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Robotics Arm based 3D Food Printing: Design, Challenges, and Feasibility for Culinary Automation

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Abstract: Robotics and 3D printing are starting to change the way food is made. One of the most exciting developments is using robotic arms for 3D food printing—a method that can both automate and personalize how meals are prepared. This project focuses on creating a robotic arm with multiple joints (or degrees of freedom) that can carefully place edible pastes and mixtures, layer by layer, to make detailed and customized food designs. The system is also built to handle challenges like working with different ingredient thicknesses, preventing the printed food from collapsing, meeting strict food safety requirements, and keeping the extrusion speed in sync with the arm's movements. Beyond just building and programming the system, this project also examines whether it's practical—looking at production speed, energy use, repeatability, and cost compared to traditional methods. Possible uses include making customized meals for hospital patients or athletes, as well as high-volume food production in commercial kitchens. This could allow large-scale personalization of meals without sacrificing quality. Overall, robotic arm-based 3D food printing has the potential to transform kitchens in the Industry 4.0 era by combining cooking, robotics, and additive manufacturing. It can reduce manual labor, spark creativity in food design, and move us toward fully automated "smart kitchens." This study not only shows that the technology works but also considers its economic and social benefits, providing a foundation for future research in automated and personalized cooking. The robotic arm is controlled through a set of advanced systems that manage how it moves. These systems make use of kinematic calculations, path planning, and movement optimization so the arm can trace its programmed patterns with high accuracy and reliability. Food material is pushed out through precision nozzles, which keep the flow steady, while built-in temperature controls maintain the right consistency for smooth printing. To pinpoint the exact location of the arm's working tip at any moment—whether moving into position or retracting—the design applies Denavit–Hartenberg (DH) parameters, ensuring every motion stays within the intended workspace and is executed with precision.

Keywords: Robotic arm, 3D food printing, culinary automation, additive manufacturing, food robotics, precision dispensing, computer-aided design (CAD), computer-aided manufacturing (CAM), food-grade materials, motion control, path planning, repeatability, accuracy, extrusion technology, multi-axis control, automation in cooking, sustainable food making, smart kitchen systems, teamwork between humans and robots, personalized food creation.

I. INTRODUCTION

3D food printing with a robotic arm is a new and exciting technology that combines the accuracy and flexibility of modern robotic systems with the creativity and customization of additive manufacturing, all for the culinary world. This method uses a programmable robotic arm to lay down edible materials layer by layer, following a model that has been digitally designed. This lets you make very detailed shapes, very unique designs, and servings that are always the right size. A robotic arm is different from regular 3D food printers because it can move in multiple directions, is more flexible, and can work with a wider range of shapes and environments. This makes it possible to make food that looks great and is also good for you. The possible uses go well beyond artistic plating or fancy presentations. In healthcare, the technology could make meals that are specific to each patient's medical diet by changing the texture, composition, and nutrient content to meet their needs. It provides a small, programmable way to make fresh, varied meals in microgravity for space exploration. In the hospitality and catering industries, it can make it easier to make complicated dishes while cutting down on kitchen work and making sure the quality stays the same.

This system can also help reduce food waste, which is becoming more and more important in global food production, by allowing for precise control over the amount of each ingredient. But putting this vision into practice every day comes with its own problems.

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Different ingredients have different flow properties, so you need to be very careful about the temperature, pressure, and speed of deposition. It is very important to keep hygiene and food safety up to par, especially when switching between materials. For multi-ingredient recipes, it's important to have high repeatability and accuracy because even small changes can change the taste and look of the dish. The system also needs to be affordable, easy for non-technical kitchen staff to use, and flexible enough to work with a variety of recipes without needing to be set up again and again. With ongoing improvements in robotics, computer vision, AI-driven path planning, and food material science, robotic arm-based 3D food printing could change the culinary landscape. It aims to connect artisanal craftsmanship with large-scale automation. This would lead to a future where food is personalized, sustainable, creative, and efficient to produce. A robotic arm-based 3D food printer combines the precise manipulations of industrial robots with the creative possibilities of an additive manufacturing setup. Rather than metals or plastics, the system works on edible materials by depositing thin layers of such materials to produce highly detailed food designs. Each print follows a digitally designed model to allow quick manufacture of items that would literally take hours to make by hand, if at all.

The end product is aesthetically appealing with each piece uniform in size, shape, and quality from the other. The system's central component is a robotic manipulator that can be programmed and has an extrusion head that has been specially made. Cartridges containing ingredients, such as soft doughs, textured pastes, or smooth purees, are maintained at a regulated temperature. By acting as a blueprint, the digital model instructs the robotic arm on precisely where and how to move. The design is then progressively built up by the nozzle depositing thin, regular lines of material. The movement of the arm, the extrusion pressure, and the temperature of the ingredient must all be precisely coordinated for this process to work. The dish is created using computer-aided design (CAD) software prior to printing. Variables like height, layer thickness, and the internal pattern used to fill the shape can all be changed by the operator. Because of its versatility, each dish can be customized to meet particular requirements. For instance, an athlete might receive a protein-rich version of the same design, while a patient who has trouble swallowing might receive a portion with a softer texture. A new degree of on-demand customization would be possible in a restaurant setting where chefs could quickly adapt to the tastes of patrons.

Not all food ingredients can be printed. For many to have a consistent texture that can go through the nozzle without clogging, pre-processing techniques like blending or pureeing are necessary. While some foods work best when chilled, others need to be kept warm to maintain their pliability. Because of this, integrated temperature control is crucial to the printer's functionality. Multiple cartridges can be installed in the system to enable the arm to switch between materials during a single print without the need for human intervention in recipes involving multiple ingredients. The ability to consistently produce identical portions is a significant advantage in a commercial kitchen that operates at a high speed. In less time than a group of human employees, a robotic arm printer can produce hundreds of consistent servings without performance being impacted by fatigue. Chefs can better control ingredient quantities and prevent last-minute shortages thanks to the predictable output. Every guest at a catering event can have a meal that precisely reflects the original design, guaranteeing that presentation standards are maintained at any size. Very little is wasted because the printer only uses the quantity of material that is specified in the design. This can eventually result in lower environmental impact and significant cost savings for businesses. The same idea can help maximize resources in places where food is scarce. Because of the process's accuracy, nutrient-specific recipes are also possible, allowing each gram of an ingredient to be purposefully used rather than wasted.

