Robotic Sensor System for Automated Machines

Ahmed Asif Shaik, G. Bright and W. L. Xu
Institute of Technology and Engineering
Massey University, Auckland, New Zealand

Abstract

Flexipicker robots, as well as many automated multi-axis machines, operate under overall 'open loop' control. The exact position in space of the end effecter or tool head is not sensed directly. The software controlling the robot or automated machine makes a calculated estimate of where the tool-head should be. This is often achieved by monitoring sensors on axes that track linear translation and rotations of shafts or gears. For low precision applications this system is appropriate. However positional errors can occur. This method may not be suitable for high precision robots and automated machine tools. There exists a need for a sensor system that is capable of acquiring the exact spatial coordinates of the tool point or end effector directly.

1 Introduction

The need for a sensor system that provides direct feedback of the end effector's spatial coordinates is essential for precise assembly and machining. The aim of this research project is to design a low cost sensor system that will precisely locate the tool points' spatial coordinates directly and aid in the reduction of errors encountered in the 'open loop' control. The system should be capable of seamless integration with existing techniques for motion control. The sensor system should be able to locate the tool head in 2D space. With simple additions and modifications it should render itself applicable to location in 3Dspace. It should be modular, sufficiently robust and error immune to work in almost any environment.

2 Current Location Sensing Technologies

There are numerous technologies available for locating objects in space. The most well known example is the Global Positioning System (GPS) and is capable of pin pointing an object's location to within 10 m. Differential GPS (DGPS) provides more accuracy, [Willgoss et. al, 2003] presents a cheap solution with errors of less than 5 cm. Bluetooth and WiFi networks also provide a means of location sensing. Bluetooth devices form mini-cells, similar to the way cellular telephone systems operate and with a sufficient number of Bluetooth cells installed, the position of a transmitter can be deduced by knowing the cell with which a device is communicating; discussed in [Dempsey, 003] for locating people in buildings.

Another method for accurately measuring the distance to targets is through the use of laser triangulation sensors. These use CCD cameras as the detectors. They are so named because the sensor enclosure, the emitted laser and the reflected laser light form a triangle. They are used for small ranges, typically a few inches. Similar methods exist that use different media; air for ultrasonic transceivers, water for sonar and general space for radio transceivers.

The above technologies cannot be used in industry. For manufacturing purposes accuracy ranges from micrometer to nanometer resolution. Laser interferometer technologies have excellent accuracy and are used in manufacturing environments, i.e. in IC design, prototyping and manufacturing. These interferometers have nanometre resolution. An optical heterodyne interferometer designed at NASA's Jet Propulsion Laboratory can measure linear displacements with an error of 20 pm (pico, 10-12m).

Grid encoders offer another solution; grids made by OPTRA have a coverage range up to 380mm × 380mm with high accuracy and excellent repeatability. These provide displacement readings to within tenths of microns and in some cases nanometer resolution.

[Ziegert, 2005] discusses a low cost solution employing a camera and LCD screen to locate an object's coordinates in 2D with high accuracy. Displacement measuring instruments utilizing eddy currents, capacitive and inductive properties exist, however they aren't as wide spread as the technologies mentioned above.

3 Proposed Sensor Feedback System

The problem of locating the end effector of a robot in real world space is first reduced to finding its position in a 2D plane with regard to a point reference. Once this is accomplished the general problem of location in 3d space is solved by attaching 2 2D planes at right angles. With such an arrangement 2 axes coincide and if the reference point of each plane coincides, the result is a 3 axis sensor system for position location. This paper attempts to document a solution of finding the end effector in a 2D plane.

After consideration of the available physical quantities used when locating objects, a laser light stimulant was found to be most fitting. A laser light sensor can be conditioned to provide a digital output. Comparatively inductive and capacitive sensors are analogue in nature and require digitization for use in digital systems. These analogue signals are compromised by atmospheric effects, temperature, humidity and unshielded noise from surrounding machinery. Triangulation utilizing radio, ultrasound or infrared waves is not suitable as multiple reflections from surrounding surfaces cause interference. They also require modulation and demodulation to distinguish the signals generated from those created by the environment.

