Closed loop sensor system for automated machines

The exact position in space of the end effector or tool head cannot be sensed directly in many automated machines. These machines operate under overall 'open loop' control as the software controlling the machine makes a calculated estimate of where the tool head should be. This is done by monitoring sensors on axes that track linear translation and rotations of shafts/gears. For low precision applications this system is appropriate. However, positional errors can occur and accumulate. There is a need for a sensor system that is capable of directly acquiring the exact spatial coordinates of the tool point or end effector.

The aim of this research project was to provide an automated machine with a cost-effective means to locate its tool head in space directly or reduce the errors encountered in the 'open loop' control. This sensor system had to integrate seamlessly with existing techniques for motion control. It had to locate the tool head in 3D space and with some simple modifications apply itself to 3D space. In addition, modularity, robustness, and noise error immunity were crucial to the design.

The project objectives were to research, design and implement a sensor system that would align a machine's end effector with its base and aid in tracking; create a mechanical platform on which to test the sensor system, research, design and construct a multi-axis machine and simulate the multi-DOF machine in a CAD package. Also to design a control system for the robot which interprets data from the sensor system, and develop algorithms for movement control and data acquisition to and from sensors. The mechatronics design approach was used in the design process.

Sensor system concept

The problem of locating the end effector of a robot in real world space was first reduced to finding its position in a 2D plane with regard to a point reference. Two of these 2D planes are then attached at right angles. With such an arrangement two axes coincide and if the reference point of each plane coincides, the result is a three axis sensor system for position location in 3D space.

The sensor system is made up of a laser and a grid of laser light detectors. These sensors can be conditioned to provide a digital output. Comparatively inductive and capacitive sensors are analogue in nature and require digitisation for use in digital systems. These analogue signals are compromised by atmospheric effects, temperature, humidity and unshielded noise from surrounding machinery.

The proposed sensor concept utilises 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 was 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). The laser light detectors are simple phototransistors. 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. A hybrid-type system would involve a sensor grid with a comparatively poor resolution. Each sensor provides a checkpoint. Instead of accumulating errors from one extremity to the next, errors only exist between successive detectors.

Mechatronic design

The mechatronic design consists of four parts - the mechanical, electronic, software and control components.

Mechanical design

The mechanical structure was designed to provide a test platform for the electronic hardware and software control algorithms. Its purpose is to validate the proposed sensor concept. The design was based on a Flex-Picker pick and place, parallel kinematics industrial robot and is a scaled adaptation.

Structural design of the modified flex-picker robot

The design consists of four articulated arms; four 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 600 mm in length, 400 mm wide and 500 mm high. Fig. 1 illustrates the design. The lower arm components are held together via two springs, one just below the ‘elbow’ and the other just above the ‘wrist’ for each forearm. The ball cup joints provide 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, each to particular angles). The laser can move about a section of space, which is roughly a hemisphere below the sensitivity area.

System modelling

The kinematic geometry of multi-DOF robotic manipulators must be analysed to determine the positions and orientations of all the members of the mechanism. This position analysis is easy to formulate, but, for certain devices, difficult to solve. The difficulty arises due to the fact that the kinematic analysis usually depends on solutions to sets of nonlinear equations. There are two types of kinematic problems for every robotic manipulator; these are the direct kinematics problem and the inverse kinematics problem [1, 2].

IPK for the delta modification using the kinematic geometry method

This model differs from the mechanical construction shown in Fig. 1 (a). The parallelograms of the lower arms have been collapsed to single lines joining the “knee” to the “ankle”. This simplification is acceptable as the parallelograms that compose the lower arms completely restrain the orientation of the end effector; as a result the end effector plane \( \{ee\} \) remains parallel to the base plane \( \{bs\} \) at all instances of its motion.

This parallel plane constraint is taken into account in the model with a few points as listed:
- The origin of \( \{ee\} \) will be the “dead” centre of the end effector.
- The coordinates of the “ankle” joints for each leg \( i \) (\( i = 1,\ldots,4 \)) on the end effector are known relative to the origin of \( \{ee\} \). These are fixed distances from the origin of \( \{ee\} \) determined at design.
- The origin of \( \{bs\} \) will be the “dead” centre of the base.
- The coordinates of the “thigh” joints for each leg \( i \) (\( i = 1,\ldots,4 \)) on the base are known relative to the origin of \( \{bs\} \). These are fixed distances from the origin of \( \{bs\} \) determined at design.
- The upper legs are restrained to have rotational motion about a plane.
- The lower legs have spatial motion.

Delta mechanism singularities

This Delta PKM is relatively free of singularities. The ones that occur are readily anticipated, i.e. when a leg is fully extended or folded. Due to symmetry these conditions may arise simultaneously in all three legs [5, 6].

Electronic hardware processors

Processes

The processors used for the electronic control system were 8 bit low-power, high-performance microcontrollers from Atmel. The Atmega8515 is a powerful microcontroller that provides a highly flexible and cost-effective solution to many embedded control applications. The peripheral features that were used most extensively were the 16-bit timers and the universal synchronous/asynchronous receiver transmitter which connects to a PC via its RS232 serial port.
Three Atmega8515 controllers were used:

Controller 1: For dedicated communication and control of data converters.

Controllers 2 and 3: Generation of the 4 PWM signals. Each controller has one 16 bit timer with 2 timer compare interrupts. With these compare interrupts each microcontroller could control two servos independently.