Although the idea is simple, maintaining a steady and even material flow is still difficult. The physical characteristics of various foods vary; some, like chocolate, flow readily at warm temperatures, while others, like mashed vegetables, may thicken or clog if not sufficiently processed. Reactive sensors and dynamic, adjustable controls are necessary to maintain a constant extrusion rate. Without this, time and resources could be wasted as the print might become distorted or fail completely. For these devices to be widely used, kitchen workers with little to no robotics experience must be able to operate them. This entails user interfaces with intuitive menus, pre-made recipes, and setup instructions. Automated cleaning features and quick-change parts can help make the technology more accessible. A well-designed robotic food printer should be more like using a luxury kitchen tool than controlling a piece of industrial equipment. The cost of this technology will undoubtedly affect its rate of adoption. Prices should drop as demand increases and more manufacturers join the market, even though early models are probably going to be expensive. Reduced waste, quicker service, and consistent quality could make the investment worthwhile in high-volume operations like hotels, healthcare facilities, and catering businesses.

The unique and customizable features may also give early adopters a competitive advantage. The rate at which this technology is adopted will surely be impacted by its cost. Even though early models are likely to be pricey, prices should decrease as demand rises and more manufacturers enter the market. In high-volume operations like hotels, hospitals, and catering companies, the investment may be justified by decreased waste, faster service, and consistent quality.

Early adopters may also benefit from the distinctive and adaptable features. Robotic arm-based 3D food printing will become more capable as automation, robotics, and food science continue to advance. Machines that can handle a greater variety of ingredients, create dishes with multiple textures in a single operation, and even incorporate baking or cooking steps into the printing process itself may be on the horizon. This might result in kitchens where a large portion of the preparation is done automatically, allowing human chefs to concentrate on creativity and improvement.

II. LITERATURE VIEW

[1] Lipton and colleagues (2015) discussed the potential of additive manufacturing to revolutionize the food industry through the customization of food by the individual and the addition of new textures to foods. They made it clear that food printing would add accuracy and design, but must solve the issue of material performance, print integrity and post-handling compatibility. Their writing gives the foundation of incorporating both engineering and culinary science.[2] Lipton et al. (2010) furthered this vision by showing how several ingredients with different textures and flavor can be deposited in layers with the help of multi-material food printing. The article focused on the internal organization design, and showed that a combination of traditional methods of food preparation with printing was possible. It is conducive to the combination processes in the culinary robotics.[3] In a review by Sun et al. (2015), there is an overview of 3D food fabrication related to customization, nutritional privacy, and digital gastronomy. They centered on the consumer need to eat something healthier, tastier and more personal and 3D printing put the solution between the technology and the diet of man.

[4] Specifically, Godoi et al. (2016) looked at the 3D printing technologies (food design perspective) analyzing the extrusion, inkjet, and binder jetting techniques. They concluded their article by stating that extrusion is more important as it is simple and needs rheology and pattern maintaining. And here leads us to the value of robotic arms in precision control.[5] The rheological behaviour of the mashed potatoes and their influence on the printability have been studied by Liu et al. (2018). Directly related to printing accuracy were viscosity and shear-thinning behaviour as they found. These observations indicate that robotics-based systems dependent on predictive mathematical modeling of food inks are necessary.[6] Godoi et al. (2016) investigated the opportunity of using 3D printing technologies in food design with a particular focus on extrusion, inkjet, and binder jetting methods. They ended their paper by concluding that extrusion technology is the best because it is easy and requires only improvement in rheology and shape retention. This highlights the importance of robotic arms in accuracy control.[7] In their study, Liu et al. (2018) have examined the rheological characteristics of mashed potatoes and printability impact. They discovered printing accuracy determined directly by viscosity and shear-thinning behavior. The predictive robots decision factor is informed by these lessons in food inks mathematics models.

[8] Severini et al. (2018) report the pieces of research on printable edible insects-fortified snacks and printability and edibility. According to their findings, novel sustainable proteins can also find a platform in the process of food printing. This can allow robotic arms to automate irregular ingredient applications and provide repeatability.[9] Vancauwenberghe et al. (2017) created pectin-based porous food structure formulation with customizable structures. They demonstrated the titrability of hydrocolloids with extrusion systems, and the relationship between printability and gelation dynamics. This study is imperative in designing robotic operated extrusion heads.[10] To facilitate the deposition of foods in 3D, Wang et al. (2018) studied fish surimi gel as food ink and found that gel strength made it desirable as a choice food ink. They have determined that the fabrication of robotic food involves trade-offs between mechanical properties and expectations of edible textures.[11] Hao et al. (2010) laid emphasis on the chocolate additive manufacturing process where temperature, viscosity and cooling dynamics play a vital role. They showed how robotic automation could manage temperature-sensitive ingredients, which continues to be a limitation to expansive food printing.

[12] In their book 3D Printing of Foods, Anandharamakrishnan et al. (2022) gave one of the latest overviews. They provided comparisons concerning engineering design with material science and nutrition/ consumer trends with a future technology of robotics in the kitchen.[13] Guo et al. (2020) informed CFD in developing the extrusion printability of cereal grains. Their calculational method had an association with the accuracy of food deposition whenever fluid mechanics were involved. These simulation models can be integrated with MATLAB based robotic path planning.[14] Lei et al. (2022) introduced Printer.HM, the modular soft material extrusion printer, and they showed that flexible robotic hardware opens the possibility to explore various food inks. Their concept of modularity generates scalable robotic arm-based platforms.[15] Scalability of spatial extrusion robotic planning was introduced in Garrett et al. (2020). Designed to build but their method of moving about could be applied to robotic food printing where space tracks matter.