The defining component of this sensor system is a grid of laser light detectors. The detectors need to have a narrow sensitivity bandwidth to prevent wrongful stimulation and spurious results. The proposed sensor concept utilizes a direct approach, with a laser attached to the end effector and the sensor grid (the sensor plane with laser sensors equally spaced in rows and columns) mounted directly above it. This is a natural choice as the coherent nature of laser light makes finding the end effector in 2D space easy if the laser beam remains perpendicular to the sensor plane at all times. The end effector's location is the same as the sensor which is stimulated (in a 2D plane, depth has no meaning). It must be stressed that this sensor system requires only bit (1 or 0) information for each sensor. Each sensor is either stimulated or not stimulated. A stimulated sensor indicates position on the plane as explained. This makes data processing and transfer far simpler and makes control easier. The resolution is limited to the spacing between sensors. If the spot light is smaller than the spacing between sensors, these will represent a dead zone where beam tracking will be lost completely. The laser light detectors are simple phototransistors with an additional transistor arranged in a Darlington configuration. Current fabrication techniques can accommodate hundreds of millions of transistors on a sliver of silicon. These fabrication methods can be used to construct a detector screen with an exceptional and practical resolution. Resolution affects data output, a greater resolution implies more data per unit area (more sensors). A hybrid type system would involve a sensor grid with a comparatively poor resolution. Each sensor provides a checkpoint. Knowing the exact spatial distance between these detectors provides the controller a means to limit the errors incurred. Instead of accumulating errors from one extremity to the next, errors only exist between successive detectors.

The array of data has to be placed in a data format or byte structure to facilitate processing. This is made possible by a large scale encoder. To make a numerical example a 380mm × 380mm screen utilizing a phototransistor with a sensitivity area of 0.12 mm^2 [1] would comprise 1 203 333 ($380^2/0.12$) detectors. A 3 byte (224 - 1) data format would be more than sufficient to indicate any single stimulated sensor. If this system were to incorporate 2D orientation then multiple lasers would be used. They would be arranged in a grid and selected lasers would then be switched on to form a geometric pattern. Recognizing this pattern on the sensor grid can provide orientation information. However a different data format would be necessary to determine the stimulated sensors. In this case each bit represents a single detector, 1 203 333 sensors can be represented by 150 417 (1 203 333 / 8) bytes of data (≈ 151 KB). If it takes 30 single cycle instructions of a CPU to process 1 byte of data (to determine stimulated sensors), it would take 4.53 million instructions (30×151K) to determine all stimulated sensors. Using an 800 MHz RISC processor this amounts to 5.66 ms (800×106)-1×4.53×106). Note that this is a very conservative estimate. Figure 1 displays high level architecture of the detector screen.

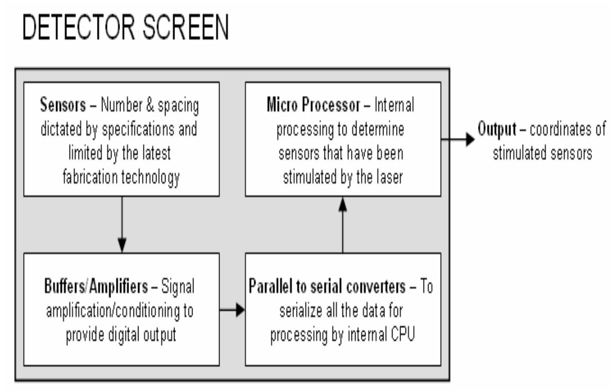

Figure 1 - Block Diagram of intended sensor system.

4 Mechatronic Design

The mechatronic design consists of 3 parts the mechanical, electronic and software components. As stated in [Bolton, 2003], the term mechatronics is used for the integration of microprocessor control systems, electrical systems and mechanical systems. The mechanical structure was designed to test the electronic hardware and software control, the purpose of which is to validate the proposition. The design is documented to deliver a simple prototype.

