Development of an RFID-Based Semi-Autonomous Robotic Library Management System

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***Abstract*—A novel low-cost robotic solution is proposed to automate the library inventory management process of book arrangement with little to no human intervention. A line following robot with multiple sensors and actuators has been designed to operate on a path connecting bookshelves and the drop location. A CAD model for the robot is designed and various subsystems have been described in detail. The riser subsystem has been simulated to evaluate the design parameters with a desirable factor of safety. The working principle of the robot and control algorithms involved in path planning and locomotion has then been discussed through the electronic architecture and software stack sections. A simple PID control scheme for lower-level actuation has been used to control the four traction motors. The feasibility of the proposed scheme is then validated with the development of a simple pilot prototype.**

***Index Terms*—Mechatronics, Library Management System, Scissor-lift mechanism, RFID based navigation, path planning**

I. Introduction

Library management requires high-volume, repeatable and time-consuming tasks. Consequently, it has become a necessity to automate the process of library management through robotization. As a result, there have been several attempts to develop automated robotic systems for libraries in the past few years, capable of autonomously navigating through libraries and doing all the associated jobs without much human intervention and assistance. Thus, library management systems using intelligent technologies have now become an emerging topic of immense importance. Early developments in such library management systems include [1], [2] which use RFID based book shelving system, that helps in finding misplaced books. [3] uses a mobile robot to navigate in a library, scan all books and generate databases on missing and misplaced books. However, there is still a shortage in automated machines [4] that can perform tasks like book sorting, placing the returned books in allotted shelves, etc. These tasks still rely on manual operations.

In this paper, we propose a highly efficient robotic solution that automates the process of returning books to their proper shelves. Introducing robots for this task will not only reduce curator inconvenience but also increase the efficiency of the placement of books as a consequence of the improvement of speed and accuracy in which the tasks are performed. The solution is proposed in such a way that the robot will be performing the tasks during nights, when the library is closed, thereby not interfering with the regular working of the library. The robot will be able to carry books from the docking station, identify the exact location after scanning their tags, plan the shortest path, navigate to the correct shelf, separate book form the stack, lift it to the required shelf height and finally place the book in the shelf.

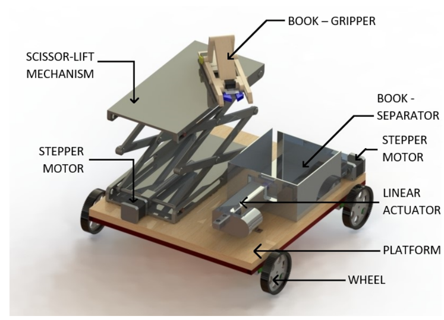

Fig. 1. CAD model of the robot.

II. Mechanical System Overview

The mechanical design primarily addresses the problem of picking up the book from the book holder and placing it in the corresponding shelf at the required height. The modular, lightweight, easy to assemble design makes the solution robust enough to work in various libraries. The robot model is designed and analyzed in SolidWorks 2017 software.

A. Chassis

Steel extrusions with square cross-section have been used for the frame of the chassis. This frame stabilizes the base and provides rigid support to hold all other subsystems of the robot. Light-weight plywood is used to cover the frame.

B. Book Holder Subsystem

An aluminium tray, mounted on the chassis, is used to place the books in a stack. It is fitted with an L-shaped rotating platform, powered by a stepper motor, at one end which is used to tilt and separate the last book in the stack. The gripping subsystem further picks up the tilted book and it is followed

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up by filling up the space created in the stack by pushing the remaining books by a linear actuator.

C. Book Gripping Subsystem

A zero offset slider-crank mechanism with a gripper performs the task of picking a book from the book holder and placing it on the correct shelf of the library. The gripper is attached to the slider thereby allowing it to move linearly with a stroke length of 20 cm. A two-geared mechanism transfers the input rotational motion from the servo motor to the crankshaft. This mechanism is connected to a stepper motor thereby allowing it to rotate about an axis perpendicular to the platform.