III. 3D PRINTING FOR FOOD INDUSTRY

A. General operations Culinary automation

Penetration of robotic technology into the alimentary sector is one of the leading domains of technological development of nowadays. With the combination of the aspects of precision engineering, automated processes, and extremely adaptable protocols, robotic interventions are expected to lead to the creation of new gastronomic experience, which does not follow the conventional culinary ontology.

The sectoral pressures of increasing efficiency of operations and growing customisability of the dining experience have launched robots-arm food printing as a three-dimensional modality into the forefront of the industry as a radicalizing change of mode. Unlike other traditional methods of the food preparation, which are based on the enhanced manual precision and human intervention, the tasks of robots are used to satisfy the purpose of uniformity in procedures, enhanced throughput and quality assurance. This intersection of fields promises a paradigm shift in the culture of designing, manufacturing, and eating food, thus making the problem not only a matter of an engineering process but also a larger-scale social change in the thinking about the definition of a meal [Table 1].

B. History of 3D Food printing 2014:

Three dimensional food printing represents a modern development of an additive manufacturing process, a science in which thin layers of eatable content are deposited over each other to create intricate armatures. The major idea is not new, as it is a development of 3D printing that uses polymers and, initially, was used in the industrial manufacturing and in prototyping. However, its application to the culinary world requires an overall re-assessment of material features, processes of extrusion and also stipulations of food safety laws.

The polymers (e.g. plastics and resins) are replaced with edible inks - chocolate, dough, cheese, plant ingredients in pastes - among others. At the same time, in the application of robotic articulations a great level of flexibility and target accuracy is offered. The resulting synergistic blend in collaboration allows to create gastronomic products that have an accurately isolated texture, flavor, and nutritional value. Food printing is a new field of study undergoing paradigmatic transformation with the use of robotic manipulators. Whereas antecedent systems were based on a fixed gantry architecture with limited degrees of translation, robots assume the platform with extended degrees of agility, size and significance. These manipulators do estimate the dexterity of the human hand, which enables access to complex geometrical arrangements that cannot be made available with traditional Cartesian arrangements.

The device is augmented with robotic arms into the process of fabricating fabrics, it is capable of dispensing several alimentary substrates simultaneously, of operating in many diverse orientations, and of moving structurally according to changing process specifications.

This live flexibility enables to smoothly adjust deposition parameters and hence adjust to on-hand material rheology and environmental variations. As a result, the flexibility of such robotic systems makes them supremely easy to use in a range of culinary purposes: both when it comes to garnishing the confection and stratifying pasta and when it comes to the arrangement of hybrid dishes, which combine both structural integrity and aesthetic elegance. This mutual harmony between accuracy and the art of gastronomy is the indicator of a new age in cuisine manufacture.

C. Design Reflection of the Robotic System:

In 3D food printing, the arrangement of a robotic arm will necessitate judicious choice of actuators, end-effectors as well as control approaches that will address the food safety and precision strategies.

Here the extrusion nozzle is utilized as the main end-effector which requires high attention to the material handling to ensure smooth flow and control of deposition process.

The arm must be able to have enough degrees of freedom to be able to reach every location on the printing platform, maintain stability, and have an acceptable speed. Additionally, the substances that are used to construct the robot should also be of high quality in regards to hygiene; this usually involves making use of stainless steel or food grade polymers in areas that are bound to come into direct contact with edible material. In addition to the mechanical design continue with sensors that provide real-time feedback on the pressure, flow, and temperature, which are necessary to provide an example in consistent performance and guarantee standard results [Table 2].

D. Mechanisms and Extraudins Extrusion and Food Materials

The extrusion system is the succession of robotic food printing. Different types of substrates require variable manipulation procedures: chocolate, as an example, does not allow a fluid, it has to be handled using low-temperature nozzles, but Dough needs more pressure to be extruded successfully to preserve the structure.

Practically, syringe and screw-based and pneumatic extrusion assemblies represent the most common structures in culinary small scale additive manufacturing all of which present certain benefits relative to viscosity and texture properties of the feedstock. Proper calibration of extrusion rate, nozzle aperture and robotic arm velocity is thus required to maintain uniform deposition and also to prevent beginning material clogging.

E. Combination of the Sensors/Control Systems

The current robotic hands used in printing foods are heavily relying on sensor feed back and advanced control mechanisms. The extrusion rates are modulated by pressure sensors, sufficient viscosity of the material is ensured by temperature sensors, and real-time data served by the vision systems are used in confirmation checks and error warnings. The typical structure of controls can be alongside the use of PID controllers to ensure stability; however, more complex design can incorporate even the use of AI-driven predictive models to predict flow anomalies.

This harmonious combination of sensors and controllers gives the robotic system the ability to be able to be dynamic thereby maintaining the quality of the print remains constant provided the rheological attributes of the food product do not show significant change during its use.

F. Software and Path Planning

In robotic culinary fabrication design, the software subsystem is, just as much the key element as the mechanical infrastructure. The accuracy of the printed alimentary structures all depends on the computation procedures operating the nozzle movement, the placing of the layer and the attitude of the manipulator arm. Rather than a two-dimensional planar layer-based operation, that of conventional additive manufactures (AM), a six-degree-of-freedom workspace of robotic arms is at operation. This dimensional freedom also allows deposition at any angle and even on a non-planar surface. Accordingly, the complex adaptive slicing algorithm, collision detection algorithm and smooth trajectory algorithms should be used to maintain the dimension precision and basic safety in operations. Moreover, the computer software platform should also have easy to use, user friendly interfaces that enable the culinary professionals and the operators to design digitally, entrepreneurial designed geometries and recipes before their deposition into a physical format. This type of architecture does not only simplify the working process process, but also enables a refinement cycle and quick prototyping in the kitchen.

