Towards Object Retrieval Robots for Industrial Material Handling Systems using Bar-coding Technology

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ABSTRACT

The design methodology of a mobile autonomous robot intended for fully automatic identification and retrieval of objects from uniformly arranged mass storage systems of commodities, such as inventories maintained in industry warehousing, is described in this paper. An economical and elementary technique is first used to provide unique signatures to objects and a robot is then constructed to the required specifications to provide the mobile framework of the retrieval system. The robot encompasses a scanning mechanism to detect and scan objects in order to realize their identities and locate a specific object. Custom built mechanisms then retrieve the located object from the accumulation. Experiments are successfully carried out to verify the design paradigms.

INTRODUCTION

A new and emerging trend towards industrial and domestic automation is ubiquitous robotics. Ubiquitous robotics has to do with the presence of robotic-based systems in numerous aspects of our daily life. The development of robotic platforms utilizing embedded computer systems, microcontrollers, sensory devices and actuators and their use throughout our physical environment to perform unmanned tasks, replacing human manpower and revolutionizing the way key tasks are now executed refers to ubiquitous robotics. A survey of literature provides an excellent account of how such ubiquitous robots are now working in daily life (Yuta, 2001).

In addition, numerous instances of autonomous robots being used in material handling and warehousing, in the assembly line and in the execution of common household chores are given by Fukuda and Hasegawa (2003). Multi-faceted, multi-tasking, service robots used for cleaning and housekeeping, commercial construction and inspection, surveillance and search operations are also quoted to have been developed and deployed in real time. Moreover, the number of robotics related journals and conferences around the world including, but not limited to, Robotics and Autonomous Systems (RAS), Intelligent Autonomous Systems (IAS), International Conference on Robotics and Automation (ICRA), Computational Intelligence, Robotics and Autonomous Systems (CIRAS), Field and Service Robotics (FSR) and Intelligent Robots and Systems (IROS) is also evident of the growing research and development concerning robotics and automation. According to Holland and Nof (1999), the total number of robots in the world in 1982 was 35,000; in 1996 677,000 and (was expected to reach) 950,000 in the year 2000. That this number will continue to rise astronomically is not to be doubted.

Service and task oriented robots is one of the multitude of the more common robotic application fields among researchers. Some examples are security and Sentry robots (Carnegie et. al, 2004), nursing robots, escort robots (Ohya, et. al 2002), and autonomous vacuuming and lawn mowing robots to name a few. This has principally been feasible because tasks which are standardized, such as mail delivery and material transportation, consist of a sequence of activities that are repetitive in nature and can be easily replaced by robots that mimic or replicate the sequence of movements and actions that constitute the task.

Such robots have emerged as leading embedded control solutions and each of these radical inventions have set an unprecedented level of automatia while simultaneously having the net effect of establishing a reduction in the need for human intervention in the task to be executed. In this paper, our aim is to realize the design concept of a mobile robot with the ability to search and retrieve a user-specified object from a mass accumulation of objects. The contrivance of such a robot offers interesting possibilities in the manufacturing and warehousing domain where there already exits autonomous mobile robots for material handling and transportation. For developmental convenience, the specific object selected here is a book that will be retrieved from a bookshelf full of books. However, by analogy to mass storage systems in the warehousing milieu, the design conceptualization derived from this scenario is sufficiently generic and robust to be applied to the retrieval of varying genres of objects with minimal application-specific changes.

The organization of the paper is as follows. First, the benefiting implications of an object retrieval robot are given in Section 2. The design specifications of the robot are then presented in Section 4. The design methodology of the robot is then given through Sections 4, 5, 6 and 7 discussing object identification, mechanical hardware, electronics and software development, respectively. Requirements elicitation and experimentation results are given in Section 8. Section 9 concludes the paper, summarizes the attained results and provides recommendations for further work.

IMPLICATIONS

Modern manufacturing industries are characterized by utilization of state of the art automated systems in numerous aspects of operation and
the emergence of innovative developments and the subsequent progress through recent years has catapulted manufacturing industries to the pinnacle of automata. However, an area within the manufacturing milieu that has received less attention compared to other heavily automated areas, such as assembly and distribution, is the phase of object retrieval from mass storage systems. An activity that is executed prior to product assembly, this often involves retrieval of objects to be used in product assembly on a stupendous scale and therefore warrants automation.

With robots already having a significant role in industrial and manufacturing systems, evident from the omnipresence of robots from factory floors to the assembly line, an object retrieval robot would provide enhancement of the retrieval process resulting in a highly articulated material handling system. Ordinarily, a typical retrieval system has parochial efficiency. Synergetic integration of the object retrieval robot with existing material handling methods in manufacturing environments will provide impetus and accelerate the retrieval of objects from voluminous storage systems. Accession to this level of automation will decimate losses incurred from the delays sustained from un-automated search and retrieve systems leading to enhanced productivity. More importantly, this would free and elevate humans to a more potent role as planner and supervisor.