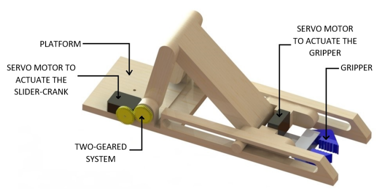

Fig. 2. CAD model of the gripper subsystem.

D. Riser Subsystem

A two-cross scissor-lift mechanism is used to raise and lower the book gripper sub-system. The scissor-lift is actuated by a lead-screw mechanism connected to a stepper motor. A platform at the top holds the book-gripper subsystem. The force for actuating the lead-screw is calculated using equations (1) - (3) and from Fig. 3. as in [5]. Table 1 shows the parameters and their corresponding value range. Fig. 4. shows the variation of effort required to rotate the screw with the height of scissor lift mechanism

$$P = \frac{W \times g}{\sin\theta} \tag{1}$$

$$F_R = P \times \cos\theta \times tan(\phi + \alpha) \tag{2}$$

$$F_L = P \times \cos\theta \times tan(\phi - \alpha) \tag{3}$$

TABLE I
LIST OF SYMBOLS USED

Details	Symbol	Values
Force acting along the length of the links	P	[28.32N,176.22N]
Total average weight of the book gripping subsystem, platform and a book	W	5 kg
Acceleration due to gravity	g	$9.81 m/s^2$
Angle made by the link with horizontal	θ	[8°,60°]
Friction angle	ϕ	21.8°
Helix angle of the lead screw	α	3.47°
Effort required to rotate the screw while increasing the height	F_R	[6.66N,82.37N]
Effort required to rotate the screw while lowering the height	F_L	[4.69N,57.81N]

The stress distribution and displacement of the scissor-lift mechanism under the influence of maximum load are

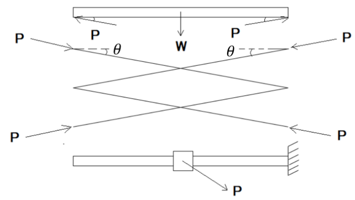

Fig. 3. Free body diagram of the scissor-lift mechanism when the links make an angle θ to the horizontal.

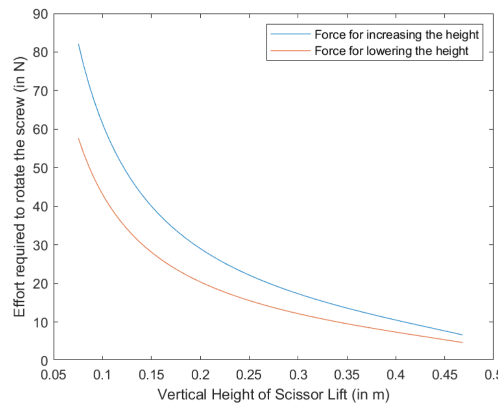

Fig. 4. Plot of effort required to rotate the screw vs. vertical height of the scissor lift.

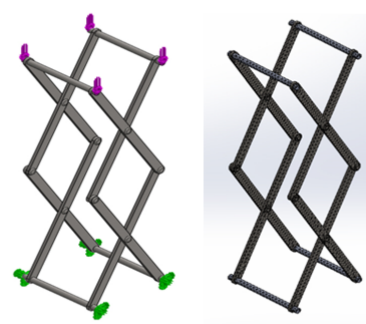

Fig. 5. (a) The fixed points and loading points of the model, (b) The mesh structure of the model.

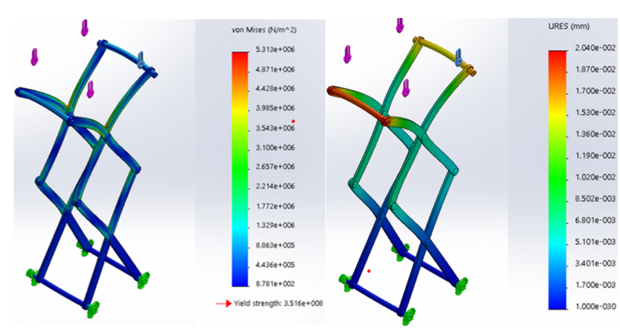

Fig. 6. (a) Stress distribution, (b) Deformations in the scissor-lift.

determined using finite element analysis as used in [6]. The base and the top platform are removed during this analysis as they were non-critical to the deformation of the scissor lifting system. The links are fixed at an angle of 60° from the horizontal surface as shown by the green coloured fixtures in Fig. 5(a). Considering a combined weight of the platform and a book as 50N, the loads are applied to the four points which connect the lifting mechanism to the top platform in the downward direction as shown in Fig. 5(a).

