Intelligent Book Grip Robot

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***Abstract*—Looking for books in a library is time-consuming and may sometimes cause trouble for someone else. Therefore, we proposed a new design of a robot arm that could work as an agent in automated libraries. There is a total of five degrees of freedom (DOF) consisted in the design in order to perform action of grasping in multiple angles and delivering the book to students. We tested feasibility by creating a 3D model and simulating the forward and inverse kinematics of the robot. The main advantage of this design is that it saves much time for students and school faculties, and it protects books from being damaged during the process of borrowing and returning.**

I. Introduction

Looking for books in a library can be really annoying, especially when the book was placed in the wrongs section; it could be extremely time-consuming since sometimes it's unlikely for students to return a book back to where it was borrowed. Therefore, it needs librarians maintain orderliness. But humans make mistakes. So, we have proposed our design of a robot arm that could grab the book for students, and return the book to the original location.

II. Literature review

Currently, there are a couple of similar products but none of them have the exact same functions as we do. The first product is a robot that locates misplaced books and flags them [1], so that the librarian would be able to place the book in a rightful place as soon as possible. Another product uses Radio Frequency Identification (RFID) system to retrieve and return books based on library book tagging [2]. The other product is an autonomous assistant that could pick up a book from the shelf and put it on the table [3]. The robot arm is attached to a car which helps it move. The main difference between our robot arm and the autonomous assistant is that our design is specifically attached to the shelf and our has a return system.

III. System Analysis

We had an initial design whose idea came from normal vending machines. In this design, we created an H- shape rail attached to a book shelf with a gripper in the middle to grasp books like a vending machine. However, since the only components of our prototype were rails, it only had two degrees of freedom. Due to the limitation of DOF, we faced the challenge of how we could take the book off the shelf and deliver it to students.

Hence, we proposed our new design. It came with two major parts: a rail and a robot arm. The rail is attached to the shelf so that the arm can shift back and forth for different locations of books at the same level of the shelf. It can also be regarded as a prismatic joint with one degree of freedom and only responsible for the horizontal movement of the arm. The robot arm has four joints: three revolute joints and one prismatic joint. Revolute joints are designed for the convenience of different levels of the shelf, and the prismatic joint on the robot arm is responsible for its elongation to reach the top level of the shelf. Together, there are five degrees of freedom, which assure the arm could be able to handle most situations.

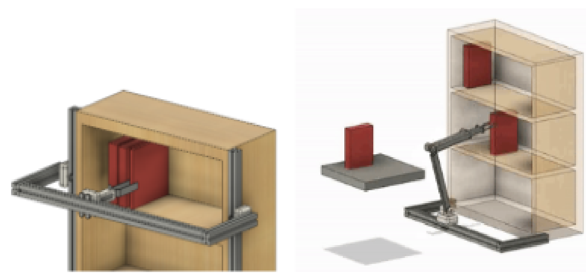

Fig. 1. 3D model of old and new design

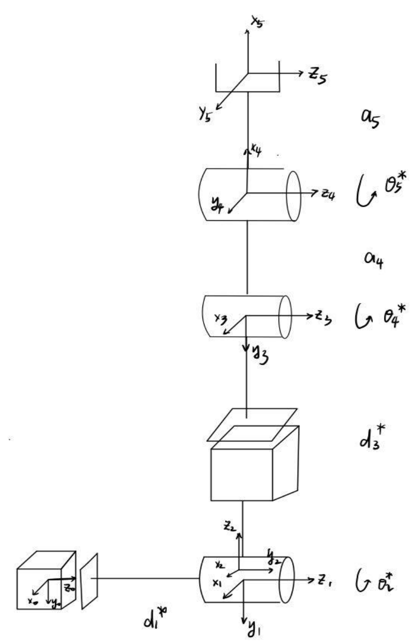

Fig. 2. Frame of robot arm

TABLE I. DH PARAMETERS

link	*α*	a	*θ*	*d*
ground→0	-90°	0	0	0
1	0	0	0	d_1^*
2	90°	0	θ_2^*	0
3	-90°	0	0	d_3^*
4	0	a_4	θ_4^*	0
5	0	a_5	θ_5^*	0

A. Jacobian and singularity analysis

For the part of Jacobian, to calculate the J matrix, as well as the A and T matrix of every joint, the forward kinematics of the robot arm is needed. From the DH-table, we can easily get the results of A and T matrices, while according to every joint's type and these 2 matrices, we can get unit vectors z_i and the coordinates of the origins $o_1,\ldots,o_n$. Then we can calculate the result of Ji and Jw. To determine the singularity of the robot, the following equation need to be satisfied:

$$\det J(\boldsymbol{q}) = 0$$

so after using Matlab to calculate the function, when the determinant equals to 0, s_2 is 0, which is $\theta_2 = 0$ or π.