SPECIFICATIONS

The following subsystems are the key specifications that the overall design of the robot must conform to. In order to maximise the usefulness and applicability of the robot design paradigm over varying genres of objects, it is important to keep these specifications independent of application and object type. Listed in the order in which they constituted the design methodology, the design considerations are:

Establishing Object Signatures. An inexpensive and easy to implement method of providing unique signatures to objects must be utilized. The method must be one that can readily be implemented on objects or commodities of any kind immaterial of size, make or nature and without any form of overhead.

Object Detection and Identification. A means of detecting and realizing object identities must be contrived. Compatible with the method chosen above, it must be computationally elementary, yet accurate. Moreover, the technology adapted must present the object identities in a form suitable for processing.

Robot. A mobile robot must then be constructed to provide the framework on which the object detection and retrieval system will be based. The robot must be highly manoeuvrable and encompass an appropriate locomotion and navigation system.

Control Electronics. The electronics that control and coordinate the overall mechanical operation of robot need to be deigned. This includes the power supply, actuator, sensor and transducer circuits.

Intelligence. That appropriate software is custom developed for the robot cognition and intelligence, for the realization of the overall task, is the final requirement of the system.

DESIGN METHODOLOGY

This section describes the conceptual framework of the overall system.

Establishing Object Signatures

Radio Frequency Identification (RFID) technology has gained notability as the leading solution to tag objects with unique signatures. They have found applications in port terminals and many manufacturing industries that demand tracking of objects or commodities. Accordingly, RFID technology may be often selected as the de facto technique in object tagging. However, the immensity of the single most important biasing consideration of RFID technology is often unrealized and that relegates RFID useless in automatic search and retrieves systems such as the robot discussed in this paper. The fact that RFID chips propagate radio waves in all directions has the implication that a scanning mechanism may detect an RFID chip from a position that cannot be deemed to be true position of the RFID-tagged object. Accordingly, RFID technology is clearly ineffectual in automatic search and retrieve systems and hence conventional bar-coding technology was investigated and employed for tagging objects with unique identities.

Bar-coding is the method of digital representation of alphanumeric strings by the conversion of character strings into corresponding scan codes and creation of corresponding barcodes with a combination of bars and spaces of varying width. Taking into account the factors of cost of production, customization, and level of implementation skill required, bar-coding technology fares better than RFID technology in all aspects. Barcodes can be developed with any point of sale (POS) based software and printed by any standard printer. A typical bar code is shown in figure 1.

In contrast to RFID technology, a barcode scanner works on a line of sight basis. Accordingly, detection of a barcode exclusively occurs with the apparition of the barcode in the scanning field of view of the scanner, when it is precisely aligned with the subject barcode. Hence the exact reference point for the object extraction operation can be established. Moreover, another merit of bar-coding technology over RFID technology is that the unique signature to be encoded into barcodes and the barcode size is fully customizable. Most importantly, a key feature of barcodes and barcode scanners is that they offer a digital capture system which has important implications in computational processing. Accordingly, barcodes were accordingly using freeware software to encode unique identifiers and were affixed to the lower spines of books as illustrated in figure 2.
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Object Detection and Identification
For ease of implementation and mass-market appeal, the device chosen for the identification of books had to be an optimum non-volatile, passive (requiring no external power) memory product, inexpensive and readily available. A key criterion of the device had to be that its output should be available digitally. This feature would make it possible to implement comparisons in software through the use of elementary decision structures.

The best candidate thus identified was the barcode reader/scanner. Tomizawa et al. (2002, 2004) and Prats et al. (2003) have used computer vision and Optical Character Recognition (OCR) respectively but the astronomical costs associated with such high technology products eliminated these options outright. In some ways a laser-based barcode scanner may be even considered to be a hybrid form of laser technology since it uses laser light to read barcodes. In fact, a laser based barcode scanner is easier to incorporate into a robotic application than laser technology or computer vision since it can be readily interfaced to a Personal Computer (PC) and provides input ready for processing unconditionally. Moreover, a modest statement can also be made that a barcode scanner is actually more effective than computer vision using OCR technology. Consider the results of Prats et al. (2003). Since these researchers used computer vision and OCR, this sustained computation overheads including but not limited to image processing, line detection, magnification, histogram equalization, binarization, filtering, translation of pixels to text using OCR, contour detection and expansion. Thus it comes as no surprise that their results state that it takes a maximum of 1 second to localize a label from an image and an additional 5-10 seconds for the image processing and OCR phase. This is an adverse effect of using computationally exhausting tasks; a barcode reader on the other hand can identify book with considerable ease. The selection of a suitable barcode reader was then made based on a number of considerations, listed in Table 1. In conformation to these specifications, the barcode reader thus selected was the ProTracer ANL810-K with PS2 interface.

