A Robotic Library System for an Off-Site Shelving Facility

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Abstract

This paper describes a unique robotics project, Comprehensive Access to Printed Materials (CAPM), within the context of libraries. As libraries provide a growing array of digital library services and resources, they continue to acquire large quantities of printed material. This combined pressure of providing electronic and print-based resources and services has led to severe space constraints for many libraries, especially academic research libraries. Consequently, many libraries have built or plan to build off-site shelving facilities to accommodate printed materials. An autonomous mobile robotic library system has been developed to retrieve items from bookshelves and carry them to scanning stations located in the off-site shelving facility. In subsequent stages, remote users will be able to trigger this process through a web interface in order to achieve real-time browsing of printed materials. Enhanced commercial robot systems are used in this project. The developments of the robot design, control systems, simulations, experiments and results are presented.

1. Introduction

1.1 Background and goal

This paper describes a unique robotics project, Comprehensive Access to Printed Materials (CAPM), within the context of libraries. As libraries provide a growing array of digital library services and resources, they continue to acquire large quantities of printed material. This combined pressure of providing electronic and print-based resources and services has led to severe space constraints for many libraries, especially academic research libraries. Consequently, many libraries have built or plan to build off-site shelving facilities to accommodate printed materials (and sometimes microfilm and microfiche collections as well). These off-site facilities offer lower real estate costs and provide superior environmental conditions for printed materials (i.e., controlled temperature and humidity). However, given that these locations are not usually within walking distance of the main library, access to these materials, specifically the ability to browse, is greatly reduced, if not eliminated. Libraries with such facilities offer extensive physical delivery options from these facilities, sometimes offering multiple deliveries per day. Even with such delivery options, the ability to browse in real-time remains absent. The goal of the CAPM Project is to build a robotic, on-demand and batch scanning system that will allow for real-time browsing of printed materials through a web interface. Additionally, an economic cost-benefit analysis of the system has been conducted concurrently. We envisage the system will work as follows: an end user will identify that a monograph is located in an off-site facility. This end user will engage the CAPM system that, in turn, will initiate a robot that will retrieve the requested item. The robot will deliver this item to another robotic system that will open the item and turn the pages automatically. By using existing scanners, optical character recognition (OCR) software, and indexing software developed by the Digital Knowledge Center (a research and development unit of the Sheridan Libraries at Johns Hopkins), the CAPM system will not only allow for browsing of images of text, but also for searching and analyzing of full-text generated from the images.

1.2 Overview of this paper

The contexts presented here consist of developments in the robot design, control systems, simulations, experiments and results. The robot is initially equipped with a database system of book locations and a global map of the off-site shelving facility. This facility consists of more than thirty rows of >10-foot-high bookshelves with 6-feet wide aisles between shelves. At first, the robot is parked at the docking station waiting for an item request. After receiving a request, the robot will autonomously run along a known path to the book location and retrieve the requested item from the shelf. The robot will carry the item back to the scanning station, and will then return to the docking station. Each item is assumed to be stored in a specific designed case, and arranged side-by-side with a small gap between cases.

Enhanced commercial robotic systems are used in this project. An ultrasonic ranging system and an infrared sensor system are employed in order to improve the navigation system of the robot. A barcode scanner is used to ensure the precision of book picking.

In 1995, Hansson introduced an industrial robot in a Swedish library [1]. Safaric *et al* presented an example of a telerobot controlled via Internet [2]. Byrd introduced a successful service robot used to survey and inspect drums containing low-level radioactive waste stored in warehouses at Department of Energy facilities [3]. This mobile robot also required similar structure to our robot.

The CAPM system differs from existing systems in the following ways. First, the system retrieves individual items, as opposed to boxes of items, such as the system at the University of California-Northridge [4]. Second, the CAPM system does not assume an existing or fixed shelving and space arrangement. This flexibility will allow it to work in many diverse environments. Third, the CAPM retrieval robot is autonomous and can navigate independently (i.e., it does not require remote control). Fourth, the economic analysis has provided evidence that the *relatively* inexpensive system is cost-effective, especially in comparison to potential benefits. Finally, the page-turning system, to be built in the subsequent phase, will accommodate a wide diversity of paper types and materials.

In subsequent sections of this paper, we report the design, control systems, experiments and results of an autonomous robotic library system for an off-site shelving facility, the Moravia Park shelving facility, a part of the Sheridan libraries at Johns Hopkins University. Section 2 describes the robot design and navigation system. Section 3 explains the robot control systems and software used in this project. We then report on the simulations, experiments and results in section 4.