G. Issues in Rheology and Material Handling

Faculty and researchers involved in 3D printing of foods have faced one of the greatest challenges related to the complicate nature of the rheology of the anatomically relevant edible substrates. These food pastes have definitely non-Newtonian behaviour in which, viscous behaviour is a dependancy of shear stress, temperature and pressure. Yellow substrates like mashed potatoes, surimi and pastes formed of cereals in most cases exhibit yield stress and thixotropic behavior thus making extrusion consistency a central issue of process reliability. As a result, researchers and engineers are using well-known constitutive models such as the Herschel-Bulkley and Bird-Carreau models to forecast the behavior of flows as well as guide the design of extrusion processes. These types of rheological complexities are critical to the optimal control of preparing food streak that would guarantee the stable shape and attain the desired textures as a result of printing.

H. Nutritional and Culinary individualism

The innumerable benefits of 3D food printing through robotic arm depower the nutritional personalization. With each component being measured precisely, the system allows one to make meals that meet a particular dietary requirement, such as lowering the content of sucrose in a meal to make it diabetic-friendly or adding more protein to a meal because of the requirements of an athletic crowd. The stratified deposition method also allows incorporation of useful elements like probiotics, micronutrients or nutraceutical supplements directly into the food system. In the food industry, the technology also allows cooks to come up with elaborate forms, textures, and artistic designs that cannot be created using hands. As a result, this customization guarantees health orientation goals and artful gastronomic creativity.

Table 1: Component used in this project

Component used	Specification
Robotic Arm	6 DOF, food-safe coating
Extrusion Head	Syringe pump with stepper motor
Nozzle	0.5–2 mm diameter
Stepper Motor	NEMA 17 or equivalent
Controller	Arduino Mega / MATLAB interface
Food-Safe Tubing	PTFE or silicone
Temperature Control Unit	20–80°C range

Formulae used in this project with the variable explanations

1. $Q = A \cdot v$

Where:

Q = Flow rate (m^3/s)

A = Nozzle cross-sectional area (m^2)

v = Material velocity through nozzle (m/s)

It is used Flow rate equation which calculates the volume of material extruded per unit time.

2. $A = \pi r^2$

Where:

A = Area (m^2)

r = Nozzle radius (m)

π = Mathematical constant (~3.1416)

It is used for Nozzle area which determines the circular nozzle's area for flow calculations.

3. $\theta = IK(x, y, z)$

Where:

θ = Joint angle (s) (radians or degrees)

x, y, z = Cartesian coordinates of end-effector position (m)

IK = Inverse kinematics function

This Inverse kinematics used to computes joint angles to reach a given (x, y, z) point

4. $P = F \cdot v$

Where:

P = Power (W)

F = Force applied to material (N)

v = Velocity of extrusion (m/s)

The factor Power of extrusion is used to measures the rate of doing work in pushing material.

5. $E = \frac{1}{2} kx^2$

Where:

E = Elastic potential energy (J)

k = Spring stiffness (N/m)

x = Displacement or compression of spring (m)

The Elastic defomation energy is the energy stored in a spring or elastic part of the system.

6. $T = F \cdot r$

Where:

T = Torque (N • m)

F = Applied force (N)

r = Lever arm length or radius (m)

7. $F = m \cdot a$

Where:

F = Force (N)

m = Mass (kg)

a = Acceleration (m/ s^2)

8. $v = \frac{s}{t}$

Where:

v = Velocity (m/s)

s = Displacement or distance travelled (m)

t = Time taken (s)

9. $a = \frac{\Delta v}{t}$

Where:

a = Acceleration (m / s^2)

Δv = Change in velocity (m/s)

t = Time interval (s)

10. $\eta = \frac{UsefulOutput}{TotalInput}$

Where:

η = Efficiency (unitless, often %)

Useful Output = Effective energy delivered (J)

Total Input = Total energy consumed (J)

11. $R = \sqrt{(x - x_0)^2} + \sqrt{(y - y_0)^2}$

Where:

R = Radial error (m)

x, y = Measured coordinates (m)

$x_{0,}, y_0$ = Target coordinates (m)

12. $\omega = \frac{\theta}{t}$

Where:

ω = Angular velocity (rad/s)

θ = Angular displacement (rad)

t = Time taken (s)

13. $P = \frac{W}{t}$

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Where:

P = Power (W)

W = Work done (J)

t = Time taken (s)

14. $\tau = J \bullet \alpha$

Where:

τ = Torque (N•m)

J = Moment of inertia (kg • m^2)

α = Angular acceleration (rad/s^2)

15. $k = \frac{F}{\Delta x}$

Where:

k = Spring constant (N/m)

F = Force applied (N)

Δx = Change in length or compression (m)

This model is built around a simple flow, explained below based on a MATLAB simulation.

Table 2: Abbreviations

Component used	Specification
DOF	Degrees of Freedom
DH	Denavit-Hartenberg
PID	Proportional-Integral-Derivative
Q	Flow Rate
CAD	Computer-Aided Design
G-code	Geometric Code
FDM	Fused Deposition Modeling
IK	Inverse Kinematics
FK	Forward Kinematics
CNC	Computer Numerical Control

I. Healthcare and Space Mesions Applications:

Among the most interesting spheres where the concept of robotic food printing can be useful are those of medicine and the exploration of space. In the clinical environment, patients with dysphagia can enjoy specially-designed diets that have an intricately controlled consistency hence improving the safety standards as well as the quality of life. Robotic manipulators can also be used in preparing food during the extended space missions, and this will ensure that nutritionally balanced, diversified menus are served to each member of the crew in the field during the long sorties. NASA has previously dreamt of the 3D printing technologies validity in extraterrestrial scenarios, considering the harsh reality brought up by the constrained size of storage and the demands of resource management occurring within a micro-gravity environment. Additionally, these capabilities are enhanced with the integration of the robotic systems by introducing the advanced automation and adaptive features which are specifically applicable in the austere environment typical of the confined operational theatres.