Selection criteria Num. 1 was imperative in the software programming of the barcode reader. With several types of barcode encoding formats present for example UPC, UPCE and EAN13, criteria 2 ascertain the non-restriction of the usability of the barcode reader while criteria 3 ascertains the operation of barcode scanner with the onboard laptop computer. For the reason that the internal physical construction of a barcode reader varies from manufacturer to manufacturer, its operation is therefore treated in oblivion to the internal electronics and hence they are not presented here; only the data written by the scanner to the PS2 port is of specific importance and the software retrieval of the data from the PS2 port is provided in subsequent sections. Figure 3 shows the subject barcode reader.

Table 1. Barcode scanner selection criteria

<table>
<thead>
<tr>
<th>Selection Factor</th>
<th>Present</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS2 Interface?</td>
<td>Yes</td>
</tr>
<tr>
<td>Multiple barcode decoding?</td>
<td>Yes</td>
</tr>
<tr>
<td>Free from hardware emulation for laptop operation?</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Fig.3. Barcode scanner for book identification

ROBOT CONSTRUCTION

The robot deployed for the purpose of book retrieval consists of a mobile wheel-driven platform base encompassing a gripper and book retrieval manipulation system with four axes of movements. The size of the robot is chosen such that it is able to accommodate a laptop computer (the principal controller) while simultaneously minimizing the weight, mechanical complexity and constructional cost. The maximum height of 1.5m to which the gripper rises is attributed to the anticipated height of the bookshelves. This book retrieval robot is capable of retrieving a book of dimensions 25x17x8 cm and of weight 1 kg.

A differential drive steering mechanism is used to provide locomotion to the robot with the main chassis being built over this steering base. The base has passive castors for stability and a line tracing mechanism to follow the navigation route. The navigation route is a white line leading to and running along a bookshelf. A two-finger gripper configuration is used to securely grip a book. The barcode scanner, gripper and book retrieval mechanism are constructed precisely over each other, as the barcode scanner provides the reference point for the book extraction execution. To provide vertical directionality to the barcode scanner, gripper and the book retrieval mechanism, a lead screw and pulley-based mechanism is used to provide vertical actuation so that the robot can scan and retrieve books from different heights with sensors indicating the different heights of the bookshelves. The control electronics encompass direct current (DC) motor controller circuits, infrared sensors for obstacle detection, line tracer sensors for navigation, force sensors for the provision of force dexterity, limit switches and the respective interfacing circuits.

Chassis
The main platform or chassis of the robot is generally simplistic in nature with this being attributed to the fact that its sole purpose was only to provide mobility. It is a skeletal rectangular-prism structure of dimensions 75cm x 50cm x 40cm.

Angle iron of dimensions 40mm x 40mm and thickness 3mm has been construction. The selection of iron over other alternative, lighter aluminium was made in this phase as the greater weight of iron would
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Fig. 4. The book retrieval robot.

The chassis more stable during deployment. The method of physical connection angle iron segments in the construction of the chassis was welding.

A differential drive steering mechanism is used to provide locomotion to the robot with the main chassis being built over this steering base. The placement of the wheels and DC motors are such that they are mounted along a common axis and are hence centred on the center of gravity of the main chassis.

Attendant freely rotating passive wheels, castors, are fixed at the two front ends of the mobile base for easy movement and stability. Rectangular slots measuring 210 mm x 60 mm are fabricated into this sheet metal to allow the extrusion of the wheels.

The exhibit of figure 4 illustrates the book retrieval robot depicting the principal components.

Gripper

A two-finger gripper configuration is used to securely grip a book. The two-finger grasp configuration is chosen as it is the simplest efficient gripping configuration and the application, the gripping of a book, is easily accomplished with this configuration. Moreover, the two-finger gripping configuration uses the minimum number of fingers thus implying ease of control (Bicchi and Kumar, 2000). In fact, for the custom made gripper used for the book retrieval robot, one of the gripper fingers is fixed and hence always remains static while the other finger is mobile and is responsible for the gripping (closing) and releasing (opening) actions. As a result, only a single actuator, a DC motor, is required for operation of the gripper. A direct result of this minimalist configuration is that it greatly simplifies overall gripper assembly. The gripper configuration is shown in figure 5. The grasping force, \( F_g \), of the two-finger gripper as a function of the actuator (motor) torque, \( \tau \), is given by:

\[
F_g = \frac{\tau}{r \cdot \tan \alpha}
\]

where, \( \tau \) is torque of the motor (N), \( r \) is the pitch radius of the thread (m) and \( \alpha \) is the pitch angle of the thread (rectangular). The minimum grasping force that suffices to securely grip an object without slip is calculated using Eq. 2:

\[
\mu \cdot n_f \cdot F_{\text{min}} = w \cdot g \cdot S
\]

where

- \( \mu \) = coefficient of friction
- \( n_f \) = number of contacting fingers
- \( F_{\text{min}} \) = minimum gripper force (N)
- \( w \) = weight of object (N)
- \( g \) = gravitational acceleration (\( m/s^2 \))
- \( S \) = safety factor

