6-DOF Serial Manipulator for Kitchen Automation

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***Abstract* – In this paper, we present the modeling and simulation of a six degree of freedom serial manipulator intended for manipulating kitchen objects. The robot's forward kinematics are calculated by both the Denavit-Hartenberg and product of exponentials techniques. Forward kinematics are combined with inertial attributes to form a dynamical model. A singularity analysis is performed. Finally, a trajectory is designed using a trapezoidal velocity profile. A simulation of the robot is presented in the MATLAB environment.**

Keywords – serial manipulator, robot dynamics, robot analysis

I. Introduction

As the world starts to embrace the changes set forth by the fourth industrial revolution, we begin to see the adaptation of automation and robotics not only in manufacturing and industrial settings, but in our everyday lives. From the many types of robots, robotic manipulators in particular have been able to integrate into many other sectors to perform repetitive and labor-intensive tasks. Because of this, the development of these robots has taken us from simple pick and place to high degree of freedom (DOF) robots that allow flexibility and manipulability in multiple settings. One such exciting new setting is the kitchen. As our lives become exceedingly busy, we have decreasingly less amounts of time to prepare something in the kitchen after work. Studies have been made that show the acceptance of a kitchen assistant robot [2]. While it may be some time before a robot parallels the culinary skills of Gordon Ramsey, we can appreciate the opportunity in everyday restaurants where a robot would thrive by performing simple but repetitive tasks, and could improve the speed and quality of the food.

Despite the difficulty of some of the applications and wide breath of environments, entrepreneurs, large corporations, and researchers are tackling the challenge head on to find areas where current robot technology can be applied in a smart and safe way. Most notably, Japan has been able to incorporate robots in the food industry. They are able to serve items ranging from ramen, to foods that require a bit more delicacy such as well-served frozen yogurt and puff pastries. As this niche industry grows, various players such as Octochef, a collaborative robot that performs various tasks from dispensing batter to using artificial intelligence to perfectly cook Takoyaki, will take center stage in the kitchen. Research is also underway by Samsung, Moley, and other researchers [1] [6] [7]to implement humanoid personal cooking assistants that have the ability to learn new recipes and cooking methods. Researchers are even tackling some of the more complicated tasks, such as cutting vegetables and meats with knives using soft robotics and innovative sensor control [3]. Robotics is still emerging in the food industry and the novelty attracts an audience. Customers come to restaurants for the experience of watching a robot dance and perform its way through a task, and some businesses are using this to create art and dazzle their customers for a premium.

The objective of this project is to design and analyze a robotic arm that assists a chef with cooking tasks. It is recognized that not all cooking is the same and certain cuisines require varying techniques and movements from a robotic arm [4] which is why we will focus on a robot that aids in making burgers. These tasks will include: place the burger on the grill, flip when ready, and place it on the bun, as well as use a secondary end effector tool to draw predetermined images on the burger using condiments of choice. The development tasks performed in this project are: forward kinematics, inverse kinematics, velocity kinematics, singularity and trajectory path generation, end-effector and robot selection. We will demonstrate the attainment of our goal by having the robot at three main configuration points. These points are home, where the robot can select an end effector tool; over the burger to place and flip; and over the completed burger to place condiments. The path would go home, grill, home, condiment area, then back home. Having the arm at three main configurations allows for an easier determination of the Jacobians, any potential singularities, and allows for optimizing arm paths.

II. Modeling

A. DH Parameters

The diagram for the UR5 Robot was determined using the vendor specifications [6] shown in Figure 1.