4.1 Mechanical Structure

The mechanical structure is based on a Flexipicker pick and place parallel kinematics industrial robot. It is a scaled adaptation. The design consists of 4 articulated arms; 4 servo motors (used in model helicopters); a plate end effector with attached laser; ball-cup joints and a mounting frame. The entire mechanical structure is 600mm in length, 400mm wide and 500mm high. Figures 2 and 3 illustrate the parts and the assembly.

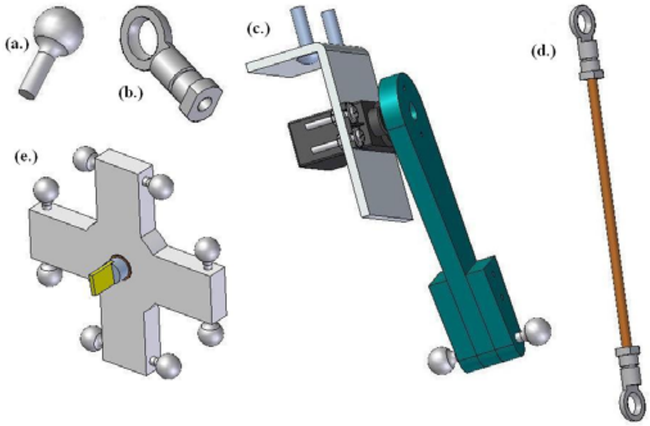

Figure 2 - Significant mechanical parts that position the laser a. Ball from bearing b. Cup from modified bearing socket c. Servo motor with upper arm attached and mounting bracket d. Lower arm component e. Laser and laser mounting.

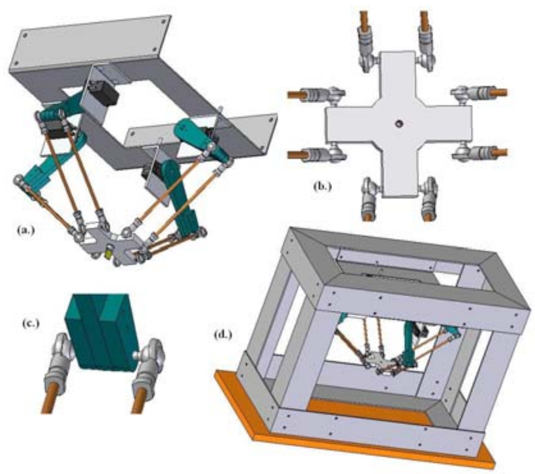

Figure 3 - Assembly of all components resulting in the final structure a. All servos mounted with upper arm and lower arm attached to laser b. Lower arm attachment to laser end effector c. Articulated arm 'elbow' joint d. Complete Assembly.

Each servo has slightly over a 180° range of motion. They require a pulse for angular rotation: a pulse of 1ms will bring the servo to its reference point; a pulse of 1.5 ms will rotate it 90° from that reference point and a pulse of 2 ms will induce a 180° rotation. Angular positioning is achieved through linear interpolation of pulse width, between the extreme positions of 0° and 180°. The resolution however is limited by the digital system in use. An 8 bit system would have an accuracy of 0.706° (180°/255) whereas a 16 bit system could achieve accuracies of 0.00275° (180°/65535). This pulse must be refreshed every 18 ms to prevent irregular behaviour. These servos require no feedback control as this is monitored by a controller within the servo package. A potentiometer is attached to the rotating shaft and provides a variable voltage as position feedback. For every pulse that arrives within the range 1–2 ms there is a linear mapping to a voltage that should appear at the potentiometer. The servo rotates until this voltage is reached and actively maintains this position.

It must be noted that the lower arm components are held together via 2 springs (not shown), one just below the 'elbow' and the other just above the 'wrist' for each forearm. The ball cup joints give a large degree of freedom. The guidelines for parallel mechanism design were followed as provided in [Creamer, 1976]. These were made from ball in socket bearings. The upper arms swing from side to side whereas the lower arms can move up, down, left and right and can even rotate about the 'elbow' by sequencing pairs of its basic motion (induced by rotating pairs of servos). The laser can move about a section of space, which is roughly a hemisphere below the sensitivity area (the square cut-out on the servo mounting frame, Figure 3 (a.).