A force sensor has been installed inside the interior surface of one of the gripper fingers. Use of the force sensor provides some dexterity to the gripper in the grasping and retrieval of a book as the software continually reads the force that is applied to the gripper fingers and keeps on winding the motor until a predetermined force is attained.

After the gripper has securely gripped the book when the Probe has pried it out of the bookshelf, it then has to retract back horizontally to retrieve the entire book out of the shelf. For this task, a drawer slider has been modified to provide forward / backward movement for the entire gripper unit. The drawer slider is simply a rotary slider that is capable of expanding its length and retracting it. The whole gripper unit has been mounted on this slider and this concept has been used in the horizontal movement of the gripper.

The gripper is the one component of the object retrieval system that is application or object specific.
Book Retrieval Mechanism
The book retrieval mechanism was contrived and constructed based on the replication of the actions of the human hand in retrieving a book.

Since the maximum height of a book to be retrieved is set to 30cm, the Probe is set at a height (30.5cm) slightly higher than this prior to the commencement of a retrieval operation. Once the scanner has identified the target book, the Probe extends horizontally into the bookshelf and is over the top of the target book. The guide motor then rotates to move the Probe vertically down, applying a downward force on the book. When a certain magnitude of force is attained (the determination of the magnitude of this force is explained in subsequent sections), the Probe then retracts back horizontally. Since there is a sufficient downward force and friction present, the book starts to tip on its end, into the gripper fingers.

The Probe is made out of aluminum and measures 25cm x 8cm. It has grooves fabricated on the end that retrieves a book to create the necessary friction. A motor is used to actuate this back and forth horizontally on a linear slider with a (nylon) rope drive being used to transmit power from the motor shaft to the Probe. It is aligned precisely with the gripper and barcode scanner as the barcode scanner provides the reference point for the book extraction operation. Additional details of the robot operation in a book retrieval maneuver are given in Chand and Onwubolu (2006, 2007). A 3D model of the entire book retrieval mechanism, illustrating the mounting of the barcode scanner and placement of the gripper is given in figure 6.

CONTROL ELECTRONICS

This section describes the electronics implementation of the robot.

Power Supply
Direct current (DC) is far by the most predominant power source in mobile robotic applications. Thus two rechargeable, lead acid 12V 7Amp/hr batteries have been used for providing current in the book retrieval robot with one of the batteries used to supply current to all the motors and the other for all the electronic and sensor circuits. A simple regulator circuit regulates the 12V supply to 5V for the electronic and sensor circuits. With typical loading, the robot can continuously operate for approximately ninety (90) minutes.

Controller
The hub of operations and intelligence of the book retrieval robot is a Pentium IV 1.5GHz laptop computer running under the Red Hat Linux operating system. All electronic and sensor circuits and control hardware are interfaced to this laptop as shown in figure 7 through the enhanced parallel port using a custom designed interfacing card described in subsequent sections. Customized software written in the C++ programming language provides the cognition and intelligence for the robot.

The secondary controller of the robot is a PICmicro® microcontroller, specifically the Microchip Technology PIC16F877 eight bit CMOS microcontroller with built in EPROM. The microcontroller is available as a 40-pin DIP package containing a central processor, EPROM, RAM, timer(s), and TTL / CMOS compatible or user defined input and output lines (Microchip, 1999). This microcontroller is responsible for coordinating and receiving sensory information from some of the sensors. Use of this microcontroller as a secondary controller also provides a method of distributed computing and decentralization of the robot operations. Also, the interrupt feature of the microcontroller is heavily utilized for retroactive and instantaneous detection of sensor outputs.

Parallel Port Interfacing Card
The onboard laptop requires an appropriate interfacing medium to physically interface with the control hardware. For this a custom designed, Enhanced Parallel Port (EPP) based, bidirectional, software selectable, input and output card encompassing a 74LS00 NAND gate, 74LS04 inventor, 74LS138 Decoder, four 74LS373 tri-state latches, two 74LS244 buffers, eleven (11) 150Ω resistors and two (2) 1kΩ resistors was used. The laptop is physically connected to this card via a

Fig. 6. Diagram of guide depicting mounting of gripper, barcode reader and book retrieval mechanism

Fig. 7. Laptop – electronics interfacing via parallel port interfacing card
male to female parallel port cable, mated with a DB25 Pin 90 PCB Mount connector mounted on the printed circuit board (PCB).