UR5				
Kinematics	theta [rad]	a [m]	d [m]	alpha [rad]
Joint 1	0	0	0.089159	π/2
Joint 2	0	-0.425	0	0
Joint 3	0	-0.39225	0	0
Joint 4	0	0	0.10915	π/2
Joint 5	0	0	0.09465	-π/2
Joint 6	0	0	0.0823	0

Figure 1 DH Parameters for the UR5 Robot

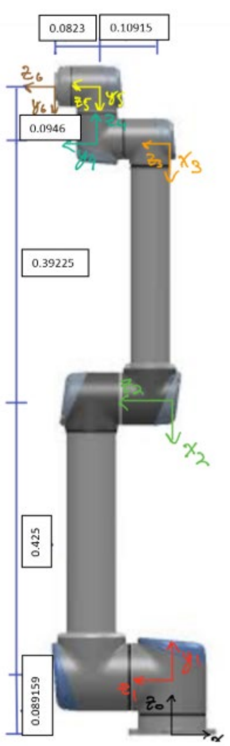

Figure 2 Visual DH Configurations for the UR5 Robot

Using the specifications above, the DH Parameters in Figure 1, and the generic homogeneous transformation matrix (Eq 1), the forward kinematics for the robot were constructed and used throughout the robot planning and movement.

$$H_n^0 = \begin{bmatrix} C\theta_n & -S\theta_n C\alpha_n & S\theta_n S\alpha_n & a_n C\theta_n \\ S\theta_n & C\theta_n C\alpha_n & -C\theta_n S\alpha_n & a_n S\theta_n \\ 0 & S\alpha_n & C\alpha_n & d_n \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Equation 1

The UR5 is a versatile robot and can achieve any location in the recommended workspace shown in Figure 3.

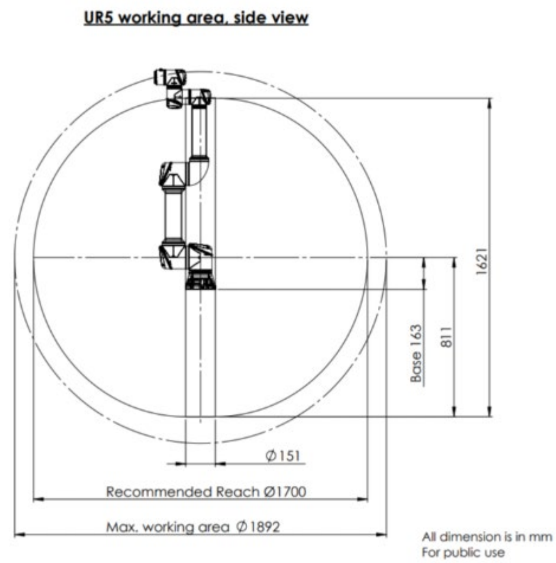

Figure 3 UR5 Workspace

B. Product of Exponentials

Product of exponentials is alternative way of determining the forward kinematics (FK) of an arm robot. The steps below will describe the use of the product of exponentials technique in confirming the FK derived from the DH parameters above.

Here are the steps for determining the FK using this method:

- Consider the robot in its home position
- In the home position, calculate both position and orientation of the end effector frame with respect to the base frame and form the 4x4 homogeneous transformation matrix which is M
- Find the screw axes (Si) with respect to the base frame
- Create Se(3) matrix from, Si, for each joint

- Create $e^{[\mathrm{Si}]\theta i}$
- Create $T_{\mathrm{on}} = e^{[\mathrm{Si}]\theta i} \ldots e^{[\mathrm{Sn}]\theta n} M$, where n is the final joint

C. The Jacobian

The Jacobian relationship between joint velocities vector $\dot{q}$ and end effector velocities $\dot{x}$ is:

$$\dot{x} = J\dot{q}$$

Equation 2

The Jacobian was constructed using calculation methods described in Figure 4:

	Prismatic	Revolute
Linear	$R_{i-1}^{0}\begin{bmatrix}0\\0\\1\end{bmatrix}$	$R_{i-1}^{0}\begin{bmatrix}0\\0\\1\end{bmatrix} \times \left(d_n^0 - d_{i-1}^0\right)$
Rotational	$\begin{bmatrix}0\\0\\0\end{bmatrix}$	$R_{i-1}^{0}\begin{bmatrix}0\\0\\1\end{bmatrix}$