Sensor board detectors

The LPT133 phototransistor was chosen as the detector. This sensor has a daylight filter to prevent wrongful stimulation by ambient light. It is sensitive to light wavelengths in the range 600 – 900 nm. There are 128 sensors spread about 2 PCBs (64 sensors each) covering 25600 cm² each. There is a 20 mm resolution between sensors on both the vertical columns and horizontal rows. The resolution may be improved by using surface mount components or creating a custom screen. The detector screen made provides coordinates for check points in space. These are used to correct position errors in the robots workspace. Errors are no longer accumulated from one extremity to the next but are limited to the spacing between sensors. The sensor screens are shown in Fig. 2.

Buffers/amplifiers

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). For this purpose each sensor on each column is passed to a transistor driver within a ULN2803. These consist of 8 transistor drivers per chip. Sixteen driver chips are used (eight per board), one for each column on the sensor boards.

Serialisation

The outputs from each ULN2803 are fed to the parallel inputs of a parallel-to-serial-data-converter, the 74LS166. This is to serialize the data for transfer to a PC. There are 16 parallel-to-serial-data-converters one for each column on each board. The 16 output serial lines from the data converters are fed to the communications microcontroller. The controller then collates the 16 bytes of data and transfers it to the PC.

Printed circuit boards

The functionality was split into separate modules. Two detector screens were made, one for each of the vertical and horizontal planes. Each of these detector boards are composed of 64 LPT133 phototransistors, 8 ULN2803 driver chips and 8 74LS166 parallel-to-serial-data-converters. These two boards then connect to a PCB dedicated for communication. It also controls loading and transfer of data from the 16 parallel-to-serial-converters. The main components of this board were the microcontroller and the MAX232 level shifter. The last of the essential PCB’s was made for the microcontrollers that generate the PWM signals.

Software

The software has two parts to it, i.e. the microcontroller code and the user interface. An architectural overview of the software and all the dependencies is illustrated in Fig. 3.

Discussion

Simulation results

The most important aspect of the mechanical structure is the articulated arms. A simulation model was created in Solid Edge V17 to simulate and animate its movement, to ensure that it complies with the requirements of the design. A motion generator is attached to each servo head and is set to follow a harmonic function. The end effector’s motion spanned all of the sensor plane throughout its motion, this ensures that the laser beam is always perpendicular to a detector.

Performance tests and results

The performance tests carried out were to determine accuracy, precision, timing and repeatability of positioning as well as repeatability of sensor stimulation. Additionally approximations of velocity, acceleration and force were calculated from the timing measurements. Implicitly the results show that the electronic and software control systems work in synergy, and that the mechatronic approach to design yielded positive and tangible results.

Mechanical (positioning)

Accuracy is the degree of conformity of a measured or calculated quantity to its actual or true value. Accuracy is closely related to precision, the degree to which further measurements or calculations will show the same or similar results.

The position offset was taken to be the distance from the centre of the laser point to the centre of the LPT133 footprint. Twenty-five readings were taken for each 16 sensors on one of the detector screens. The results are shown graphically in Fig. 4 (a) indicating the offset averages. The accuracy of the positioning is 3.5 mm, which is the maximum measured deviation from an intended point of destination. The total mean of all errors is 1,093 mm. The precision is therefore 2.407 mm (3.5 – 1,093). The reasons for the positioning inaccuracy are a direct result of hysteresis as well as backlash in the servo gear mechanism, and the ball socket joints.

Acceleration:

There are 10 timing measurements for each of four separate straight line paths, shown in Fig. 4 (b). The distances were 60 mm (P1-P13), 66 mm (P1-P14), 90 mm (P1-P16) and 90 mm (P4-P13). The average times were 1,197 s, 1,265 s, 1,488 s and 1,5 s.

Electronic (sensing) repeatability

The repeatability measurement for the detector screen was done outside the positioning capabilities of the rig. The laser was manually positioned at 0 cm, 10 cm, 20 cm and 35 cm, and 25 attempts made for each of the 16 sensors. The repeatability for each distance is taken as the average of all the readings in the group measurement, and expressed as a percentage of the 25 attempts and are 99.25%, 95.25%, 89.75% and 74.25% respectively.

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Conclusion

This project was centered on a laser light sensor system, designed to reduce errors encountered in the so-called ‘open loop’ control of robotic mechanisms. The sensors are arranged in a planar grid with a resolution of 20 mm and by itself functions in 2D space. A 3D system was created by attaching two of these 2D sensor planes at right angles. The detector screen’s nature was inherently modular thus allowing it to integrate with existing techniques for motion control without difficulty. The laser and its detectors also make the system robust and immune to errors. The mechanical structure was a scaled adaptation of a Flex-Picker robot. Spherical joints were used for the “knee” and “ankle” joints as these give it more freedom than the universal joints used in the conventional Delta mechanism. The most difficult problem here was obtaining the ball and cup for each joint. These were eventually made from ball-in-socket bearings.

A simulation model was created to simulate and animate the movement of this Flex-Picker’s arms. It confirmed that the end effect or would remain parallel to the sensor plane at all instances of its motion. The software was composed of the embedded system microcontroller code and the PC user interface. The embedded system has to receive and interpret commands from the PC; acquire data from sensors; transfer that data and generate PWM signals for servo rotation. Custom data transfer routines were written to increase the speed of code execution and decrease the SRAM memory used in the microcontroller. They also facilitate easier processing. The PC control software has to transmit commands, receive and display data, and allow for different control methods.

Performance tests carried out were to determine accuracy, precision, timing and repeatability of positioning as well as repeatability of sensor stimulation. Approximations of velocity, acceleration and force were then calculated from the timing measurements.

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Acknowledgement

This paper was presented by the authors at the 2007 IEE Africon, and is published with permission.

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