprocessor to count the encoder increments, it required digitisation into a pulse train rather than a digital representation of the analogue signal that the DAC would provide. Converting this analogue signal into a pulse train proved very time consuming.

The cost of replacing these encoders with modern industrial encoders was looked at. However, the cost of the new encoders was deemed too expensive in comparison with making up a signal conditioning circuit from discreet components. Using knowledge of electronics and signal processing, a circuit was designed. The encoders used for each motor were quadrature encoders. Two pairs of signal lines were provided but it is the differential output of a pair of signal lines that provide the encoder line information. Amplification of the signal was accomplished by using a standard LM741 operational amplifier to amplify the differential of each pair of signal lines. But the conversion of the amplified signal into a pulse train was not possible. It was not until an encoder circuit from a PUMA 560 Mark II robot was obtained, that the problem could be overcome.

On the PUMA 560 Mark II model, this problem with the encoder sine wave output was corrected by placing the circuitry within the encoder. Upon inspection, it was found that a voltage comparator IC was used to obtain the square wave output. Once a voltage comparator IC was purchased, the LM339, it did not take long to get the desired result for the analogue-to-pulse train circuit. The circuit is shown in Figure 3.3.
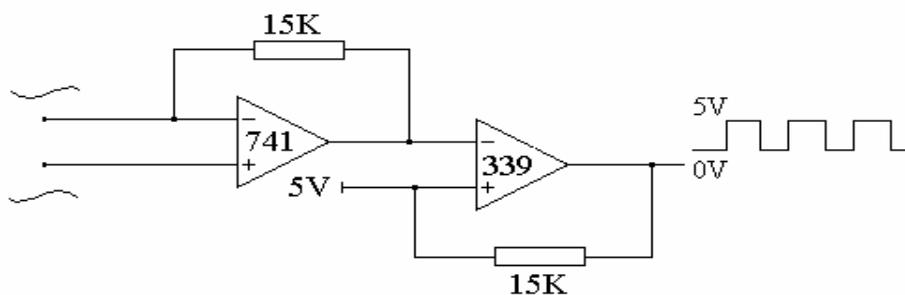

Figure 3.3 Encoder output conversion circuit

This circuit was implemented on each of the encoder lines of the six motors. Therefore twelve of these circuits needed to be made. They were all first implemented using matrix board. But because of errors in the circuit, the high density of the circuit, and other design problems, a more modular design was created using an electronic PCB design program. This design was then etched onto a PCB.

3.4 Modular Design

One of the objectives of the project was to create the system that was modular. The idea behind this was so that, when a part of the system is not working or broken, it can easily be replaced by another module. When looking at existing modular industrial systems, ie. PLCs, it was found that most use a standard 19″ racking system. Modules slide to position

and plug into the back of the rack or are daisy-chained to other modules already on the rack. For this project, the modules that slid into the rack were the control cards. The rack used was a standard 19" rack system that was donated by a lighting company.

The cards that slid into the rack used to be lighting dimmer control cards. All the lighting components were removed, except the gold terminals and PCB used to plug the card into the rack. These cards were then fitted with all the components necessary for the control of two motors. Each control card module contained a BrainStem Moto 1.0 and two Devantech MD03 H-bridge Motor Drivers. With each control card module it was therefore possible to control two motors. The BrainStem offeres several control options that make the card flexible enough to control almost any two motors rated below 50V and 20Amp. Because the BrainStems can also be daisy-chained using an I²C bus, extra control cards can be placed anywhere on the bus. All that is required is for each modules I²C bus address to be set up on the BrainStem before "plugging" the card in.

All the inputs and outputs were routed to the back of the module so that each module simply plugged into the rack. The I/O from the BrainStem was wired to the back with ribbon cable and a female DB-25 pin connector was used to plug the I/O into the rack.

The rack had several buses on the back of it. These were used for the 5V and 0V logic supply, the 40V and 0V motor power supply, and the I²C bus. The rack was modified for the added male DB-25 pin connectors used by the cards.

The connection of the umbilical cord to the PUMA 560 required consideration because the connector used was an old, high density connector which was no longer commercially available. An industry standard Wieland connector was used instead. The motor wires were separated from the signal and logic wires and were given their own connector.

Wieland connectors are available in a variety of pin options. A 12 pin Wieland connector was used for the motor wiring and a 24 pin Wieland connector for the signal and logic wiring. Wieland connectors use screw-in terminals rather than crimps that make wiring more flexible and convenient. The Wieland connectors thus add to the modularity of the system by giving it a generic plug so that other robot umbilical cords or machinery using motors, can be easily plugged in.

