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Closed-loop Sensor System for Automated Manufacturing Machines

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Abstract. Many automated multi-axis machines operate under ‘open loop’ control. The exact position in space of the end effecter or tool head is not sensed directly. The software controlling the robots or automated manufacturing machines make 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 often 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. The aim of this research project was to design a low cost sensor system that would precisely locate the tool points’ spatial coordinates directly by ‘closed loop’ control. This aided in the reduction of errors encountered in ‘open loop’ control. The system was capable of seamless integration with existing techniques for motion control. The sensor system was able to locate the tool head in 2D space. With simple additions and modifications it rendered itself applicable to 3Dspace location of the tool head. It was modular, sufficiently robust and error immune such that it would work in almost any environment.

Keywords: Automation, Manufacturing, Closed Loop Control

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 objective of this research project was to design a parallel robot that would have an integrated sensor system. The sensor system should be low cost and be capable of locating the tool points’ spatial coordinates directly or aid in reducing the errors encountered in the ‘open loop’ control. The system should be capable of seamless integration with existing techniques for motion control and should be able to locate the tool head in 2D space. With simple modifications it should render itself applicable to location in 3D space. It should be modular, sufficiently robust and error immune to work in almost any environment.

There are numerous technologies available for the purpose of locating objects in space. These are the Global Positioning System (GPS – with 10 m accuracy, a Differential GPS solution by [1] reduces the errors to less than 5 cm); proximity location through Bluetooth, WiFi and Cellular networks (position is deduced by knowing the cell with which a device is communicating) and triangulation systems (using lasers, ultrasound, etc.).

In addition there are imaging methods used to determine position. [2] Discusses a low cost solution employing a camera and LCD (Liquid Crystal Display) screen to locate an object’s coordinates in 2D with high accuracy. VSLAM (Visual Simultaneous Location and Mapping) systems used in mobile robotics use cameras to build a map of its surroundings for navigation purposes. There are also image processing techniques that can determine movement from consecutive frames provided by a camera. These images also provide information regarding the surroundings and are completely passive. The accuracy and resolution however depend on how far from the object the camera is and the resolution of the camera itself.

All these technologies are suitable for locating large objects in a relatively large space, for instance locating people in buildings [3]. In industry, however, robotic arms used for assembly, welding or spray-painting move in a confined space and the position of the end effector must be determined with millimeter to sub-millimeter resolution.

For manufacturing purposes the resolution of computer numerically controlled (CNC) machines range from micrometers to nanometers. For such purposes Laser interferometer technologies are sometimes used. These position sensing systems have excellent resolution as well as accuracy and are used in manufacturing environments for IC (Integrated Circuit) design, prototyping and manufacturing. An optical heterodyne interferometer designed at NASA's Jet Propulsion Laboratory can measure linear displacements with an error of 20 pm (Pico-meters, 10^{-12}m).

Grid encoders offer another solution; grids made by OPTRA have a coverage range up to 380 mm × 380 mm. Their accuracy and repeatability lie in the same range as Laser Interferometers (i.e. micro- to nanometer resolution). Both Grid encoders and Laser Interferometers are expensive technologies, usually costing hundreds of thousands to millions of dollars. Furthermore, they can not measure absolute position directly; they both use fringe patterns (due to light wave interference) to measure relative displacement. The integration of these displacement measurements coupled with the knowledge of the end-effectors’ initial position yields the current position.

2. 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. The general problem of location in 3D space is solved by attaching two 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 (ultrasound, infrared light, radio waves, etc.) used when locating objects, it was decided that a laser would be most suitable for the reasons that follow. A laser light sensor can be conditioned to provide a digital output. Comparatively analogue sensors require digitization for use in digital systems. 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 and provide unreliable results. They also require modulation and demodulation to distinguish the signals generated from any that can be created by the environment. The proposed sensor concept utilizes a direct approach, with a laser attached to the end effector and a sensor grid (a grid of 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 effectors' location is the same as the sensor which is stimulated (in a 2D plane, depth has no meaning). This perpendicular constraint can be enforced by the use of tilt sensors that can tell the orientation of an object, corrections can then be made to keep the end effector perpendicular. Also the inherent nature of the robot can be sufficient to force this condition. The Flex-Picker is one such example as its arms force the end-effector to remain parallel to its base at all times.

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. 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 phototransistors with a Darlington configuration. Current fabrication techniques can accommodate 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 lower 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

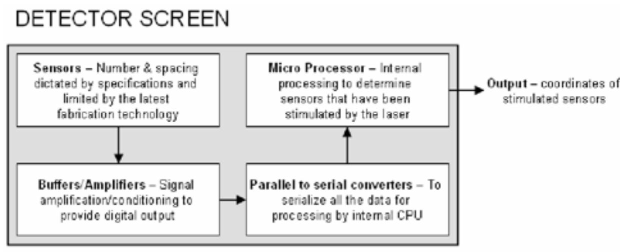

Figure 1.1. Block Diagram of intended sensor system.

3. Mechatronic Design

The mechatronic design consists of 3 parts the mechanical, electronic and software components. As stated in [4], 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 mechanical design was also undertaken to explore parallel mechanisms. The design is documented to deliver a simple prototype. The specification on resolution was relaxed as it was stated that fabrication techniques can produce a screen with a realistic resolution. More emphasis was placed on creating a cheap system that could reduce errors.

Mechanical Structure:

The mechanical structure is based on a Flex-Picker pick and place parallel kinematics industrial robot. It is a scaled adaptation. The design consists of 4 articulated arms; 4 servo motors; 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 1.2 and 1.3 illustrate the parts and the assembly.