Out of the twenty five (25) pins of the parallel port, eleven (11) are of specific interest as the operation of the interfacing card is totally centered on these pins. Eight of these, Pins 2 to Pin 9 are the data pins; it is through these data pins that codes are generated by the software and sent to the electronic devices and actuators for activation and deactivation. (The codes are in the form of logic pulses. Logic high activates an electronic component, say a DC motor, and conversely logic zero deactivates the motor). These data pins are the common inputs of two 74LS373 latches; the primary function of the 74LS373’s is to latch the data sent through these pins. The eight outputs of the two 74LS373’s each are then the inputs of two 74LS244 buffers which boost the current. The outputs of the buffers then form the overall output port of the parallel port interfacing card containing sixteen individual output pins in the form of PCB connectors.

For the input port, PCB connectors have similarly been used to interface any input devices, such as limit switches, to the interfacing card. There are sixteen individual input pins on the input port; these are then fed to two 74LS373 latches so that any input data is latched. The outputs of these IC’s are then interfaced with the eight data lines coming from the parallel port.

At this stage, it is worthy to note that both the output lines and input lines of the parallel port interfacing card utilize the same eight data lines of the parallel port. By implication, a means of selecting the interfacing card’s instantaneous role as either an output device or input device had to be formulated. For this, a selector, more specifically the 74LS138 decoder was used where, in addition to the eight data pins already used elsewhere, three control signals, namely the Address strobe, Data strobe and Write Enable pins of the parallel port are used as the control signal lines of the 74LS138 decoder. Two outputs of the decoder (Q5 and Q6) are then interfaced to the two output 74LS373 latches and likewise two more outputs of the decoder (Q1 and Q2) are interfaced to the two input 74LS373 latches. The selection of the interfacing card as either an input device or output device is implemented in software by selecting values of strobe, Data strobe and Write Enable such that the respective decoder output, either the output that controls the reading of data (Q5 and Q6) or the decoder output that controls the writing of data (Q5 and Q6) from the parallel port is activated. The value selection originates from the decimal value of each pin of the parallel port. In this way, the robot can generate control signals to control some electronic hardware as well as to read sensor inputs.

**Motor Controller Circuits**

The technology employed for motor controlling in this research project was a motor driver monolithic IC, specifically the SN754410NE Quadruple Half-H Driver from Texas Instruments. This integrated circuit has two complete internal H-bridge circuits that can be used to independently power and control two separate DC motors and it is capable of supplying a continuous sustained current of 1A and 2A of current momentarily. The IC is available as a 16-pin DIP package containing internal protection diodes, anti-sinking / sourcing circuitry and TTL and low-level CMOS compatible, high-impedance, diode clamped input lines. The internal flyback diodes are a desirable feature as once it has been switched off, the back electromagnetic (emf) force or voltage spike generated by the inertia of a motor can easily damage the electronics of the integrated chip and this is a problem commonly encountered in the designing of motor controller circuits. Other features of the SN754410NE include an automatic thermal shutdown facility should the temperature rise abnormally, a wide supply voltage range from 4.5V to 36V and separate supply voltages for the logic input pins and output driver pins for minimized power dissipation. Though the SN754410NE has a peak current output of only 2A, and the motors used for the robot may well exceed this amount in the current it draws, a very useful feature of the SN754410NE IC is that it can be cascaded in parallel for increased output current. The way in which the motor direction is controlled, based on the input signals provided to the SN754410NE, is illustrated in the truth table of Table 2.

<table>
<thead>
<tr>
<th>In 1</th>
<th>In 2</th>
<th>Out 1</th>
<th>Out 2</th>
<th>Motor direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0V</td>
<td>0V</td>
<td>stop</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0V</td>
<td>12V</td>
<td>clockwise</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>12V</td>
<td>0V</td>
<td>anti clockwise</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>12V</td>
<td>12V</td>
<td>-</td>
</tr>
</tbody>
</table>

The exhibit of figure 8 illustrates the basic functional circuit diagram of the SN754410NE being interfaced to two DC motors. The control input and enable signals (In1, In 2 and EN respectively) to control the rotational directional of the motor are generated by the laptop and transmitted through the output port of the parallel port interfacing card.

**Sensors and Transducers**

Four major types of sensors and transducers are used in the robot for sensory information feedback.