4. Hardware Control

4.1 H-Bridge Motor Drivers

The direction in which a permanent magnet motor turns depends on the direction of the current flowing through the armature coil. To reverse the direction of the motor, the current through the armature coil needs to be reversed. This could be done by physically changing over the supply terminals to the motor. This is highly impractical, so an electronic circuit, called an H-bridge, is used to do this and is shown in Figure 4.1.
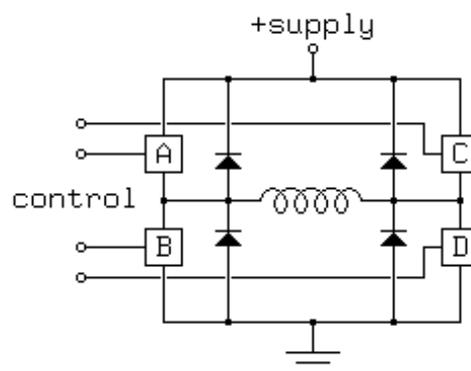

Figure 4.1 H-Bridge Circuit (Jones, 2001)

In the figure, A, B, C, D are transistor switches. The switches used in the H-bridge must be protected from the voltage spikes caused by turning the power off in a motor winding. This is usually done with diodes, as shown in the figure.

With four switches, the basic H-bridge offers 16 possible operating modes, 7 of which short out the power supply! However, only the modes that give the direction of the motor are of interest. The Forward mode has switches A and D closed (see Figure 4.2). Reverse mode has switches B and C closed. These are the basic modes required by an H-bridge that allows the current through the motor armature coil to be changed.
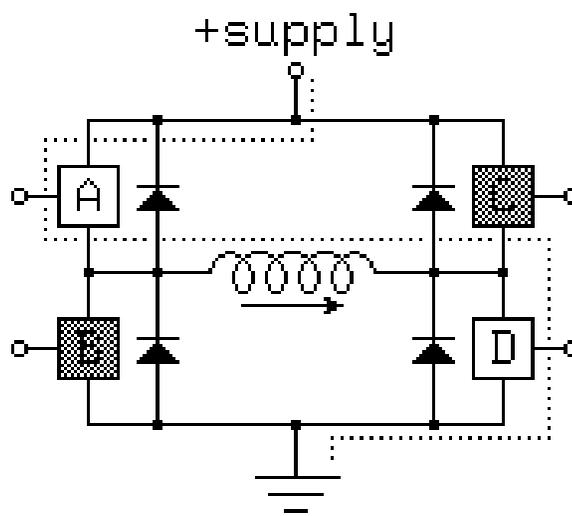

Figure 4.2 H-Bridge Circuit in Forward mode (Jones, 2001).

The H-bridges used for the project were the Devantech MD03 as they offered the voltage and amperage requirement of the system. Rated at 50V 20Amp, the MD03 H-bridge is a medium power motor driver. It has high degree of flexibility with several modes and control options. Each MD03 requires a 5V logic supply and a separate motor voltage supply that can be anything from 5V to 50V DC.

The MD03 has four control modes. It can be controlled using a standard I²C bus, 2 analogue modes, and a remote control mode used for control directly from an RC receiver. The mode of interest to the project was one of the analogue modes, the Analogue Mode – 0V-5V. This mode is useful because it can also be controlled using the digital TTL logic levels which come from the microprocessor. The SDL input of the MD03 is used to indicate the direction, logic 0 for reverse direction and logic 1 for forward direction. The SDA controls the amount of voltage sent to the motor. 0V indicates no power and 5V indicates full power. This mode allows a pulse width modulation (PWM) signal to be used instead of an analogue voltage on the SDA input. A resistor/capacitor filter on the MD03 generates an analogue voltage from the input PWM signal.

PWM is a technique used by most microprocessors and other controllers to control an output voltage at any value between the power rails. It consists of a pulse train whose duty cycle is varied so that it creates variable "on" and "off" states. The average output value will be approximately the same percentage as the "on" voltage. So, in the case of MD03 H-bridge mode that was used for the project, a 0% duty cycle represented 0V supplied to the motor, a 50% duty cycle represented half of the supply voltage available to the motor, and a 100% duty cycle indicated maximum voltage.