4.2 Electronic Hardware

The system designed is a hybrid type as mentioned in section 3. The resolution is poor due to the 5mm LED type package of the laser sensor. Also the PCB tracks between sensors occupy significant space. To improve resolution a smaller package should be used, preferably surface mount, however working with these packages is difficult. The sensor grid consists of 64 LPT133 phototransistors arranged on an 8x8 grid. The resolution (distance between sensors) is 18 mm on both the rows and columns. This phototransistor has a daylight filter to prevent wrongful stimulation by ambient light. It is sensitive to light wavelengths in the range 600–900 nm. A 650 nm key-ring laser is being used as a sensor stimulant. This is a cheap and effective solution. Although the output power of this laser is less than 1mW, it is sufficient to turn the phototransistor on. Even at a 400 mm distance most of the output optical power falls on the phototransistor base due to the coherent nature of laser light. This laser cannot be used continuously as it overheats which leads to destruction of the diode. The nature of this design however does not require a continuous stream of optical power. The laser can be switched off just after loading of the parallel to serial converters with the sensor data through the data transfer stage until the next acquisition. The data transfer takes 30 ms (section 4.3 Software, Data Transfer) and the LPT133 needs 10 us to switch on completely. Utilizing a necessary design factor of 100 yields a laser switch on time of 1 ms (100×10 us). This implies that the laser is on 3.33% of the time which is sufficient to ensure prolonged life.

The sensed signal has to be buffered/amplified to ensure that the voltage level output from the LPT133 is within the proper digital range (0 – 0.8 V for a logic 0 and 3.5 – 5 V for a logic 1), according to [6] for proper electronic design. For this purpose each sensor on a column is passed to a transistor driver within a ULN2803, which consists of 8 transistor drivers. Eight driver chips are used, one for each column. The outputs from each ULN2803 are fed to a parallel to serial data converter, the 74LS166 to serialize the data for transfer to a PC. The 8 output serial lines from the data converters are fed to an ATMEL ATmega8515 microcontroller. There are eight bytes of data and each bit represents one sensor's current state. The controller is used to transfer the 8 bytes of data to the PC via its USART transceiver and the PC's RS232 serial port.

It also controls the 74LS166 data converters and the servo motors. The microcontroller enables the data converters and clocks the data out of each of them (Figure 4).

4.3 Software

The software has 2 parts to it i.e. the microcontroller code and the user interface.

Microcontroller Code

There are 4 parts to the microcontroller code, i.e. receiving and interpreting commands from the PC; sensor data acquisition; data transfer and servo rotation.

Receiving and Interpreting Commands

The first part of the command set is the activation code. When the microcontroller is told to activate it runs the 'sensor data acquisition', 'data transfer' and 'servo rotation' subroutines continuously until a deactivation command is received. Servo rotation commands are also received; these indicate a particular servo and a rotation value (pulse-width) with regard to its reference.

Sensor Data Acquisition

This routine enables/disables; clears and clocks the data out the parallel to serial converters. The 74LS166 function table illustrates how the control lines are used, refer to its datasheet. Steps 1 to 5 in Figure 4 must be followed to ensure that the registers are loaded with sensor data. The data is shifted through the output line, bit at a time, most significant bit (MSB) first with every clock signal. The register has to be clocked 8 times to read the 8 bits. In block 8 of the flow chart (Figure 4) the pipe character (|) is a C bitwise OR operator. An OR operation is performed with the incoming serial bits from each data converter and the least significant bit (LSB) of the corresponding data byte. The << character is a bitwise left shift operator, e.g. Data_Byte = Data_Byte << 2 would shift all bits in Data_Byte one position to the left 2 times. In this manner all the data bits from the shift registers populate the data byte variables, as indicated in [Deitel et al., 2001].