Figure 4 Summary of methods for calculating Jacobian

The Jacobian has 6 columns, because there are 6 joints in the UR5 robot.

$$J = \begin{bmatrix} z_0\, x\,(o_6 - o_0) & z_1\, x\,(o_6 - o_1) & z_2\, x\,(o_6 - o_2) & z_3\, x\,(o_6 - o_3) & z_4\, x\,(o_6 - o_4) & z_5\, x\,(o_6 - o_5) \\ z_0 & z_1 & z_2 & z_3 & z_4 & z_5 \end{bmatrix}$$

Equation 3

where $z_i$is the z-rotation of i and o_i is the position of the frame or the 4th column of the homogeneous matrix. z_0 is the identity matrix. This equation is used in the next section to analyze the singularity of the UR5 robot.

D. Singularities

There are three singularity positions that must be avoided for this robot: the elbow, wrist, and shoulder [10]. These positions must be avoided in the prescribed motion for the application because these positions limit the range of motion of the robot and they significantly deteriorate the performance of the robot arm. The determinant of the Jacobian was used to identify where these singularity positions are within the UR5 robot workspace.

The fully stretched elbow forces the robot into a singularity, shown in Figure 5. This corresponds to 0 deg.

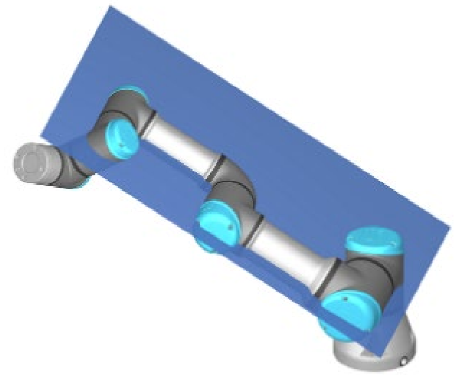

Figure 5 Elbow Singularity

The shoulder singularity occurs when the axes of joints 5 and 6 are bisected by the joint 1 and 2 axes. In the shoulder singularity, it can be seen that the singularity is dependent on both θ_2 and θ_3, with the value of θ_3 at the singularity location changing depending on the value of θ_2.

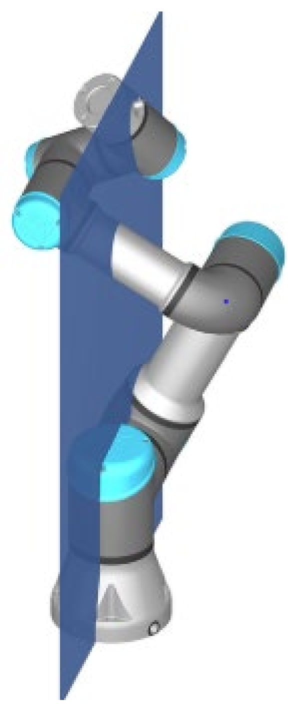

Figure 6 Shoulder Singularity

The wrist singularity, shown in Figure 2.5 occurs when the axes of joints 4 (arrow 3 below) and 6 (arrow 4 below) become parallel or point in the same direction. This occurs when θ_5 = 0°, θ_5 = ±180° or θ_5 = ±360°.