4.2 PIC Motor Control

The motors of the robot were controlled using a PIC18F252 microprocessor. This PIC has been implemented in a module called the BrainStem Moto 1.0 by the Acroname company. Acroname has been able to implement all the features of this PIC microcontroller into a small motor control package. The main features of the BrainStem Moto 1.0 are as follows:

- 40MHz RISC processor.
- 2 motion control channels with PWM frequencies from 2.5kHz-5kHz.
- 1 dedicated 10-bit ADC.
- 1 dedicated digital I/O line.
- 1 Mbit I²C port.
- I²C routing.
- Status LED.
- 11 1k TEA file slot and 1 16k TEA file slot.
- 368 byte of user RAM.
- RS-232 serial port communication.

Mode Descriptions	
PWM	Enables you to vary the amount of power sent to the motor. This is a useful starting point to verify motor and h-bridge operation. This mode does not provide position or speed feedback.
PWM - Encoder	This mode works like PWM, but provides encoder input for measuring motor velocity. This mode also includes the ability to set an input offset value and encoder sampling rate.
PWM - A/D	This mode works like PWM, but provides input from an A/D channel. The value is displayed but not used as feedback for motion control. This mode is the starting point for doing Back-EMF control as it lets you configure your system to suit your motors.
A/D PID	This mode uses the feedback from an analog channel to determine the position of the system. A PID control loop attempts to maintain the desired position.
A/D Velocity PID	This mode uses the feedback from an analog channel to determine the velocity of the system. A PID control loop attempts to maintain the desired velocity.
Encoder PID	This mode uses the feedback from an encoder to determine the position of the system. A PID control loop attempts to maintain the desired position.
Encoder Velocity PID	This mode uses the feedback from an encoder to determine the velocity of the system. A PID control loop attempts to maintain the desired velocity.
Off	Disables all PWM and control outputs and sets the channel's digital IO pins to be inputs.
Step	Provides stepper motor control. This mode requires a different H-Bridge specifically designed for stepper motor control. This bridge component will be available as an optional driver bridge in the future.

Table 3. Mode Descriptions (Acroname, 2003)

The Moto module is pre-programmed with seven different modes. All of these modes allow for custom settings and configuration depending on the type of motors that are used and the type of sensors used to monitor feedback from the motors. The following Table 3 lists the modes available with a brief description of what they do.

The modes of particular interest for the PUMA 560 robot's motors were the Encoder PID and Encoder Velocity PID modes. The Encoder PID mode makes adjustments to the

position of the motor based on feedback from the motor's encoder. PID control is used in an algorithm on the PIC to determine how much PWM is applied over time to the motor in order for a desired position to be reached and maintained. Proper selection of PID gain constants minimise oscillations of the motor (Acroname, 2003). The following Figure 4.3 shows how the overall flow of the control loop is done.

Figure 4.3 Basic logic flow of the Encoder PID mode (Acroname, 2003)

The Encoder Velocity PID works similarly to the Encoder PID mode, however, instead of moving to a given setpoint and maintaining that setpoint, the mode allows motion at a constant setpoint speed and maintains that speed. This mode did not prove very practical for the project implementation, so it was not used. Instead, encoder PID mode was used for the project.

The other important feature of the PIC is the use of reduced instruction set computing (RISC). The Moto responds to a limited set of pre-programmed commands. Acroname provides a reference library on its website with information of how these commands work.

4. Software Development

4.1 PC Graphical User Interface

The Graphical User Interface (GUI) was developed using a common object-orientated programming language, Visual Basic 6.0. The GUI was developed to test the functionality of the system. It communicates with the microprocessors through a serial cable connected a com port on any PC. The GUI communicates with each of BrainStems through the first BrainStem Moto module, which acts as a router. Each packet of data sent from the PC contains an address for the respective BrainStem the data is meant for. If the packet is not addressed to the first router, it sends the pack on the I2C bus until it reaches the appropriate module. The main GUI serves the following major functions:

- Communication management of packets between the BrainStems and the PC.
- Inputs for setpoints for each motor that is to be controlled.
- Allows manipulation of the settings of programs running on the PIC. In the case of the BrainStem, this includes such things as PID control settings, mode selection, PWM, register monitoring, etc.

5. Discussion

When the entire system was put together, adequate control of the robot was possible. Overall the system performed well enough to get controlled motion of the six joints of the PUMA robot arm. The system was also subsequently used to control a CNC lathe. There were, however, a few problems with the final system. The system also requires some further enhancement to achieve better control of joint positioning.

The main problem occurred with the logic power supply. Every now and then the logic power, which supplies all the encoder circuits and microprocessors, would fail to power the most essential parts of the system. This would result in unpredictable behaviour from the robot arm and make it unsafe. It was found that the grounding of the logic power supply was floating causing differences in the ground of the system components. By using the ground of a bench-top power supply, this problem was solved.