Data Transfer

Once the 'Sensor Data Acquisition' routine completes, the 8 bytes of data await transfer. The serial port of the PC works with the ASCII character set, where a byte of data received by the PC represents letters of the alphabet (A-Z, a-z), digits (0-9) or special characters ($, %, & etc.). The data bytes could be sent directly but would then mean further decoding by the user interface program as the data sent by the controller was intended as integer data not character data. This complicates matters further if instructions or status reports have to be sent from the microcontroller; all of these would be interpreted incorrectly. Each data byte representing a number in the range 0-255 must be sent out the microcontroller's serial port via 3 ASCII characters (one character for each of the hundreds, tens and units digits) representing numbers (0-9 which in ASCII is 0x30-0x39 in hexadecimal notation). Figure 5 illustrates the embedded program for data transfer.

Routines that accomplish tasks in blocks 1, 2, and 3 were derived to increase speed of execution and code space. [Shaik et. al., 2006] describes these routines in detail. The algorithms are not found in any microcontroller course, and are not standard techniques to achieve the desired aim. In total there are 32 character bytes (4 character bytes per data byte, including byte completion character) transferred from controller to PC. Using a Baud Rate of 9 600 (bits per second) and including a parity check bit (9 bits per byte) this takes 0.03 s to complete.

Servo Rotation

As there are 4 servo motors, 4 pulse-width modulated signals have to be generated as described in section 4.1. Incoming commands indicate a particular servo and the length of its pulse-width. The pulse-width value will be received in 3 bytes, for the reason mentioned in section 4.3 Software, 'Data Transfer'. In total there are 16 character bytes transferred from PC to controller (4 bytes per servo) to position the laser as required. The time taken to do this is 0.015 s (9 600 Baud). Timers within the controller will ensure that the PWM signals comply with the desired range of 1-2 ms

User Interface

The user interface provides a visual display of the data received, 64 coloured circles represent the 64 phototransistors. Textboxes display the incoming character data, when a completion character 'X' is received the 3 digit number in the text box (which is text at the moment) is converted to an integer number to be used in the display routine. The display routine simply searches through each data byte (columns) for low bits (rows) and changes the colour of the corresponding circle (blue when not stimulated, red when stimulated). The interface also allows the user 2 options for control; either via a mouse or a selection grid. With the mouse the user can manually control the laser and move it anywhere with its mechanical constraints. When the selection grid is active the laser will position itself, first finding a reference point and then move along rows and columns. It will pass over all sensors which have been selected by the user. See section 5 for results and illustrations.

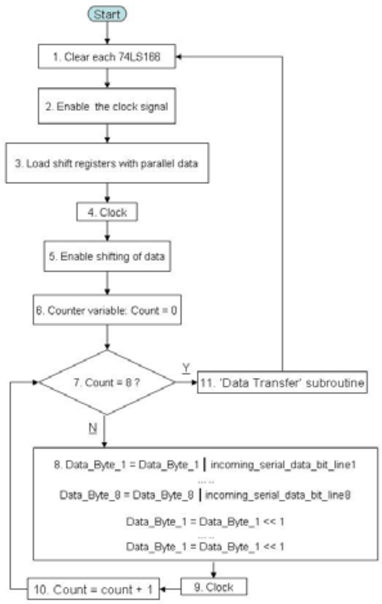

Figure 4 - Program flow for 'Data Acquisition'

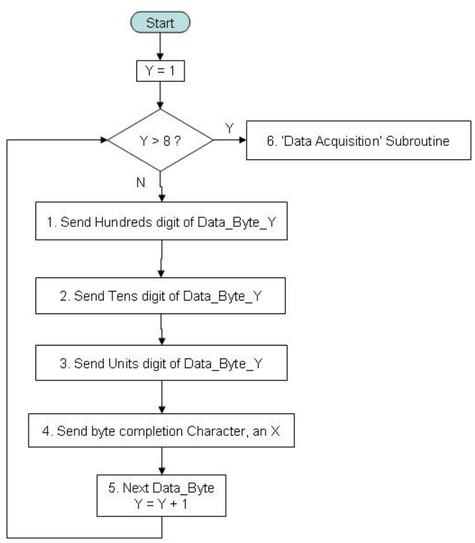

Figure 5 - Program flow for 'Data Transfer'