2. Mechanical Structure and Navigation System

2.1 Mechanical Structure

In this section, designs and descriptions of two major components in the CAPM library robot are presented. The two major subsystems for the design are the manipulator arm and the locomotion device. The manipulator arm is responsible for picking and retrieving the books and the locomotion device is responsible for the gross motion of the robot.

2.1.1 Manipulator arm system

In order to retrieve books from the bookshelves and carry them to the scanning stations, a specific manipulator arm system is designed. Since each bookshelf is >10-foot-high, we require a vertical translation system to move the robot manipulator to different altitudes. The vertical translation system is a sliding rod with an electric motor for driving a lead-screwed rod. An enhanced commercial 6-DOF robot manipulator, the F3 made by CRS Robotics, Inc., is affixed to a platform which is a part of the vertical translation system. The robot manipulator requires a driver/controller unit and a power source. Therefore, both the controller and power source must somehow be carried by the locomotion device. We will briefly discuss how we integrate both the controller and power source in the next subsection. Figure 1 illustrates the integration of the vertical translation system and the robot manipulator.

A homemade passive gripper was built and installed to the end-effector of the robot manipulator. The gripper is used to passively grasp the bookcase. The structures of the gripper and bookcases are designed to fit to each other. A barcode scanner is installed inside the gripper in order to recognize and ensure the precision of picking a requested item. Another advantage of having the barcode scanner installed in the gripper is the freedom of the sensor's motion in 3-D space, similar to the concept of eye-in-hand manipulator. The barcode scanner used in this project is similar to the type which is currently used in the main library. Therefore, the barcode system of the library is not affected as a result of using this project. Figure 2 shows the gripper and barcode scanner installed in the gripper.

Figure 1: The vertical translation system integrated with the robot manipulator.

2.1.2 Locomotion device

The locomotion device is responsible for the gross motion of the robot. We have modified a commercial servo-controlled mobile robot platform, the Labmate made by Helpmate Inc., to be the driver of the system. Since we require a robot manipulator controller and a power source, an aluminum-alloy cart is built and attached to the Labmate mobile platform. This cart is used to store the robot manipulator controller and the power source while the Labmate mobile platform is used as the base of the manipulator arm system (i.e., vertical translation system, robot manipulator). A ranging sensor system is installed on the mobile platform to corroborate and improve the navigation system. We will discuss about the sensor system in the next section. All electronic devices used to control the vertical translation system and sensor systems are installed on the mobile platform. The high level controller of the library robot system, an Intel Pentium II notebook, is separately installed on the cart attached to the mobile platform. Because of the installation of a power source onboard, the robot does not require an external power line while working. Figure 3 illustrates the modified platform with installed onboard devices.

2.2 Navigation System

In its operation, the library robot will follow paths based on a global map. The library robot is taught to know the global map of the experiment areas such as the docking area, paths to bookshelves, and the book-table destination. As in any system where we state a trajectory and expect the system to follow it, perturbations can cause deviation from the programmed route. In our system, possible disturbances are things such as wheel slippage, which is common in the differential steering scheme used by our mobile platform, and the floor of the library, which is not a perfectly level surface. In order to counteract these disturbances and stay on a trajectory that is as close to the desired as possible, a simple feedback control system is employed. Feedback for our system's trajectory is given in the form of range sensor distances.

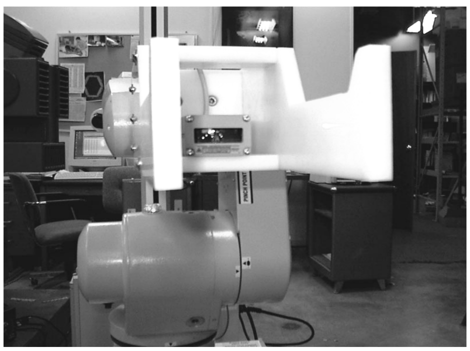


Figure 2: The gripper with a built-in barcode scanner.

Figure 3: The modified platform with installed onboard devices.

Figure 4: The sensor module.

For our ranging sensor system, 4 sensor readings are taken. Two are from the front side of the mobile platform symmetrically opposite each other on the left and right side. The other two are from the left and right side of the mobile platform. Using these measured distances, we can generate an error signal to correct the path instantaneously and successfully adhere to the desired route.

In actuality, due to limits of sensor performance, 8 sensors are used: 4 sonar sensors and 4 infrared sensors. A sonar and infrared sensor are paired together to get each of the 4 sensor readings needed. This is done because of the distance measuring limits which each have. The Polaroid 6500 sonar sensor used has a range of 15-1067 cm while the Sharp GP2D02 infrared sensor used has a range of 10-80 cm. It can be observed that by using these two sensors as one, we can achieve a range of 10-1067 cm of reliable distance measurement. Each sensor is controlled and interfaced to the main computer via a micro-controller (BASIC Stamp II). Figure 4 shows the sensor module, which consists of the 8 ranging sensors.