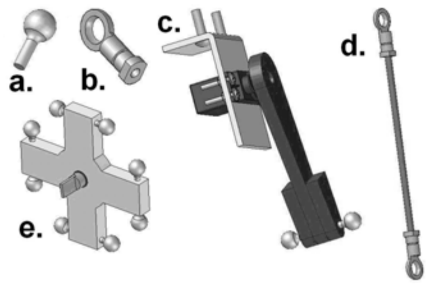

Figure 1.2. Significant mechanical parts that position the laser: (a) Ball from bearing, (b) Cup from modified bearing socket, (c) Servo motor with upper arm attached and mounting bracket, (d) Lower arm component, (e) Laser and laser mounting

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. 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 1.3 (a). The guidelines for parallel mechanism design were followed as provided in [5].

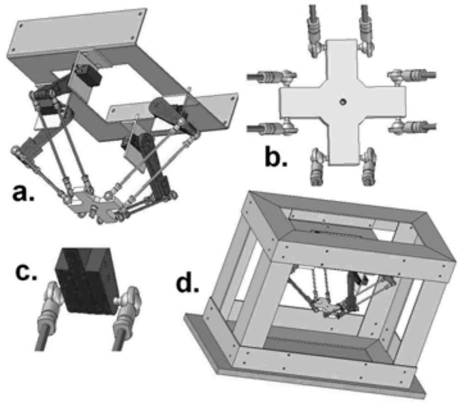

Figure 1.3. Assembly of all components resulting in the final structure: (a) All servos mounted with upper arm and lower arm attached to laser, (b) Lower arm attachment to laser end effector, (c) Articulated arm 'elbow' joint, (d) Complete Assembly

Electronic Hardware:

The system designed is a hybrid type as mentioned in section 1.2. The resolution is low due to the 5 mm diameter of the LED type package of the laser sensor. Also the PCB tracks routing sensors to buffers and data converters occupy significant space, which could not be avoided. To improve resolution a smaller package should be used, preferably surface mount, however these could not be sourced at the time this screen was made. Each sensor grid consists of 64 BP103 phototransistors arranged on an 8x8 grid. The resolution (distance between the centres of 2 successive 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 1 mW, it is sufficient to turn the phototransistor on. 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.

Software:

The software has two 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 – There are commands for activation, sensor data acquisition, data transfer and servo rotation. These tell the controller when to run the corresponding routines.

Sensor Data Acquisition - This routine enables/disables; clears and clocks the data out the parallel to serial converters. See [7] for a complete description of how this is achieved.

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. 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).

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. Incoming commands indicate a particular servo and the length of its pulse-width. The pulse-width value will be received in 3 bytes. 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 colored circles represent the 64 phototransistors. The display routine searches through each data byte (columns) for low bits (rows) and changes the color 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 within 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.

Control Design Overview:

The sensor grid provides direct feedback of the position of the laser/tool head at discrete points in space. The purpose of the grid is to reset accumulated errors in the positioning control system. The coordinates of the sensors are stored in the controlling software. When errors are accumulated and need to be reset the end effector is moved to sensor that is closest to the end effector. Once it is positioned and the sensor is not stimulated it knows that there are errors in its positioning and it then spirals out to locate the sensor and reset the error.

4. Performance/Operation

The novelty of this sensor system lies with the fact that it can determine the position of the end effector directly, provided that the constraints mentioned are strictly adhered to. It does not determine position from calculation as in laser triangulation systems and it does not integrate displacements as in laser interferometers.

The novelty of the mechanical design is with respect to the 4 arms that attach to the end effector. The arrangement and configuration has the advantage of easier control, a simplified kinematics model and added stiffness.

Sensor Grid:

The sensor grid operates as intended after having integrated all the functions described on the microcontroller. The project is still in the testing phase and is currently being integrated into the system. Much work is still needed to ensure the screen works properly with all data conversion and transfer routines. The second version of the screen is currently being designed to improve resolution and system repeatability.

Mechanical Structure:

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 1.4. A motion generator is attached to each servo head and is set to follow a harmonic function. The end effectors' 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. The singularities for this mechanism occur when the arms are completely extended or folded, when the upper and lower legs are co-linear. This situation was avoided in the simulation and can be avoided in reality.

5. Conclusion

The objective of creating a parallel robot with an integrated sensor system has been met. The mechanical system works with the control system designed. The only issue with the mechanical aspect is that the ball joints. They do not provide sufficient positioning accuracy and repeatability. The use of high performance ball joints or compliant joints in a future version of the robot will eliminate this problem.

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.

A fair comparison with best practices of industry can only be made with a sensor system that has roughly the same resolution and accuracy. This project sought to test the theory that such a system could be created, and if it would be useful. As such it has accomplished its purpose, but a fabricated screen could provide proper quantitative performance measures.

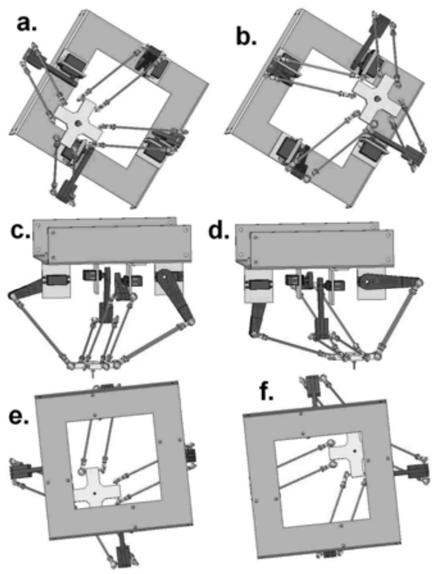

Figure 1.4. Simulation of laser tool head movement: a and b Bottom views, c and d Side views, e and f Top views

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