**Obstacle Detection.** Sharp infrared GP2Y0D02YK sensors having a detection range of 80cm ± 10cm have been installed in the front and rear panels of the book retrieval robot to detect any dynamic obstacles, should one obstruct the path of the robot. The selection of these sensors is primarily attributed to their ease of implementation and more importantly the fact that the TTL compatible, Boolean logic output of the IR sensors can be directly and unconditionally interfaced to a digital circuit, more specifically the input port of the parallel port interfacing card using only pull-up resistors to ensure correct logic levels.
The laptop controller coordinates and processes the sensory information from these sensors with one of the input ports of the parallel port interfacing card being interfaced to the sensors. The interrupt handler for the event when an obstacle is detected generates and transmits logic low signals to the wheel motor controller circuits through the parallel port and the corresponding interfacing card so that for as long as the sensor outputs are low, the robot moves continually; otherwise if a sensor output is high, the robot halts indefinitely.

**Navigation.** The book retrieval robot uses a guided navigational technology, namely line tracing similar to that of Kumar and Onwubolu (2003). Guidance is chosen for the reason it is best suited where path flexibility is not critical or where there are no immediate plans to alter the vehicle path layout in the intended environment of the robot. Since bookshelves are normally unlikely to change their orientations and positions without human intervention, the book retrieval robot is guided by pre-arranged external signals, in the form of suitable guide paths that lead to the book shelf. The basic idea is to set up the highways and paths that the robot will take utilizing suitable guide paths. With this priori knowledge, the robot knows what the navigation route is. All it does is to follow the navigation route upon commencement of the software execution. With the current experimental setup, a single bookshelf is used implying a single guide path. However, the concept can be easily be extrapolated to consider a number of bookshelves. In this scenario, there would be a number of navigation routes and the robot would have to make a decision on the selection of one route. The analysis of the target book’s call number will do this. Different shelves will have to have some distinction in the guide paths that lead to it, depending on the order and pattern of the placement of books. Routing could then be implemented in hardware, possibly using different colored or frequency emitting guide paths or alternatively, that routing could be implemented in software. The controller is used to coordinate the sensors used to trace the guide paths. The sensors are the SLD-01 line tracer sensors from Lynxmotion with 50mm white lines leading to and running along the bookshelves representing the route the robot has to follow. A deviation of the robot locomotion to either side of the route causes the interrupt handler to execute correctional moves for the realignment of the robot with the navigation route.

**Force Feedback.** Force feedback and dexterity is provided to the robot gripper during a book extraction operation by means of a force sensing resistor (FSR). The Flexiforce A201 force sensor illustrated in figure 9 exhibits a decrease in resistance commensurate with an increase in the force subjected to its active sensing area and vice versa.

Fig.9. Flexiforce force sensor

Two of these force sensors have been utilized in the book retrieval manoeuvres. The first sensor is attached to the book retrieval mechanism to determine the correct magnitude of force that suffices to retract a book out of the bookshelf while the second sensor, attached to the inside one of the gripper fingers, determines the force with which the gripper securely grips a book. The magnitudes of these forces are determined empirically during the testing and experimentation phase and then used as a reference set in the software.

Quantification of the analog output voltage into a discrete digital representation is then achieved using the internal 8-bit, self-clocking and successive approximation analog to digital converter (ADC) of the PIC167877 microcontroller with the output voltage being interfaced to one of the ADC ports.

**ROBOT INTELLIGENCE**

The software that provides the robot cognition and intelligence is written in the C++ programming language under the Linux OS (Red Hat distribution version 9). Linux is chosen as it provides direct access to hardware and fares better than other conventional operating systems such as Windows in real time hardware operations.

Notably embedded systems designs encompass concurrent and iterative designs of hardware and software. Therefore the incremental model (Pressman, 1997) may be the best model for creating the software for a hardware embedded application. This model characterizes the iterative nature of development where initial iterations attain basic functionality and subsequent iterations implement more advanced functionalities.

All behaviours of the robot (mechanical actions) have been represented as functions and all attributes are represented as data variables in the software. Invocations of these functions in their required sequences attain the book retrieval manoeuvres. Logically related functions and data are then grouped together and have been implemented in classes as methods and attributes which imply Object Oriented (OO) methodology. The software development phase has utilized the OO methodology to attain abstraction and modularity.

There are in fact three layers of the software, representing a three tier system. The first tier is the human-machine interface in the form of a Graphical User Interface (GUI). The GUI has been developed using Borland’s Kylix C++ IDE. The second layer is the main robot control software encompassing the robot intelligence, logic behaviours and mechanical functions. This tier is developed using the Linux g++ compiler. As stated previously, a PIC microcontroller has also been used as a secondary controller and this constitutes the third tier encompassing the utilization of features such as interrupts and an analog-to-digital converter (ADC). The software organization is demonstrated in figure 10.

