Warehouse Pallet Placer

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***Abstract*—With the development of advanced technology, production of goods has reached rapid speeds, making the use of storage facilities, such as warehouses, all the more necessary. However, current warehouses fail to maximize efficiency in their use of limited storage capacity. To combat this problem, a robot was designed to maximize the space available for storage. Forward and inverse kinematics as well as trajectory planning was performed to simulate the robot. It was found that the robot was more efficient and economical than other options available, helping to reduce the cost associated with storage and increase safety for humans.**

I. Introduction

Driving through the suburbs, one may notice many large, plain buildings with numerous semi-truck trailers parked along them and wonder what those buildings are. They are most likely warehouses, and they serve as buffers in the supply chain. Most companies will need to utilize warehouses to store goods until they are needed. For example, manufacturers may store raw materials until they are ready to be processed into finished products, and wholesalers may store finished products waiting to be distributed to retail stores. However, not all goods have a quick turnaround time. Seasonal goods, such as Christmas ornaments, may be produced months in advance, so they will sit in storage for long periods of time until the right time comes. As a result, the warehouse may run out of space for further storage as more goods are received or produced.

A. Problem Statement

Space in warehouses is often not filled to the fullest, so there is more empty space that can be utilized as storage space. Thus, the problem to be solved is the inefficient use of storage space in warehouses; not utilizing every bit of space available is costly due to the unused space being wasted. The motivation to solve this problem is to minimize the cost associated with storage by maximizing the efficiency of the limited storage capacity of existing warehouses. Since the storage capacity is constrained by the physical dimensions of the building, increasing it would be difficult and costly. Additional land would need to be purchased and new buildings would need to be constructed. At the same time, the costs associated with storage can be minimized by replacing the use of human resources, which is one of the most expensive costs, with robots to place pallets onto as well as remove them from storage racks. However, this problem is challenging because in order to maximize storage efficiency, space not used for storage, such as the space between storage racks, must be minimized. Because the workspace for the robot would be very compact, accuracy is essential for safe practice. The robot must be coded precisely so that during the process of moving it does not hit the storage racks, which can lead to a catastrophic disaster such as the entire warehouse collapsing.

B. Literature Research

The most common solution one might think of for the problem of limited storage space is probably expanding the size of the warehouse. However, as mentioned previously, that is very difficult and expensive. Thus, researchers have come up with various solutions that do not require an expansion of the warehouse.

One solution is increasing the height of the storage racks to create more pallet levels. However, storage racks cannot be extended all the way to the ceiling. They can only be extended vertically up to a certain height below the ceiling so that safety systems, such as fire sprinklers, can still function properly. Although this is less costly than expanding the warehouse, it requires evaluation by a structural engineer, for a rack that is too high can be unstable and collapse [1].

Another solution is using temporary outside storage, such as trailers. However, this is not an ideal solution as renting these temporary trailers can be expensive. In addition, they take up space outside, which can make it more difficult for trucks to maneuver when arriving or leaving the warehouse. Some goods also need to be stored in a controlled environment, such as a certain temperature and humidity, so putting them outside where the condition of the environment can vary drastically is not a feasible option [2].

Figure 1. Pallet Shuttle System.

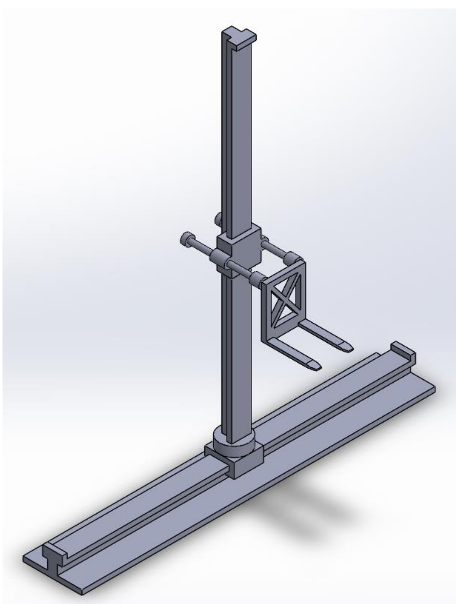
A third solution is using a high-density storage rack with a pallet shuttle system. In this solution, the storage rack is divided into multiple slots with each one having a pallet shuttle that moves in and out of the storage rack as seen in Figure 1. The issue with this method is that in order to reach the innermost pallet, all the pallets in front of it must be taken out first, so it would not be efficient unless the pallets contained the same goods. Since the pallet shuttle cannot move left and right or up and down, but only in and out of the storage rack, each slot would require its own pallet shuttle, which would add a significant load that the storage rack must support. The complexity of the system also makes any malfunctions difficult to resolve. For example, if a pallet shuttle got stuck because the battery died, it would be difficult to reach it, especially if it was higher up in the storage rack, as there are pallets all around it. Lastly, the pallet shuttle system still requires the use of a forklift to place the pallets onto and remove them from the end of the slots. With the dimensions of the slots being tight in order to be compact, the higher slots may be difficult for the forklift driver to see [3].