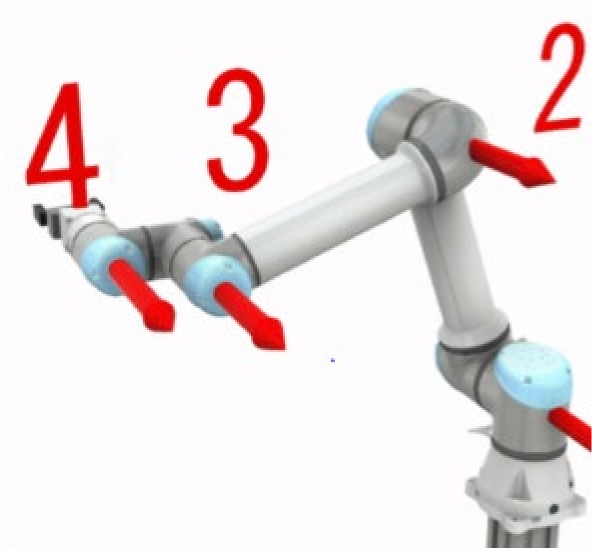

Figure 7 Wrist Singularity

E. Motion Planning

For our motion planning, we first created the environment using the collisionBox function to create our table as well as our left, right, and grilling surfaces. Once the surfaces are modeled, we can input our joint configurations for the robot to use the trapveltraj function to obtain our joint velocities and accelerations. We used the interactive rigid body tree function to bring up a figure window of the robot arm moving throughout its space with all of the collision surfaces represented.

F. *Dynamical Modeling*

A dynamical model of the robot was formulated using the Lagrange method. Link inertia was modeled with point masses. The following steps were used in forming the model:

Find the robot's homogenous transformation matrix H_n^0
Use H_n^0 to find the Jacobian
Apply the Jacobian to joint velocities $\dot{\theta}_1 \ldots \dot{\theta}_n$ to find end effector velocities $v_1 \ldots v_n$
Solve for the kinetic energy of each link using $k_i = \frac{1}{2} m_i {v_i}^2$
Solve for the potential energy of each link using $p_i = m_i g H_i^0(3,4)$
Sum all kinetic energies into k and all potential energies into p
Define the Lagrangian $L = k - p$
Find $\tau_1 \ldots \tau_n$ using $\tau_i = \frac{d}{dt}\frac{dL}{d\dot{\theta}_i} - \frac{dL}{d\theta_i}$
For $\tau_1 \ldots \tau_n$, gather the coefficients of $\ddot{\theta}$ and g. All other terms are Coriolis couplers.
Write the gathered terms in the final matrix form

The solution is a set of six torque equations in the form of:

$$\begin{bmatrix} \tau_1 \\ \vdots \\ \tau_n \end{bmatrix} = \begin{bmatrix} M(q) & M(q) \\ \vdots & \vdots \\ M(q) & M(q) \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \vdots \\ \ddot{\theta}_n \end{bmatrix} + \begin{bmatrix} C(q,\dot{q}) \\ \vdots \\ C(q,\dot{q}) \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \vdots \\ \dot{\theta}_n \end{bmatrix} + \begin{bmatrix} G(q) \\ \vdots \\ G(q) \end{bmatrix}$$

The mass m_6 constitutes the sum of the final link's mass and the mass atop the final link (mass of tools/food items).

IV. Results and Discussion

The problem this project solves is the preliminary design of robot manipulators for a kitchen environment. Due to the nature of robots, there is an inherent lack of spacial recognition compared to a human cook. Using collision avoidance in addition to the path planning here can make working with a robot much safer. For the UR5e system, we were quoted $27,960 for one "system" which consists of the robot, control box, teach pendant, and cables. This is roughly the same cost as a full-time employee at $13.44/hour for a year. However, the robot system is a one-time purchase. While there are minor maintenance costs, the employee has significant, indefinite recurring costs. Also, robots do not need things such as hazard pay, workers compensation, healthcare, raises, or other benefits that human employees will incur over the course of their time working. Aside from the restaurant environment, having a robot in a home kitchen is a good way to increase productivity while obtaining repeatable results for busy families.

III. Conclusion

Engineering theory underpinning the design of a 6-DOF kitchen assistant arm is well developed. The Forward kinematics, Jacobian, singularity analysis, motion planning schema, dynamical model, and simulation presented here are generalizable for any serial manipulator. This specific application requires more research into manipulator design and control policy before any real-life burgers can be flipped.

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