4.4 Control Design Overview

The sensor grid provides direct feedback of the position of the laser/tool head. Upon startup the laser may point to an area lacking sensors. One of the control challenges was to first find a reference for the controlling software. As the beam is small enough to fit between sensors it is possible for the laser to move in a path and not hit a sensor. A few strategies were devised to solve this problem. The laser may be moved randomly until a sensor ids found. This solution has the advantage of a quick find but also a far worse disadvantage of never finding or taking a long time to find a sensor. The second strategy involves scanning the detector board in lines, moving either horizontally or vertically. The lines have the same thickness as the laser beam diameter. This strategy guarantees a find but at the expense of speed. The final strategy involves a spiral movement. From its current position it spirals outward until it finds a reference. This is the most efficient with regard to speed and is guaranteed to find a reference. Once the reference point is found the laser may then be moved along sensor columns and rows to find a particular area of interest. An interpolation method may then be implemented to find a particular point between sensors.

5 Performance/Operation

5.1 Sensor Grid

The sensor grid operates as intended after having integrated all the functions described on the microcontroller. Figure 6 illustrates how the data is displayed visually in the user interface program.

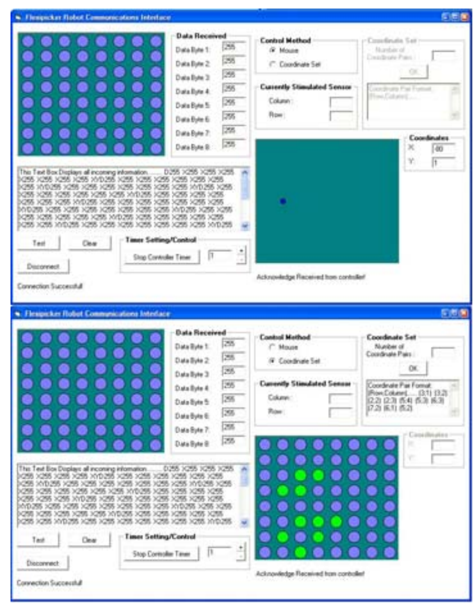

Figure 6- Testing of sensor board and user interface with laser stimulation a. Control via mouse b. Selection grid active for automated movement

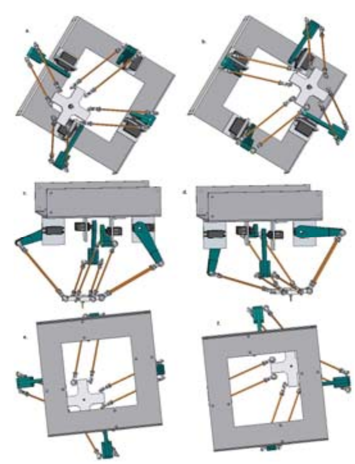

Figure 7- Simulation of laser tool head movement a,b Bottom views c,d Side views e,f Top views

5.2 Mechanical Sturcture

The most important aspect of the mechanical structure is the articulated arms. A simulation model was created to simulate and animate its movement, to ensure that it complies with the requirements of the design. The results are shown in Figure 7.A motion generator is attached to each servo head and is set to follow a harmonic function. The end effector's motion spanned the entire range of the sensitivity area. Most importantly the laser mounting remained parallel to the sensor grid PCB (sensor plane) throughout its motion, this ensures that the laser beam is always perpendicular to a detector.

6 Conclusion

The electronic and mechanical designs are complete. Electronic testing is complete. Controller and software design are ongoing processes to achieve better control and faster code execution. Self diagnostic features will be added to indicate malfunctioning sensors.

The objectives of this project have been met. The sensor system is of low cost and provides direct feedback. Resolution is currently the only problem, but as mentioned fabrication techniques can resolve this issue. This system is modular and facilitates inclusion in existing systems. 3D location is possible with two of these sensor grids placed at right angles to each other. The sensor grid is also robust and is not affected by ambient light.

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