II. Solution

A. Design

The goal of designing this robot is to make a manipulator with characteristics similar to that of conventional forklifts with compact size and better efficiency so that innovative control algorithms can be designed and implemented. Design parameters of the robot include payload, reachability, accuracy, repeatability, size, and cost. A mid-range size is considered for this technical paper to perform the task of picking and placing pallets.

Figure 2. Design of Robot.



The robot consists of three sliding joints and one revolute joint as shown in Figure 2. A pallet would have been moved to the end of the storage rack by a forklift or automatic guided vehicle. The robot picks up the pallet slightly above the ground, approximately 20 inches, then it slides using the first sliding joint to reach the desired position along the storage rack as fed by the computer programmer. Next, the robot moves in an upward direction using the second sliding joint to reach the height of the desired shelf on the storage rack. The robot then rotates 90 degrees, either clockwise or counterclockwise depending on which shelf it is placing the pallet onto, and then the third sliding joint moves in the forward direction so that the pallet is in the storage rack. It places the pallet by moving the second sliding joint slightly downwards. Finally, the robot goes back to the initial position and repeats the cycle.

B. Forward and Inverse Kinematics

In designing the robot, finding the Denavit-Hartenberg parameter is the initial step to derive the forward kinematics of the robot. The coordinate system is provided to the robot according to DH convention and shown in Figure 3. The DH table of the warehouse pallet placer is shown in Table 1. Using the given table, kinematics of the robot will be obtained [4].

Figure 3. DH Convention.

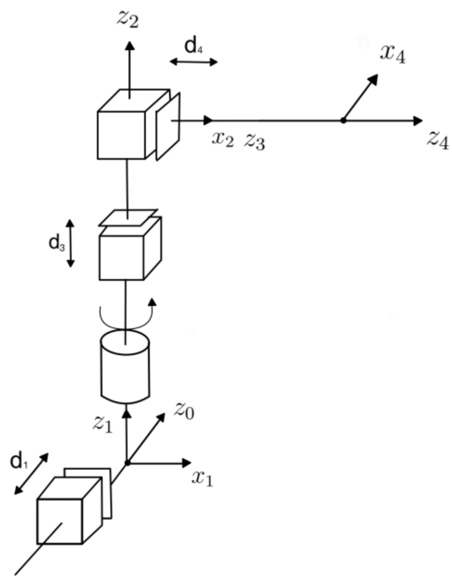


TABLE I. DH Parameters

Link	a	α	d	θ
1	0	90	d_1	0
2	0	0	0	θ_2
3	0	90	d_3	90
4	0	0	d_4	0

Forward kinematics is solved by multiplying the transformation matrices using the formula in Equation 1.

$$T_0^4 = T_0^1 T_1^2 T_2^3 T_3^4 \tag{1}$$

The transformation matrix is given by Equation 2.

$$T_0^4 = \begin{bmatrix} -s_2 & 0 & c_2 & c_2 d_4 \\ 0 & 1 & 0 & d_3 \\ c_2 & 0 & s_2 & s_2 d_4 + d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

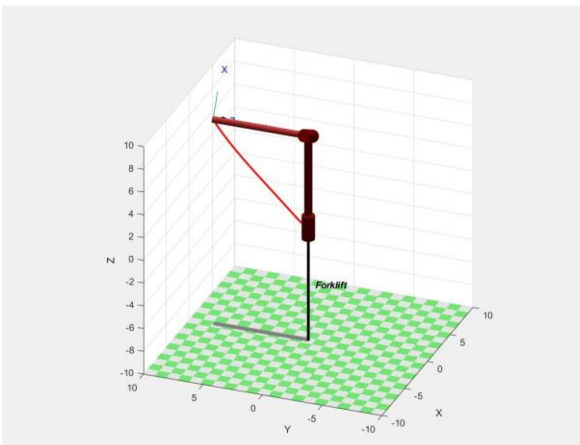
The forward kinematics can also be found using Peter Corke's robotics toolbox [5], which can be found in Figure 5 in the Appendix, with a specific orientation.

The inverse kinematics can also be found using Peter Corke's robotics toolbox [5], which can be found in Figure 6 in the Appendix, with a specific orientation.