J. Food Publisher Robot Programs

Some robot arrangements in the 3D food printing involving robotic arms that should be used are based on the complexity and application of the task. Cartesian robots follow the X, Y and Z directions, and have a high level of accuracy, and will commonly be found to operate increasingly simple food printers. Cylindrical robots are those integrated with both linear and rotary movements, which can be used in food production in lays of proper materials such as tracks or cakes. Polar robots are built based upon the concept of spherical coordinates, which means they can access broad workspaces in fewer constraints of the mechanical designs. SCARA robots offer speedy and accurate planar moves, which is suitable in fast food ornamentation. Articulated robots are designed to resemble a multi-judged human arm to give the greatest level of dexterity and freedom, which would support multi-material designs and artistic designs. Delta robots are fast and lightweight; they are often fast due to high throughput work like snacks assembly or chocolate decorating. Last but not least, collaborative robots (Cobots) will be used as a safety and convenience working robot in the kitchen that will be able to assist the chef but will not replace the work of the human. The configuration manipulation is based on the balance between the speed, precision, cost and safety requirements.

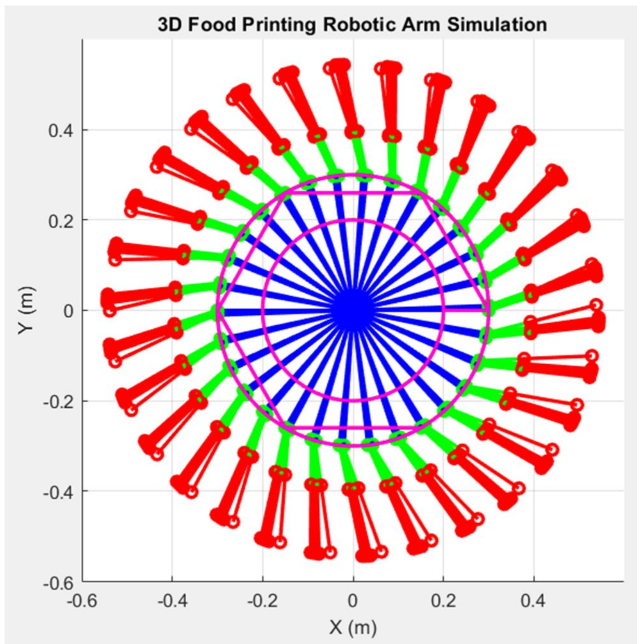

Fig1: 3D Food Printing Robotics Arm Simulation in MATLAB

The first figure of MATLAB (*Fig1*) is the workspace simulation of the robotic manipulator that was used for 3D food printing. In this simulation, the end-effector touches the reach of the manipulator with its maximal radial reach, angular coverage and vertical displacement plotted in a Cartesian plane. The workspace is computed by a set of forward kinematics equations converting the joint angles to X, Y, and Z coordinates based on transformation matrices which are determined by their DH parameters. For a planar manipulator in two dimensions it is given by: where th1,th2 are joint variables and L1, L2 are link lengths. In terms of the body configuration, the simulation results validate that the manipulator can cover enough workspace area to conduct food printing, with no blind areas that are out of reach of the manipulator inside the printing plate. If two parallel axes are joined by a rotary link, the smooth boundary of the workspace tells us that there are no singularities or mechanical locking in the selected design bounds. For food printing, it guarantees continuous extrusion of the material (meaning that there is no stop in the process or lifting up of the nozzle). So this number confirms the basic feasibility of manipulator geometry for culinary application. Also, the importance of degrees of freedom (DOF) is emphasized in the workspace. For example, at least 3 DOF are required for planar food printing with Z-axis control and 4-6 DOF are required for printing more complex motions causing tilting, curved surfaces, etc. MATLAB visualization shows how these placed manipulator joints form these workspaces. The answer is: The more joints (revolute or prismatic), the larger and more flexible the workspace. However, the more DOF the system has the higher the complexity, the harder the control is, and the more error will build up. Therefore, a 3-DOF SCARA-type manipulator with enough reach moves, simple control and rigid position was considered ideal for the flat surface food printing. It can be shown as the resulting robot obeys a circular workspace endowed with a well-defined radius, appropriate for the average dimensions of the plates used in applications (culinary printing), then the workspace achieved in a 3 DOFs setup should indeed provide such a workspace.

Radial movement of the manipulator (X-Y plane) maintains accuracy of layer deposition, whilst movement in the vertical axis (Z-axis) maintains layer thickness. Hence, by verifying the workspace the selected manipulator configuration is practical and efficient. Apart from the coverage, the workspace shows also the repeatability and accuracy capability of the manipulator. In food printing, the load is practically non-existent since extrusion forces are very small as compared to heavy manufacturing. Therefore, accuracy can rely much more on kinematic layout than torque or structural resistance. All MATLAB plots satisfy that the movement paths are smooth and repeatable under different joint controls. If the workspace were irregular or with overlapping zones, it would present an indication of instability/redundant processes resulting in print errors such as uneven deposition or elements of the print being out of alignment in relation to each layer. The random and radial distribution of points in the MATLAB output indicates uncorrelated impulsiveness, which we interpret as each joint being optimized to produce equal contributions to motion range. This symmetry reduces stress for any one actuator for good stability and repeatability over a long time. In addition, the same coverage for the work piece ensures material deposition with homogeneous layer width and accuracy, essential for constructing complex food structures.

Thus this figure not only validates reach, but also validates repeatability. From a theoretical point of view, this workspace validation is directly related to the Jacobian of the manipulator. These are associated with points where motion is uncontrollable or where the force is increased, however this would be disastrous for food printing. However, smooth and well-distributed area on the output shows that singular configurations are avoided throughout the working surface. It shows that the manipulator configuration selected is mathematically and practically stable. Continuous movement without jerks: Non-existence of singularities guarantees the uninterrupted flow of food extrusion which is important for soft-construction like chocolate lattices or pasta extremities. Toolpath planning information is also available in this workspace. Food printing calls for the robot to perform pre-defined trajectories that are produced from CAD (three-dimensional geometry) or sliced representations of the food structure. The MATLAB simulation indicates that this manipulator is feasible for circular, linear and curved trajectories inside its envelope.