$$\begin{bmatrix} 0 & x_1 & x_2 & x_3 & x_4 \\ 0 & x_5 & x_6 & x_7 & x_8 \\ 1 & 0 & 0 & x_9 & x_{10} \\ 0 & 0 & 0 & x_{11} & x_{12} \\ 0 & 0 & 0 & 0 & x_{13} \\ 0 & 1 & 0 & x_{14} & 0 \end{bmatrix}$$

where

$$x_1 = -(d_1c_4 + a_4s_4 + a_5c_2s_4c_5 + a_5c_4s_5)$$

$$x_2 = s_2$$

$$x_3 = -c_2(d_1c_4 + a_5c_4s_5 + a_4s_4 + a_5s_4c_5 - d_1)$$

$$x_4 = a_5s_2s_4s_5$$

$$x_5 = a_4c_4 + a_5c_2c_4c_5 - d_1s_4 - a_5c_4s_5$$

$$x_6 = c_2$$

$$x_7 = c_2(a_4c_4 + a_5c_2c_4c_5 - d_1s_4 - a_5s_4s_5)$$

$$x_8 = -a_5s_2c_4s_5$$

$$x_9 = s_2(d_1c_4 + a_5c_4s_5 + a_4s_4 + a_5s_4c_5 - d_1)$$

$$x_{10} = a_5s_2s_5 + a_5s_2s_4c_4c_5 - d_1s_2c_4 - a_5s_2s_4c_2c_4c_5$$

$$x_{11} = s_2$$

$$x_{12} = s_2c_4$$

$$x_{13} = s_2s_4$$

$$x_{14} = c_2$$

Fig. 3. Jacobian Matrix

B. Inverse Kinematics and Workspace Analysis

The robot has 5 joints, but there are only 4 constraints of DoFs: : x, y, z, $roty$. So it is a redundant robot and a new constraint needs to be induced:

$$\beta = \theta_2 + \theta_4$$

which represent the orientation of the second to the last link to help avoiding collision between the robot and the shelf.

Then the inverse kinematics equations have the form,

$$\begin{cases} x - a_5\sin\gamma - a_4\sin\beta = d_3\sin\theta_2 \\ y = d_1 \\ z - a_5\cos\gamma - a_4\cos\beta = d_3\cos\theta_2 \\ \gamma = \theta_2 + \theta_4 + \theta_5 \\ \beta = \theta_2 + \theta_4 \qquad\qquad \text{(assigned constraint)} \end{cases}$$

Simplify it, and get the inverse kinematics result:

$$q = \begin{bmatrix} d_1 \\ \theta_2 \\ d_3 \\ \theta_4 \\ \theta_5 \end{bmatrix} = \begin{bmatrix} y \\ \arctan\dfrac{x - a_4\sin\beta - a_5\sin\gamma}{z - a_4\cos\beta - a_5\sin\gamma} \\ \left[(x - a_5\sin\gamma - a_4\sin\beta)^2 + (z - a_4\cos\beta - a_5\cos\gamma)^2\right]^{1/2} \\ \beta - \arctan\dfrac{x - a_4\sin\beta - a_5\sin\gamma}{z - a_4\cos\beta - a_5\sin\gamma} \\ \gamma - \beta \end{bmatrix}$$

As for workspace analysis, use python to find the point where the end effector may move according to DH parameters. As Fig. 4 shows, the end effector has great flexibility so that it can reach a considerable range of books.

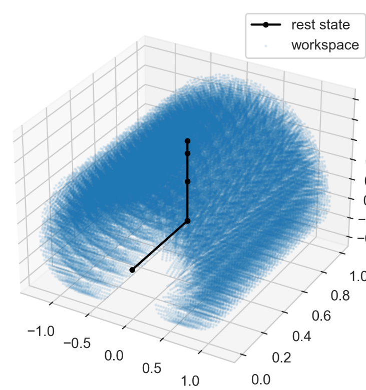

Fig. 4. Workspace Analysis

C. End-effector and Joint Trajectory Analysis

For this robot, the most difficult part is to grip the books without collision of effector and shelf. Therefore, the revolution of the end effector is splitted into 8 phases, which is consisted of 4 static phases and 4 dynamic phases. For each dynamic phases, the following cubic polynomials are used for trajectory planning.