The stress distribution and the amount of deformation is determined after mesh formation in the scissor lifting system. The number of nodes and the number of elements were 19926 and 9922, respectively. The mesh structure is shown in the Fig. 5(b).

The stress distribution is determined by the package using the maximum strain energy method. The maximum stress in the system was found at the junction of the upper scissor, as shown in Fig. 6(a). The stresses are considerably lower in the lower scissor as compared to the upper one. The maximum deformation of 0.0204 mm is observed at the connection points of the lifting mechanism and the top platform, as shown in Fig. 6(b). The deformations of the lower scissor are extremely less as compared to the upper scissor. Since the values are low, these will not affect the desired operation of the lifting mechanism.

E. Drive Mechanism

Skid steer drive mechanism is used in the robot for better manoeuvrability and zero-radius turning [7]. Each wheel of radius 5 cm, is driven at various speeds in both forward and reverse direction independently with the help of DC motors, causing it to skid on the ground. The wheels are attached to motors through a separate shaft and the motors are mounted on the chassis.

Fig. 7. The actual prototype.

III. Embedded System Architecture

This section deals with the embedded architecture of the system which powers the peripherals, senses the environment variables and actuates based on the commands generated by the decision making software stack. Also, the specifications of actual components used and their interdependence on each other has been listed.

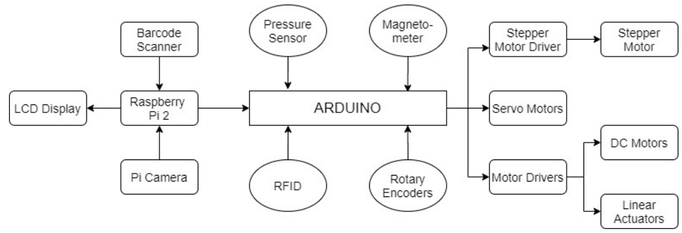

Fig. 8. Embedded Architecture.

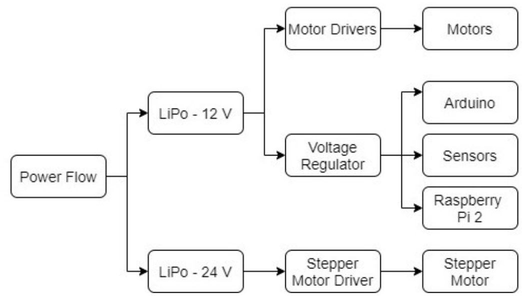

Fig. 9. Power Flow.

A. Power

The right distribution of power is crucial for any system to ensure the safety and proper functioning of all the electronic components. Thus, two different Lithium-ion Polymer (Li-Po) batteries have been used to power the robot. A 3-cell 11.1 V battery has been used to power the drive motors and the linear actuator. The sensors and motor controllers are also powered using this battery after proper adjustments made by a suitable buck converter. The other 6-cell 22.2V battery powers the stepper motors to meet the high torque requirements.

B. Sensors

A barcode scanner is used to read the barcode present on every book belonging to the library, for acquiring information pertaining to where it resides. An RFID sensor placed beneath the robot reads information from RFID tags that are placed at every junction along all paths the robot takes within the library. These act as the unique physical nodes of the mapping tree to help the robot navigate through shelves. A pressure sensor is placed on one of the arms of the gripper to check if the book has been held securely. Rotary encoders are attached to the motor shafts of all drive motors to determine the individual speed and estimate the distance covered by the robot. Raspberry Pi cam has been attached at the front to capture the guidance lines laid out on the library floor. These lines mark out the permissible paths the robot can take within the library task space.