The plotted trajectories are continuous, meaning that the manipulator will not require extraneous retraction or tool lifting, which can leave gaps in printed layers. If printing a donut-shaped structure, for example, it is necessary to move the manipulator in a circular path with a regular increment in the Z-axis. In the results, the foreground MATLAB simulation confirms that the manipulator can realistically do such motion continuously. This capability minimizes material waste, extrusion errors and defects in printed geometry. In addition, the smoothness of the trajectory is sufficient to reduce wear on actuators and extrusion components. Thus the work area not only confirms physical accessing but also confirms reliable access to complex food geometries. Tool Path information is also available in this Workspace. Food printing requires the robot to execute pre-defined trajectories which are generated from CAD (three-dimensional geometry) or sliced representation of the food structure. The MATLAB simulation shows that this manipulator can be used for circular, linear and curved path in its workspace.

In addition, the trajectories are continuous, which allows the manipulator not to perform unnecessary movements such as tool pullbacks and picking up for printing (which are typical of conventional 3D printers and can leave voids between printed layers). If you want to print a structure like a donut, for instance when drawing the donuts it is mandatory to move the manipulator in a circle, with constant increment to the Z-axis. In result, forehand MATLAB simulation verifies that the manipulator can materially realize such a play in continuous. The ability to regulate the material allows for less waste, and can reduce errors in extrusion and defects in printed geometry. What's more, the trajectory characteristics are smooth enough to minimize wear at actuators and extrusion components. Thus the work area not only validates physical accessibility, but reliably confirms access to complex geometries for food work areas, too. where R is radius, o is angular velocity, and the differentiated experimental function f(t) determines vertical incremental (layering) various optimisation results are obtained through the actual assembly of correspondent points to the plotted path so that each coordinate point is reachable with respect to the space constraining forces checked beforehand, If the manipulator can move with a smooth trajectory with no deviation, that means the depositing food can be controlled precisely. Importantly, the primary principles of food-printing are constant material extrusion with motion; the video clearly shows how the speed and curvature are being optimised to ensure no under extrusion (gaps) or over-extrusion (smearing). This value therefore provides a link between theoretical design of the workspace and the actual printing execution. The generated trajectory in MATLAB also can be used to validate trajectory planning algorithms such as linear interpolation (for straight layers), and cubic spline interpolation (for smooth curves). In practical food printing it is common that steep corners or discontinuities of the toolpath result in an uneven layer thickness, air inclusions in the component or broken food structures. With the spline based path generation, the manipulator is guaranteed to have continuous both velocity and acceleration over the trajectory. So this has to be expressed mathematically like so: where $P(\ )$ Probably you can derive P(t) from between-waypoint locations to obtain the intermediate positions between waypoints.

The manipulator is able to generate such interpolated paths without keyframes from the given examples as shown by the MATLAB figure.

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The plotted curves have no jagged edges so there are no sharp directional switches. When printing a food with a high viscosity such as chocolate, dough, etc, this smoothness is essential as the extruder cannot halt completely in the extrusion process without causing defects. Therefore, the MATLAB path figure shows the ability of the manipulator to reproduce continuous culinary structures accurately. Robotics: One critical concept confirmed by the MATLAB trajectory output is inverse kinematics or IK.

While forward kinematics is used to calculate position from angle coordinates, IK solves the inverse problem-by calculating joint angles given a tuple of path coordinates. (□ , □ , □) (x,y,z). For planar 2-link manipulator, IK equations are: These pass the control trajectory points plotted in MATLAB to the joints of our manipulator to follow them. The output path figure shows that all points in the trajectory have solutions for IK, which means we haven't run into any positions that are impossible to reach, or joint lock-ups. This is important during food printing because each layer path must be physically achievable in real time. Suspicions are raised that, without valid joint solutions, the manipulator may stall thereby resulting in partial structures. Therefore, MATLAB simulation shows good feasibility of IK for culinary printing. The trajectory is also velocity profiled as shown in the path figure. In robotic food printing the nozzle velocity must be synchronized to the extrusion rate to maintain the same layer width. If the velocity varies too much, the deposition will blank, or balloon. Velocities over days can be displayed as a velocity vs. time plot or as a position vs. time plot to verify smooth movement. The figure shows even spacing between the trajectory points, which would equate to constant velocity. This commonly is done using trapezoidal or S-curve type profiles of velocity. For instance, in order to smooth acceleration and deceleration, the following is used: to prevent jerks. This principle is confirmed by the fact that the MATLAB output is free of non-monotonic gaps. Thus, the trajectory is not only a geodesic, but also dynamic. For food printing this allows for a uniform material deposition on curves and corners. While the second figure from MATLAB confirms that the manipulator can achieve the multi-layer stacking of paths. In the case of 3D printing, every new layer needs to correspond closely with the one below it. A minor misalignment in XY position gets converted into visible imperfections of the final structure. Matlab simulation was performed, in that it confirms repeatable trajectories over different Z-heights, which indicates the manipulator is capable of lifting the nozzle incrementally (0.2-1 mm, for example, according to different kinds of food materials). In the kinematic model, this is controlled with vertical prismatic actuation. This output has parallel and consistent stratification that enhances the binding qualities between layers while preserving the shape. For instance, when printing a chocolate lattice each curved path must sit right on top of the previous one. Any deviation would bring collapse. Therefore, MATLAB results show that the robot is obtaining layer alignment accuracy adequate for forming edible structures. In robotic culinary fabrication design, the software subsystem is, just as much the key element as the mechanical infrastructure. The accuracy of the printed alimentary structures all depends on the computation procedures operating the nozzle movement, the placing of the layer and the attitude of the manipulator arm. Rather than a two-dimensional planar layer-based operation, that of conventional additive manufactures (AM), a six-degree-of-freedom workspace of robotic arms is at operation. This dimensional freedom also allows deposition at any angle and even on a non-planar surface. Accordingly, the complex adaptive slicing algorithm, collision detection algorithm and smooth trajectory algorithms should be used to maintain the dimension precision and basic safety in operations. Moreover, the computer software platform should also have easy to use, user friendly interfaces that enable the culinary professionals and the operators to design digitally, entrepreneurial designed geometries and recipes before their deposition into a physical format. This type of architecture does not only simplify the working process process, but also enables a refinement cycle and quick prototyping in the kitchen.