The rest of the problems with the final system were a result of the PID control method. The PID control was not able to account for the effects of inertia and gravity because the feedback gains of the PID algorithm were fixed. This meant that the system had a very low level of repeatability and accuracy. The Encoder PID mode of the BrainStem Moto 1.0, although working well for the wrist joints, did not perform very well for the larger joints. When a new setpoint was entered into the PID control loop, the control algorithm would output maximum voltage to the motor until it neared the new setpoint based on the feedback from the encoders and the PID gains. It did this without accounting for the effects of inertia and gravity. In practice this meant, for the shoulder and elbow joints especially, that the joint would move more rapidly in the down direction that it would in the up direction. To correct this problem, a velocity control method needs to be explored.

Another problem that exists with the BrainStem Moto 1.0, is that it only has a 16-bit setpoint number and this is reduced to 15-bits as the most significant bit is a directional bit. Due to the resolution of the 250 line incremental encoders, only limited movement of a joint can be completed with each command sent to the BrainStems.

This leads on to another problem with the BrainStem program. It is not able to detect when a movement is complete so that the next move of the robot can take place, i.e. there are no flags set to indicate a new setpoint has been achieved. This problem was overcome, in Visual Basic, by introducing a timer delay between selected movements.

A problem also occurs when the motors are powered at high speeds. At high motor speeds the PIC fails to read the encoder pulses. This results in uncontrolled motion of the joints. In some cases the encoder circuit that was developed for the incremental encoders fails to supply the pulse train signal to the BrainStems. This may be because there was a frequency limitations on the ICs used in the encoder circuit. This problem could also arise from aliasing. This would depend on the rate at which the PIC samples the input signal from the encoder circuit. The effect of this problem is that robot must operate at reduced speeds in order to maintain control.

The only other item of note is that the robot joints require calibration every time the robot is turned on. This is the purpose of the potentiometers in each motor. The potentiometers are input directly to the analogue inputs of the BrainStem Moto 1.0 that provides a 10-bit analogue-to-digital conversion of the potentiometer value. This value gives an indication of the position of the robot when it is powered up.

As these problems are overcome, further planned development of the system is to integrate it with RobotWorks, a computer aided manufacturing (CAM) package. RobotWorks is an add-on package for SolidWorks, which is a commonly used CAD program. The idea being that path planning for the manufacture of various parts and

components is all done by RobotWorks. This will remove the complexity of working out programmed motions for the robot from the user and, in effect, creates a virtual manufacturing environment.

6. Conclusion & Future Work

The objective of this project was to use a Mechatronics systems approach to develop a modular, mechatronic, plug-and-play controller for the control of an n-axis robotic system. The actuating system of the six-axis, revolute PUMA 560 series robot arm was first investigated to gain an understanding of the mechanical, electronic and software system requirements. The system was then successfully developed and included the construction of a power supply for the robot and a generic modular controller for the robot actuating system. Interfacing of the controller with a PC was also developped so that the system could be successfully controlled and tested. This was all achieved at a low cost thanks to the mechatronics approach that was used.

The system still needs further development, and future work includes the development of the system so as to integrate it with a computer aided manufacturing (CAM) package. The project did, however, effectively demonstrate that a sound mechatronic systems approach could be used to develop a working, low-cost system and a relatively short time frame.

The project also demonstrated the flexibility of a modular plug-and-play mechatronic system as the modular controller cards were used to control both the Puma 560 control arm, and a CNC lathe with only software changes required to configure the cards to each machine.

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This book is the result of inspirations and contributions from many researchers worldwide. It presents a collection of wide range research results of robotics scientific community. Various aspects of current research in robotics area are explored and discussed. The book begins with researches in robot modelling & design, in which different approaches in kinematical, dynamical and other design issues of mobile robots are discussed. Second chapter deals with various sensor systems, but the major part of the chapter is devoted to robotic vision systems. Chapter III is devoted to robot navigation and presents different navigation architectures. The chapter IV is devoted to research on adaptive and learning systems in mobile robots area. The chapter V speaks about different application areas of multi-robot systems. Other emerging field is discussed in chapter VI - the human- robot interaction. Chapter VII gives a great tutorial on legged robot systems and one research overview on design of a humanoid robot.The different examples of service robots are showed in chapter VIII. Chapter IX is oriented to industrial robots, i.e. robot manipulators. Different mechatronic systems oriented on robotics are explored in the last chapter of the book.

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