3. Controls and Software

All the processes and activities of the system are controlled by an onboard laptop.

3.1 Control of the mobile platform

The mobile platform called the Labmate has the drive system microprocessor that the user's host computer communicates with through an RS-232 serial port. The host computer always initiates communications between the host computer and the Labmate. Control programs are written in C language and downloaded to the drive system microprocessor.

The Labmate uses a Cartesian coordinate system for position control. The coordinate system is a global reference that is initialized at power up and reset. Heading is represented in degrees between 0 and 359.99. Velocity ranges from 0 to 1000 mm/sec.

Odometry (dead reckoning) is the practice of calculating position from wheel displacements. The Labmate control system depends on encoders mounted on each wheel to keep track of position. Control programs are basically composed of commands that direct the Labmate to a particular location. We assume here that the entire map of the workspace is stored in the form of a look-up table in the memory of the Labmate. If a destination is given, the Labmate computes the direction from the current location by referring to the look-up table. The direction generally consists of turns and straight-line motions in either the X or Y direction.

Essentially the same control scheme is used for both straight-line motions and turns. With the distance to the destination calculated, an incremental motion command will calculate the difference between the current location value and the commanded location value and execute and incremental motion of that value. This routine is repeated until the commanded location is attained.

Wheel slippage causes errors that accumulate over distance traveled. To compensate for the errors, we use two kinds of sensors: ultrasonic ranging sensors and infrared sensors. For more successful navigation of an autonomous vehicle over extended distances, references to the external world at regular intervals are necessary.

3.2 Control of the robot arm

We use the six-axis F3 robot system manufactured by CRS robotics. Articulated joints provide the F3 arm with six degrees of freedom and absolute encoders mounted on the motor shaft in each joint provide positional feedback to the controller. The F3 robot arm uses the Cartesian coordinate system. The controller of the F3 uses a 133 MHz i486DX for a system processor and a 60 MHz TMS320C31 DSP for motion control. The Console port of the controller uses is a standard DB-9 connector and is used to connect a development computer to the controller. The serial port is configured to communicate at 57600 baud.

Control programs are written in the C++ language and downloaded to the controller. Control programs use the ActiveRobot interface developed by CRS robotics and include two object classes of the ActiveRobot interface: one provides the application with main interface to the robot system, and the other enables the application to create and modify robot locations. The input variables to the control programs are the speed and the position and orientation of the final location of the end-effector, and the controller provides the computation of inverse kinematics.

3.3 Control of the vertical translation device

A circuit board was built to control the vertical translation device and interface with the onboard controller. This circuit board consists of a micro-controller (Basic Stamp II) and a set of electronic relay switches used to control the direction of a driving motor built into the device. The board communicates with the controller through a RS-232 serial port.

3.4 Control software

The control software is designed based on the idea of event driven programming. Principally, the main control program controls the mobile platform, the vertical translation device, and the arm through serial ports. When the main control program begins to run, it initializes the serial ports of the computer at first and starts the event listeners for all the serial ports. Then the main control program leaves the control to the listeners. It is actually these event listeners that control the movement of the platform, the vertical translation device, and the arm. Basically, each event listener will monitor the status of one serial port. Once the status of that port changes, the listener will judge what kind of event happens and execute a corresponding function. We use the word ‘lift’ interchangeably with ‘the vertical translation device’.

An important property of event driven programming is that the execution order of the functions is not fixed, it depends on the need to execute. This property is suitable for the sensor driven system of the library robot. In total four event listeners are created. They monitor the status of the platform, the lift, the arm, and the sensors respectively.

To complete the process of picking up a book, after the sensor listener receives the “ready” signal from all the sensors, it will call the platform controller to start the platform. Once the platform reaches the bookshelf, the platform listener will receive a “shelf arrive” signal, and call the lift controller to raise the lift. Once the lift reaches desired high altitude, the lift listener will receive a “lift high” signal, and call the arm controller to stretch out the arm. After the gripper catches the book and the arm folds back, the arm listener will receive an “arm done” signal and call the lift controller to lower the lift. Once the lift goes down to the low altitude, the lift listener will receive a “lift low” signal, and call the platform controller to move the platform to the desk. Then following another event driven process, the book is put on the top of the desk. Figure 5 shows the software structure of the robot.