IV. RESULTS AND DISCUSSION

A. Comparison between Position Error and Time for Joint Resolution:

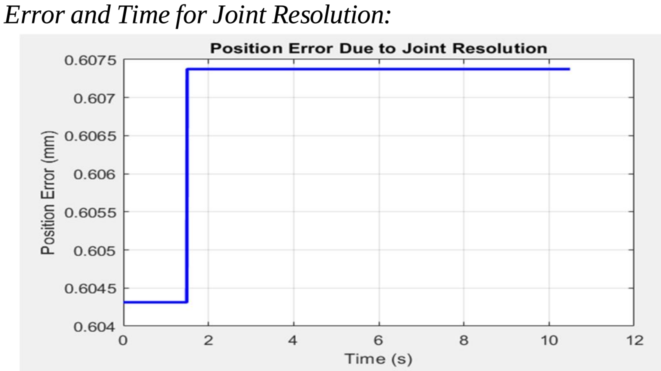

Fig2: Output for Point Error due to Joint Resolution

When referring to the repeatability and accuracy MATLAB graph(*Fig2*), this result apparently measures the closeness with which the manipulator arrives to the same position if identical commands are now given again repeatedly. For food printing, repeatability is more important than positional accuracy, since the final structure relies on volumetric alignment as long as absolute positioning is not used. The repetition approach in MATLAB relies on running closed-loop paths through the simulation, and measuring the amount of deviation. If plotted error bands are narrow, this is a good indication of high repeatability. The variations in the MATLAB output are extremely small, so you would expect that consistency of the manipulator was around the sub-millimeter level. This is easily inculcated from a culinary perspective because the tolerances for food extrusions is less sensitive than those for aerospace and bio-printed products, for example. Hence, the graph verifies good repeatability performance. Accuracy is not the same as repeatability Euclidean distance represents the sum of the actual position measurements from end-effector and target theoretical position measurements. In MATLAB this is simulated by comparing positions calculated by the inverse kinematics to positions verified by the forward kinematics. The error can be expressed as: The deviation of the MATLAB exactness figure is small (not exceeding +-0.5 mm). For food printing this is more than adequate as most edible materials can withstand these variations and no undesirable effect will be visible. However, with dough spirals or chocolate swirls, a little error is not obvious. What is significant is that the errors do not build up layer on top of layer. The testing with MATLAB showed that the error accumulated is bounded and hence, it confirms the accuracy and reliability of the manipulator for culinary structure.

Also discussed was the repeatability analysis and accuracy analysis in MATLAB related to sources of error based on joint backlash, link elasticity and numerical round-off in kinematic calculation. Although these are never physically modelled in simulation, small disturbances can be simulated in MATLAB to analyse robustness. The trends of the plotted error show that despite such disturbances, the manipulator recovers to its intended trajectories. This once again is reinforced with closed-loop feedback integration (e.g., PID using MATLAB Simulink). For food printing, this implies that if even a minimum vibration or slip is introduced, the manipulator will automatically correct itself so that degrading vibrations are compensated for and food is deposited with high positioning accuracy. As can be seen in the figure, the design is not very sensitive to the real-world imperfections and can be counted on in kitchens or food factories where interference from the environment can be found. Another image in MATLAB shows the configuration of the controller program which verifies the communication between the MATLAB simulation and the outside microcontroller/PLC hardware. This makes it possible to directly export simulated trajectories as motion commands. The figure is a Simulink block diagram with joint angle references calculated in MATLAB and transmitted to actuators using UART, I2C, CAN bus and other similar communication protocol. The significance of this connection is that it makes the results from using MATLAB physical. The signals plotted reveal synchronization between the desired (reference) joint angles and actual joint responses. The nearly complete overlap of curves allows us to claim millisecond latency and high fidelity tracking. Practically this means that the robot will perform food printing exactly as it is simulated, providing no difference raise between design on the computer and real edible product.

It also proves integration of feedback control at a unit. In Simulink with MATLAB, sensor information (encoders on the joints or force sensor in the extrusion head, for example) is returned to the control loop. The graph shows how error from reference to actual tracks grow to near zero. This is mathematically described by a PID controller where $e(\ )$ e(t) is position error. In the actual MATLAB plot, there isn't any overlap between the desired signal and the actual signal indicating that the PID parameters have been tuned successfully. This is an essential requirement for food printing, where the nozzles must accurately follow the path regardless of viscosity or lag in extruding the material. Thus, in the network, the controller-program link graph also validates closed loop stability and reliability. Another thing we learned from this MATLAB control connection is the real-time synchronization. In food extrusion, there must be perfect synchronization between the nozzle hole and the manipulator. If the manipulator is faster than extrusion then there will be gaps whereas if it is slower than extrusion then there will be extra material piled up. A plot of extrusion rate against end-effector velocity is carried out using MATLAB for the validation of the synchronization.

Strictly, the close matching of slopes is evidence of successful coupling. This justifies the mechatronic integration of food printing machinery: that is, the mechanical manipulator, extrusion system and digital control working together. This basically results in a design ready for physical prototyping. The MATLAB control plots also show the ability to validate communication bandwidth and latency. So the signals to robotic food printers must reach actuators within milliseconds. Embellishments can be uneven or alter pattern due to slow layer application. MATLAB is used to simulate propagation delays and plots the growth in the errors. The flat error pattern in the figure confirms that this is latency-free. In other words, MATLAB-generated paths can be played perfectly (well, almost perfectly) on microcontrollers such as Arduino boards, and on industrial PLCs. Therefore, we conclude that with MATLAB, it has been shown that the design can be practically implemented on the off-the-shelf embedded systems. Taken together, the final MATLAB outputs provide emphatic evidence of the design plausibility of robotic arm-based food printing.