$$q(t_0) = a_0 + a_1(t - t_0) + a_2(t - t_0)^2 + a_3(t - t_0)^3$$

The total working time is set to be 22 seconds. The first dynamic phase is from 1.5 seconds to 5 seconds, which will make the end effector move from vertical position to the position that is 140 degrees from the link connected to the end effector. This process is to fold the end effector to avoid collision with book shelf when other links move. Therefore, the coefficient of cubic polynomial can be calculated as following:

$$a_0 = q_0 = 0$$

$$a_1 = v_0 = 0$$

$$a_2 = \frac{3(q_1 - q_0) - 2(v_0 + v_1)(t_f - t_0)}{(t_f - t_0)^2}$$

$$= \frac{3(140-0) - 2(0+0)(5-1.5)}{(5-1.5)^2} = 34.286$$

$$a_3 = \frac{2(q_0 - q_1) + (v_0 + v_1)(t_f - t_0)}{(t_f - t_0)^3}$$

$$= \frac{2(0-140) + (0+0)(5-1.5)}{(5-1.5)^3} = -6.531$$

With the similar calculation, coefficient of dynamic phases are shown in TABLE II.

TABLE II. COEFFICIENT OF POLYNOMIAL

Phase	***a_0***	***a_1***	***a_2***	***a_3***	***Phase Purpose***
2	0	0	34.286	-6.531	Fold End Effector
4	140	0	-11.667	1.296	Release End Effector
6	0	0	52.500	-17.500	Grip Book
8	70	0	-23.333	5.185	Place Books on Table

The overall cubic spline trajectory is shown in Fig.4.

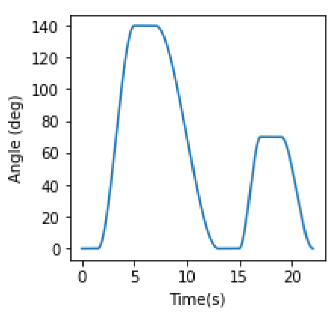

Fig. 5. Joint Trajectory of End-effector

The corresponding velocity and acceleration profile for multiple cubic polynomial trajectory are shown in Fig.6 and Fig.7.

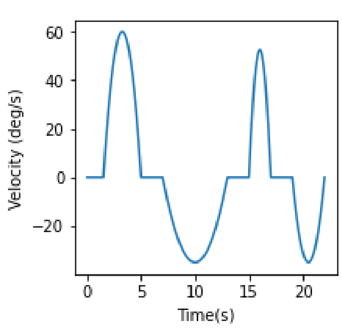

Fig. 6. Velocity Profile of End-effector

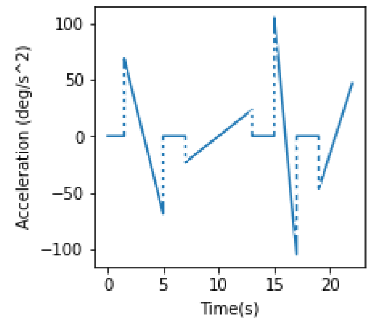

Fig. 7. Acceleration Profile of End-effector

IV. DISCUSSION

In this project, the designed robot has accomplished the task very well. However, there are still some limitations. Firstly, the balance between fripper thickness and strength is difficult to determine. For this design, to grip the book, pripper need to get into the gap between books, which will require maintaining a gap between the books. Therefore, the amount of books in the bookshelves will be limited. For future extension, a better gripper design should be considered for better efficiency. Secondly, safety issues should also be considered. One aim of this project is to handle the books to the users. When designing the trajectory planning of the robot, robot will slightly move to the opposite direction of the bookshelf first, then gripping the books to avoid collision with the bookshelf. However, moving to the opposite direction also means that the manipulator will also move to the direction of user. Therefore, a partition should also be added between user and manipulator. In addition, a distance sensor can be used to avoid hitting the user.

V. CONCLUSION

All in all, our design of book gripping robot is able to autonomously perform actions of locating, grasping, and delivering. With the redundant one degree of freedom, the robot arm would have more flexibility and higher efficiency on its job. This was demonstrated through our 3D simulation and mathematical calculations using MATLAB. We have also plotted the trajectory of our end effector reaching for books. Eventually, we would consider our robot to be successful and students and librarians who use this robot would save much of their time looking for books and keeping books in order.

A few improvements we can do in further work could be firstly finishing the entire automated system by designing a method which numbers all books in the library and give them a coordinate. And then add a return mechanism based on the coordinate system.

References

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