C. Trajectory Planning

Trajectory planning is an essential step toward making an efficient robot. Trajectory planning is defined as moving from one specified point to another specified point while avoiding collisions over time, computed in both discrete and continuous methods. The trajectory planning of the robot is derived using Peter Corke robotics toolbox [5], which can be found in Figure 7 in the Appendix, with a specific orientation. A set trajectory of the picking and placing task for the pallet is shown in Figure 4. The trajectory is optimized in a way that it can avoid collision with the storage rack. The robot picks up the pallet, then after reaching the desired position, it adjusts its height accordingly. Finally, it rotates to a desired angle as programmed to reach the desired position and places the pallet at the desired position.

Figure 4. Trajectory Planning.



III. RESULTS

To simulate the robot kinematics, MatLab was used and a path named trajectory was created. The trajectory initially starts with the robot near the pallet such that its fork reaches the pallet and lifts it about 20 inches above the ground. Next, it requires the robot to move along the track, lift the pallet to the desired height, and rotate to place the pallet. Then, it goes back to its initial position and repeats. The robot works at a slow speed to promote stability.

The simulation shows that three sliding joints and one revolute joint is sufficient to complete the task of the robot, which is to place pallets onto a rack. From the DH table, the first, third, and fourth links are sliding joints, so the only d varies. The second link is a revolute joint, so only θ varies, hence promoting a simpler design than already existing conventional forklifts and pallet shuttles. In this way, the robot is more efficient and economical as it uses a less complex mechanism to do the same work as that of a conventional forklift with complex parts. The compact design promotes space availability in the warehouse. The size of the robot is much smaller compared to conventional forklifts and provides more space in the warehouse that could be used for storage purposes. Also, we learned that the order of operation is important to maintain a safe workspace. For example, if the robot rotates before retracting the fork, it would hit the storage rack and cause damage.

IV. CONCLUSION

This paper introduces the warehouse pallet placer and the autonomous transportation system constructed by three sliding joints and one revolute joint, which allows the system to have four degrees of freedom. In the preceding section, we have presented the trajectory simulation based on MatLab Peter Corke Robotic toolbox [5] and its 3-dimensional movement animation based on SolidWorks. The animations are available online at this link [7]. The demonstration of the solution approach has been completed via three steps: first, present the calculation of DH parameters [4], second, derive the forward and inverse kinematics [6] and, third, define trajectory planning [6] of the robot for specific tasks in its workplace. Finally, we tested the capability of the system in the MatLab [5] environment and demonstrated the movement of the placer in SolidWorks. In summary, the developed system provides compact design as compared to conventional forklifts; that is, it does not require much space for its movement and helps the user to increase the efficiency of storage space use of the warehouse. In addition, the pallet placer provides a safer operation environment by only using autonomous working components. The pallet placer is more economical than other complex industry warehouse systems, which are presented in the state-of-art. It does not have vehicle components, such as a driving engine or wheels, which require servicing. Additionally, it is automated, so it does not require any operator. As a result, the robot can work continuously without a long rest period. The models and findings in the evaluations are relevant to other researchers' work in warehouse robotics, as the adaptation of the system to other platforms is straight-forward.

Future extensions will focus on several topics. First, the algorithm used in this paper on trajectory planning will be reevaluated in order to maximize transportation efficiency in different environments (i.e., when the system is installed between two intersected racks). By simulating and collecting data in numerous cases and finding out the best trajectory for particular situations in the workplace, more efficient motion planning of the robot can be determined. Secondly, deep learning and computer vision models will be included and synchronized with sensors to enhance safety of humans near the danger zone. The robot would be able to localize objects with respect to a RGBD camera or an infrared probe. Lastly, machine learning algorithms will be implemented so that the robot can learn from existing move patterns with minimal human intervention.

APPENDIX

Figure 5. Forward Kinematics MatLab Code.

```
%Forward Kinematics
values = [  theta2 d1 d4 d4 ]
forward_kinematics = r.fkine(values)
r.plot([ 5 5 5 1 ])
```

Figure 6. Inverse Kinematics MatLab Code.

```
%Inverse Kinematics

q0 = [ 0 0 0 0]
Inverse_Kinematics  = r.ikine(forward_kinematics,q0,'mask', [1 1 1 1 0 0])
```

Figure 7. Trajectory Planning MatLab Code.

```
%Tranjectory

time = 0:0.1:3;                    %initial time:time step: final time
Tranjectory = jtraj(q0,values,time)
Tr = fkine(r,Tranjectory)

for i = 1:1:length(time)
    T = Tr(i);
    trs = transl(T);
    xx(i) = trs(1);
    yy(i) = trs(2);
    zz(i) = trs(3);
end

plot(r,Tranjectory);
hold on
plot3(xx,yy,zz,'Color',[1 0 0], 'LineWidth',2)
```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