C. Actuators

Four PMDC motors have been used for the traction. Three bipolar stepper motors have been used to actuate the lead screw used in the scissor lift mechanism, rotate the platform on which the book-gripper sub-system is mounted and to rotate the L-shaped platform of the book holder sub-system. Three servo-motors have been installed for feedback control of rotary motion in the different sections - to actuate the slider-crank mechanism; to change the orientation of the gripper; to actuate the linear mechanism of the gripper. One linear actuator is used for pushing the books in the book-holder compartment to the desired position, from where they would be gripped. An LCD display module is used for displaying the scanned information from the book. It displays the book name and room number to which it belongs.

D. Interfacing

The embedded architecture on the robot is based on distributed processing of varied data and hence it is required to have a proper communication scheme at each level. Thus, Raspberry Pi 2 has been employed as the high level controller. It stores the path directory of the library and computes a path based on the input data from the barcode scanner. It communicates with Arduino MEGA board, which acts as the low level controller and sends control commands to the traction motors. It is also used to collect data from RFID tags, magnetometer and encoders and outputs to various actuators for handling the book placement task.

IV. SOFTWARE STACK DESIGN

A. Path Planning

At the time of setup, a map needs to be created connecting the book docking station and individual shelves where books are placed. The map is a tree with a parent node as the book docking station and the leaf nodes as individual shelves. Changes have to be made to this when the actual structure of the library is changed. The remaining nodes in the tree are the RFID tags that are placed at physical junctions on the paths used by the robot. The RFID tag values have been mapped to each node.The nodes store the addresses of its parent and child nodes as pointers. A mapping between the book number and its assigned shelf (leaf nodes) is maintained as a directory. The shelves are assigned to lead nodes instead of books as the books significantly outnumber the shelves. At the start of each run, a 1-D array of sequential nodes which serves as a path for the robot to traverse sequentially is generated using the map. The barcodes on the books are scanned and their assigned shelf (leaf nodes) is identified from a mapping defined at the time of setup. From each leaf node, parent nodes are sequentially traced until the starting node is reached and a path, for the robot to follow in order to place the book in its corresponding shelf, is determined. This is repeated for all the books in the stack. After this, path optimization for the shortest route, the robot should go through to place all the books, is carried out. This optimization can be understood by the example, as shown in Fig. 10.

Book 4 placed last on the robot would be the first one to be returned to the shelf. The path for Book 4 would be 1-3-7-15. Similarly, for Books 1,2,3, the paths would be 1-2-4-8, 1-2-5-11, and 1-3-6-13. After the robot places Book 4 using its identified path, the nearest node which appears in the path

TABLE II
SENSOR SPECIFICATIONS

Barcode Scanner	300 scans/sec
RFID Scanner (RC522) / Tags	WC: 13-26 mA / 3.3 V, Reading distance: 0-60 mm
Pressure Sensor	Sensing Area diameter: 0.5 in, Minimum Pressure: 0.1 kg, Maximum Pressure: 10 kg
Rotary Encoder	360720 counts per revolution
Raspberry Pi cam	5 MP
Magnetometer(GY-87)	3-axis, 9-DOF, 3.3-5 V

TABLE III
ACTUATOR SPECIFICATIONS

Linear Actuator	12 V, 500 N, 12 inch
Geared DC Motors	60 RPM, 12 V, No-load current: 800 mA, Load current: upto 7.5 A (Max), 40 kg-cm, Stall Torque: 75 kg-cm
Stepper motor (lift)	Operating Voltage: 24-48 V, Step angle: 1.8 deg, Current/phase: 3 A, Holding torque:150 kg-cm
Other stepper motors	Operating voltage: 12-24 V, Step angle: 1.8 deg, Current/phase: 2.8 A, Holding torque: 40 kg-cm
Servo motors	Operating voltage: 4.8-6 V

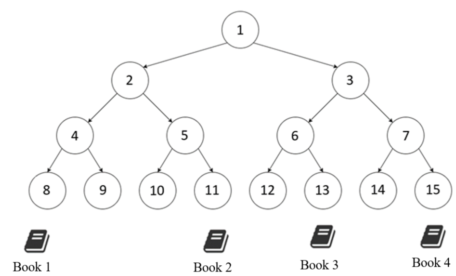

Fig. 10. Sample Library Directory.