Fig.10. Software nomenclature.
The software developed for the barcode scanner is fundamentally a half duplex, interrupt driven, software implementation of PS2 communications. Reception of a byte written at the PS2 port by the barcode scanner is automatically invoked whenever the barcode scanner scans in a barcode. The software codes for the data retrieval are part of standard C++ language/libraries and hence guarantees that the code used to retrieve data from the PS2 port will be platform-independent and thus compile under either Windows® or Linux platform while simultaneously having the merit of being machine-independent. Since it can be seen that the software retrieval of data scanned by the barcode scanner does not utilize any industry standard software such as MATLAB or LabVIEW and uses elementary C++ programming, it does not constitute computation overhead as is the case with using computer vision for book detection and identification as done by researchers (Tomizawa et al, 2003a, 2003b 2003c) in related work.

EXPERIMENTAL RESULTS

Several experiments were designed and conducted to verify the validity of the developed robot. Test cases were developed and metrics of measurement to quantify the operational performance of the robot were derived from these tests.

Amongst others, one of the more important experimentations was the determination of the optimum robot speed that sufficed to accurately scan book barcodes. The experimentation consisted of performing a scan operation with varying robot speeds, starting from its nominal speed and decrementing, and noting the corresponding accuracies. The speed at which the barcode scanner yielded the best accuracy was then the optimum robot speed. In the context represented here, accuracy was derived from some fundamental reliability-based metrics and it basically refers to the percentage of books positively identified in relation to the total books present in a shelf. The results are tabulated in Table 3 and figure 11.

Table 3. Determination of optimum robot speed

<table>
<thead>
<tr>
<th>Robot speed (cm/s)</th>
<th>% Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>2.0</td>
</tr>
<tr>
<td>55</td>
<td>5.0</td>
</tr>
<tr>
<td>50</td>
<td>6.7</td>
</tr>
<tr>
<td>45</td>
<td>6.3</td>
</tr>
<tr>
<td>40</td>
<td>25.1</td>
</tr>
<tr>
<td>35</td>
<td>35.3</td>
</tr>
<tr>
<td>30</td>
<td>61.6</td>
</tr>
<tr>
<td>35</td>
<td>83.3</td>
</tr>
<tr>
<td>20</td>
<td>98.3</td>
</tr>
<tr>
<td>15</td>
<td>100.0</td>
</tr>
<tr>
<td>10</td>
<td>98.3</td>
</tr>
<tr>
<td>5</td>
<td>100.0</td>
</tr>
</tbody>
</table>

A number of books were initially undetected at high robot speeds. It was established that the robot was travelling at speed higher than the scan rate of the barcode scanner and as a result, some books were undetected. However, gradual reduction of the robot speed yielded improved results with accuracies even reaching 100%. Henceforth, one important control parameter directly derived is the maximum speed, \( V_{\text{max}} \), with which robot can move to allow the barcode scanner to correctly read barcodes. The (maximum) speed for which the best performance values were obtained was identified as the optimum speed and from the results, the value obtained was 15cm/s.

For benchmarking and comparison with results emanating from related work, another important metric measured was the time required for the detection and identification of books. This book seek-time analysis was imperative for quantifying the efficacy of the barcode scanner as a plausible book identification device in relation to related work. Another important parameter indirectly obtained was the computational or algorithmic complexity required to perform the scanning. Configured with the optimum speed determined in the preceding experiment, the time taken for the robot to scan and localise a shelf full of books were recorded.

Table 4. Time incurred in localisation of 20 books.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Time taken to scan twenty books (s)</th>
<th>Average time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.5</td>
<td>0.475</td>
</tr>
<tr>
<td>2</td>
<td>8.9</td>
<td>0.445</td>
</tr>
<tr>
<td>3</td>
<td>9.4</td>
<td>0.470</td>
</tr>
<tr>
<td>4</td>
<td>9.0</td>
<td>0.450</td>
</tr>
<tr>
<td>5</td>
<td>9.3</td>
<td>0.465</td>
</tr>
<tr>
<td>6</td>
<td>9.5</td>
<td>0.475</td>
</tr>
<tr>
<td>7</td>
<td>9.2</td>
<td>0.460</td>
</tr>
<tr>
<td>8</td>
<td>8.8</td>
<td>0.440</td>
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<tr>
<td>9</td>
<td>9.1</td>
<td>0.455</td>
</tr>
<tr>
<td>10</td>
<td>9.0</td>
<td>0.450</td>
</tr>
<tr>
<td>Mean</td>
<td>9.17</td>
<td>0.4585</td>
</tr>
</tbody>
</table>
TOWARDS OBJECT RETRIEVAL ROBOTS FOR INDUSTRIAL MATERIAL HANDLING SYSTEMS USING BAR-CODING TECHNOLOGY