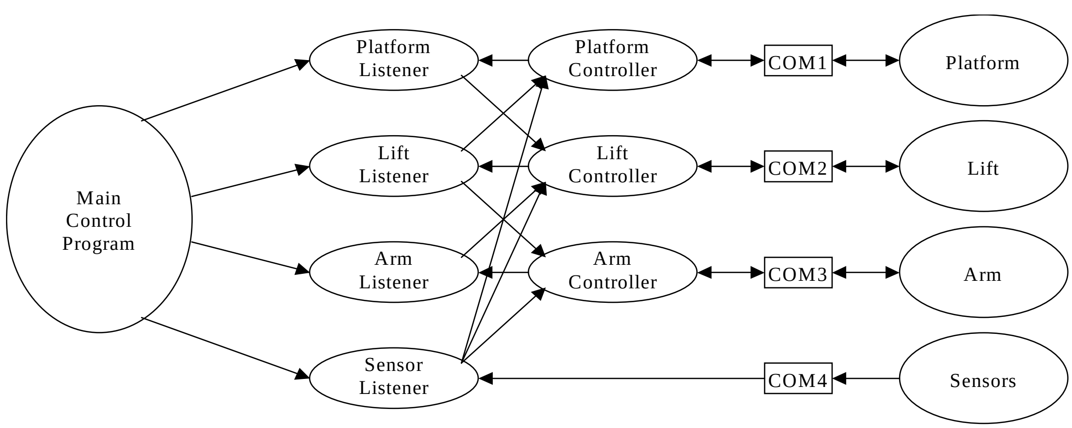


Figure 5: Software structure of the library robot.

4. Simulations and Experiments

To assist the motion planning of the library robot, the complete working process of the library robot is simulated with 3DSMAX (Figure 6). The simulation shows the library robot moving from the docking area to the desired bookshelf, picking up a book, carrying the book to the desk, putting the book on the desk, and returning to the docking area.

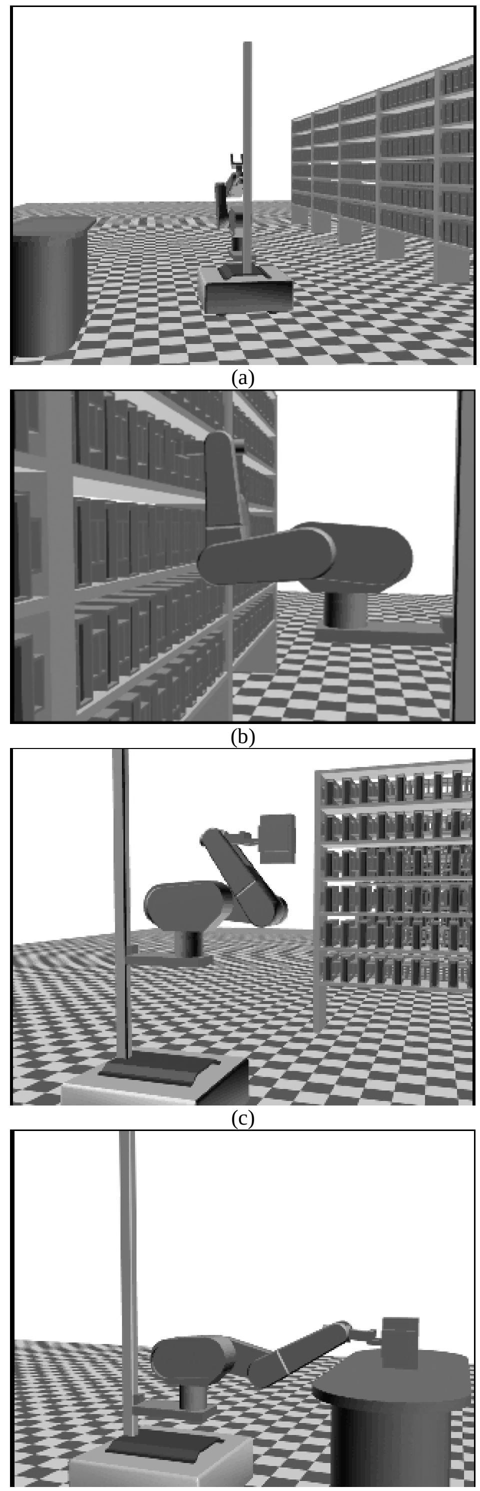
Based on the simulation, a complete path is generated, and experiments are executed to test and adjust the performance of the robot.