Fig. 11. A sample frame (left) and the processed frame (right) with the centroid in red.

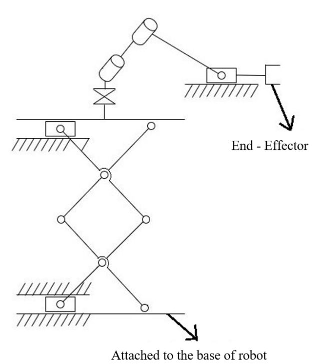

Fig. 12. Kinematic diagram of the robot manipulator.

of the next book to be placed is found. In the example, it would be Node 3. Following this, the path for the next book from that node is found and the process repeats for all the remaining books. Therefore in the example, the path followed would be 1-3-7-15-7-3-6-13-6-3-1-2-5-11-5-2-4-8-4-2-1.

B. Locomotion

The Raspberry pi captures an image for the Pi cam at a frame rate of 15 frames a second. The captured frame is filtered for colour into a binary image containing the line marking the path to be followed by the robot. The coordinates of the centroid of the path were calculated using the first moment of area of this binary image. This is taken as the center of the path and has been marked in red, as shown in Fig. 11. The x-axis pixel distance between the centroid and the center of the image is taken as the error of the robot at each frame. This error is fed to the PID controller [9] used by the drive motors for setting the motor speeds. The equation of the PID control loop is as follows.

$$u(t) = K_p e(t) + K_i \int_0^1 e(\tau)d\tau + K_d \frac{de(t)}{dt} \tag{4}$$

Here K_p, K_i and K_d refer to the proportional, integral and derivative gain constants respectively. These variables are determined by manual experimenting and are tuned until a satisfactorily smooth motion is achieved by the robot. There are other methods for the same [9] but we have chosen this for easy implementation. For a positive control variable value,

$$Motor_R = SetSpeed - u(t); Motor_L = SetSpeed \tag{5}$$

For a negative control variable value,

$$Motor_L = SetSpeed + u(t); Motor_R = SetSpeed \tag{6}$$

The Arduino uses RFID tags to mark junctions. When a tag is encountered the robot stops and turns towards the next path to be taken. In cases of tags marking shelves the robot initiates the book placement procedure. The magnetometer (GY-87) value is used while turning the robot towards the next path it has to take from that junction.

C. Robot Manipulator Control

Assuming the centroid of a book should be placed at (x,y,z) position with respect to the base of the scissor-lift mechanism. It can be identified whether the book can be placed at the current robot position or not depending on whether the point (x,y,z) lies within the robot manipulator's workspace. The workspace can be calculated from Fig 12. The workspace is a hollow cylinder of height 392.6mm with inner and outer radius 100 mm and 200 mm in this particular case. If the point lies outside the workspace, the robot must move either forward or backward to bring the point within the workspace.

V. Conclusion

The design process of a novel robotic system capable of performing the task of returning books to their proper shelves is proposed. The various subsystems along with the involved mechanisms, have been described in details. Finite element analysis on the scissor lift mechanism has been carried out and the dynamic variables involved are determined. The feasibility of the proposed robot is then realized by manufacturing a prototype, with proper material selection and optimization of design parameters. An optimal path planning algorithm and navigation strategy have been discussed. The robot is able to achieve the desired task of placing lightweight standard books in a simplified experimental setup. Further testing is being done to identify problems associated with extreme conditions like handling books of unconventional sizes. Future work includes intelligent placement of books in cluttered shelves and navigation through unknown environments without pre-defined paths. The ultimate aim is to provide a single autonomous structure to handle associated tasks in library management.

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