Aneesh N. Chand

Table 5. Experimental results for target stopping response distances

<table>
<thead>
<tr>
<th>Exp No.</th>
<th>Dist traveled by Robot (cm)</th>
<th>Deviation (cm)</th>
<th>Actual Dist. (cm)</th>
<th>Mean Dist. traveled (cm)</th>
<th>Mean Deviation (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Trial 1</td>
<td>Trial 2</td>
<td>Trial 3</td>
<td>Trial 1</td>
<td>Trial 2</td>
</tr>
<tr>
<td>1</td>
<td>33.0</td>
<td>33.0</td>
<td>33.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>46.0</td>
<td>46.0</td>
<td>46.1</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>69.5</td>
<td>69.7</td>
<td>69.4</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>4</td>
<td>92.6</td>
<td>92.6</td>
<td>92.8</td>
<td>0.1</td>
<td>0.1</td>
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<tr>
<td>5</td>
<td>115.7</td>
<td>115.7</td>
<td>115.9</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>6</td>
<td>135.8</td>
<td>135.9</td>
<td>135.9</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>7</td>
<td>180.8</td>
<td>180.8</td>
<td>180.7</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>8</td>
<td>204.5</td>
<td>204.5</td>
<td>204.2</td>
<td>0.4</td>
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<tr>
<td>9</td>
<td>219.5</td>
<td>219.6</td>
<td>219.4</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>10</td>
<td>235.8</td>
<td>235.5</td>
<td>235.7</td>
<td>0.5</td>
<td>0.2</td>
</tr>
</tbody>
</table>

standard deviation, \( \sigma \) 0.122152

Examination of the results in Table 4 shows that it takes the barcode scanner, on average 9.17 seconds to scan the barcodes of twenty books and realize their identities and an average time of 0.4585 seconds to realize the identity of a single book. Considering the results of Prats et al. (2003), where it took a minimum of 6 seconds and maximum of 11 seconds (1 second to localize a label from an image and an additional 5-10 seconds for the image processing and optical character recognition phase) to carry out the same task, it is clearly evident that a barcode scanner fares better than cameras in the process of object identification. The average time is also directly indicative of the computation power required in using a barcode scanner; this is a major merit of barcode scanners over other currently available identification techniques.

The next first important test consideration investigated was the halting of the robot upon the detection of a target book. This consideration was important because the instantaneity of the robot halting upon detection of a target book is imperative in identifying the reference point for the book extraction operation; if the robot halts the exact instant the barcode scanner has identified the target book, the robot will be positioned precisely in front of the book execution of the book retrieval manoeuvres is possible. Conversely if not, the robot then may not be precisely aligned with the target book. Therefore the experiments in this phase consisted of issuing a number of randomly selected book call numbers to the robot and measuring the target stopping response distances, including deviations if any, upon detection of the target book by the barcode scanner.

From the results tabulated in Table 3, it was noted that as the distance travelled by the robot before detection of a target book increased, the deviation increased. That is, the robot tended to travel slightly past a target book before stopping when it had travelled a longer distance. This is attributed to the fact that the momentum and inertia attained provided opposition to the robot to exit from its persisting state of motion and halt. Therefore it tended to travel slightly past the target book before coming to a complete halt. However, the mean of this deviation shows that this distance is quite minute and therefore negligible. The maximum deviation recorded was just 0.37 cm and since this value is much smaller than the width of the Probe, it may be trivialized. The fact the concept of interrupts rather than polling was used in software to send the low signals to the microcontroller motor control signal input pins led to these extremely low values of deviation.

Finally, the overall experiment involved testing whether the robot was capable of autonomously retrieving books. It was noted that the robot successfully performed a search and retrieve operation 53% of the time while book slippage occurred during the remaining trials.

CONCLUSIONS

The objective of the work described in this paper was the design and development of a robot with the aptitude to search and retrieve a specified object. This was achieved by first designing the mechanical structure of the robot. This includes the robot framework, steering mechanism, the gripper and book retrieval mechanisms. The robot moves along a predefined path leading it to the books. Various electronic technologies are implemented for, including but not limited to, the steering, locomotion, navigation, speed control and motor actuation. The employment of an innovative and practical system, a typical and inexpensive barcode reader, provides the technology with which books are searched for. The scanner scans the barcodes of books to match the scanned book call number with the user entered book call number. An affirmative match results in a positive identification and the robot then executes a systematic chain of book retrieval manoeuvres. With minor application specific changes, the system described has direct implications in the warehousing and manufacturing milieu.

The above results were attained in a controlled environment encompassing a number of constraints. Notably, books were unallowed to be tilted to the extent that the barcodes would fall outside the scanning view of the barcode scanner. This was deemed as reasonable as a certain degree of uniformity is required in the arrangement of books in order for the process to be automated. Experimental results illustrated the validity of the robot developed with the attainment of a robot prototype with a book identification accuracy of 98% and performance efficacy (percentage success) of 53% in physical retrieval of books.

As future work, possible improvements could include tele-operation control via the Internet and integration of a speech synthesizer with pre-programmed speech to incorporate verbal announcement of book retrieval.
REFERENCES