To simplify the implementation, a map-based scheme is employed to control the mobile platform. The complete path is divided into three parts (Figure 7). A fixed global coordinate system is defined with its origin at the docking spot. The positions of the intermediate stops and the destination are defined in the global system. An Optimal path is chosen to connect the current stop and the next stop. The major problem appearing in the experiments is positioning error. It is found that the positioning error is closely related to the moving speed of the platform. If the speed is low, the motor may lose some steps because of the certain heavy overall load. If the speed is high, the platform may deviate from the desired path at the turning corners because of the inertia. After a few adjustments of the speed setting, the positioning is improved considerably.

At each stop, the lift will move up and down to adjust the altitude of the arm so that the gripper can reach the books at different layers of the shelf or put the book on the desk. Sonar and infrared sensors are used to check the current altitude of the arm base so that the arm stops at the desired altitude. The lift control circuit and the sensors make up a closed control loop. The result of the experiments shows that it can guarantee a positioning accuracy of 5 mm.

After the lift reaches a desired altitude, the arm stretches out to either pick up the book from the shelf or put the book on the desk, and then folds back. The stretching-out movement is cooperation between the arm and the barcode scanner. The arm keeps adjusting the position and orientation of its end-effector until the barcode scanner confirms that the desired book has already been found. Then the gripper goes forward to pick up the book. After that, the arm folds back to its initial configuration. The experiments show that the positioning accuracy of the barcode scanner is 5 mm, and the accumulated error from previous movement has no impact on the positioning of the end-effector.

The complete process of moving to a bookshelf, picking up a book, delivering it to a desk, and returning to the docking spot was tested with all the devices and sensors working together. The library robot finished the whole procedure successfully.



(a) (b) (c) (d)

Figure 6: Simulation.

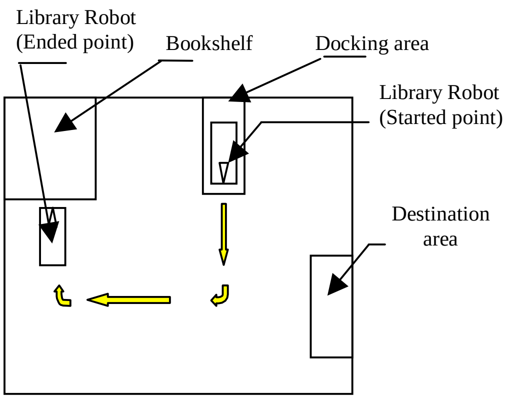


Figure 7 (a): Robot motion planning of the path section 1.

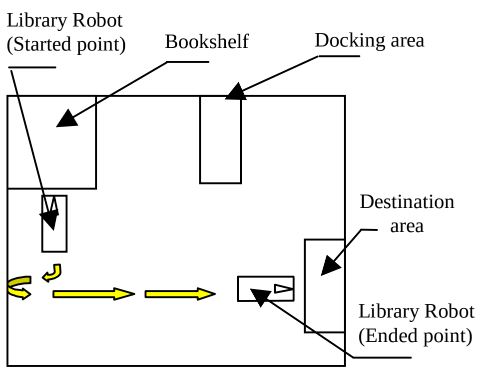


Figure 7 (b): Robot motion planning of the path section 2.

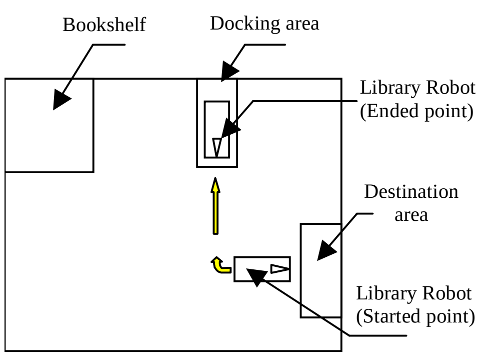


Figure 7 (c): Robot motion planning of the path section 3.

5. Conclusion

An autonomous robotic library system was built as a prototype. The robot design, control systems, simulations, experiments and results were presented. A field test will be conducted at the off-site shelving facility in the future.

While these points outline the specific benefits and qualities of CAPM, it is important to note a broader goal of this project. The CAPM Project will introduce robotics into the library and, perhaps more importantly, digital library context. As robotics have provided great impact and utility within manufacturing and, increasingly, computer-assisted surgery, it is possible that similar gains will be achieved in developing digital libraries. Already, some cultural heritage faculty and librarians have identified CAPM as the best option for digitizing the vast amounts of knowledge retained in print format. Additionally, through batch scanning, CAPM will produce automatically and systematically preserved copies of printed materials. At a recent presentation regarding CAPM, during the International Federation of Libraries Association (IFLA) conference, a cultural heritage librarian from Sweden described CAPM as a "genius project."

Reference

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