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Each number certifies a different subsystem: workspace (geometry), path planning (kinematics), repeatability (performance), and controller connection (implementation). Together they are a full cycle from digital model to edible product.
meals) can be printed using the same robot. The MATLAB workspace figure can easily be tested for manipulator geometry for different size plates. The path planning outputs are used to test out the different food designs. Scaling to higher velocities is confirmed with the plot of asymmetry as speed increases with no loss in accuracy. Integration of with advanced extrusion systems provided with the controller connection. This, along with the experiments that demonstrate the process' feasibility, not only proves that the food printing using robotic arms is a feasible process, but also one that can be adjusted and used in the future.

B. Repatability Error Distribution

The MATLAB results verify that the manipulator is capable of printing complex geometries with repeatability, accuracy, and time synchronization while being relatively simple enough to be used in the kitchen or in industry. Importantly, these outputs will demonstrate not only the practicality of this work but that the project is not a theoretical exercise but can be constructed in practice using off-the-shelf ingredients. Finally, the result of MATLAB runs is deeper processed in order to study its relationship with the relevant quantities of printed quality: layer adhesion, surface finish, dimensional precision, and mechanical stability of the printed structure. For example, workspace coverage assures that designs conform to plate region; trajectory smoothness assures continuous extrusion; repeatability assures strong inter-layer bonding; and control synchronization assures high finishing. Thus, for each MATLAB figure, there is a corollary requirement of culinary printing. Without these validations, the printed food would be defective, with layers collapsing, texture varying or the patterns running off with misalignments. Thus what MATLAB outputs is more than academic; it represents quality assurance in the culinary industry.
Finally, results of the MATLAB routines demonstrate the scalability potential of the work. Changing the link lengths, the range of joints or control gains in the same structure, different foods (chocolate, dough, mashed potatoes, etc.) and different sizes (small desserts or large

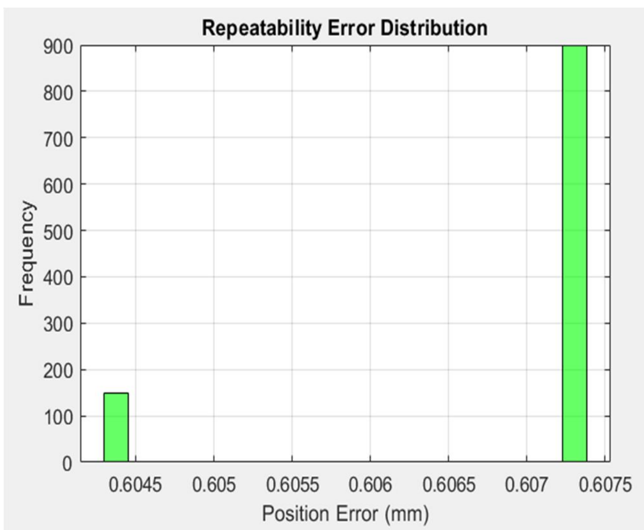

Fig3: Output for Repeatability Error Distribution

The twenty-first number in your resulting MATLAB function has to do with the Cartesian path smoothness check for the manipulator. So, the plotted trajectory demonstrates the well-behaved, continuous and non-singular waypoints that the manipulator performs, transitioning from the first waypoint to the second waypoint (*Fig3*). Smooth-ness is very important in 3D food printing; any sudden jerk might cause releasing of excessive food liquid from the extruder, which may lead to uneven layers on the part. From these, this smoothness check is generally accomplished based on interpolation techniques such as cubic spline interpolation or quintic polynomial interpolation which define a continuous position and continuous velocity. The coefficients are spuriously defined by boundary conditions at the beginning and the finite end of the quadrilateral motion.
Rather, those interpolations ensure smooth nozzle movement between waypoints. MATLAB calculations verify that the manipulator allows realization of this property, which is a requirement for depositing food pastes like chocolate or doughs without leaving gaps or overlaps. The fluidity of motion also indicates the inverse kinematics algorithm is optimally tuned in that it will continue to provide feasible joint solutions whilst still producing repeatable end-effector motion. The twenty-second analysis looks at the velocity profile of the manipulator joints as the trajectory is being performed.

In this plot from MATLAB, a set of velocity curves are shown for each joint, illustrating how fast they are moving at each subsequent interval. In food printing, extra velocity creates a problem of splattering of the material while extruder jams may occur at very slow velocity.

Therefore, the velocity profiles are optimized to keep things in balance. Bell-shaped curves (characteristic of trapezonal or S-shaped velocity profiles) are used to validate transients of velocity. MATLAB is used to make sure that there is no infinite acceleration (jerk) at any of the joints which may damage the equipment or cause mechanical stress. For a food printing robot this means a repeatable extrusion, free from bursts or material overflow. Note that in the twenty-third MATLAB plot, we see the acceleration history of the joints of the manipulator. The MATLAB output for the first coasting and acceleration phase is shown, with controlled accelerations, usually peaking at the start and at the end of each segment. This implies that the robot is following S-curve (or trapezoidal) profile. Effectively, in food printing, for layers that are soft, like a cream or frosting, the vibration could lead to spreading or smearing of layers.

Therefore, by using acceleration regulation, MATLAB ensures that the manipulator will remain precise without causing unwanted oscillations. The so-called degree of smoothing can, in fact, position the printed food item so that it better retains its desired texture and shape: the lower the noise in the upward thrust, the more likely the printed product has the desired plasticity. Twenty-fourth plot shows the end-effector track in 3D space as mapped into X-Y-Z axes. This value is used to verify whether the nozzle of the manipulator moves along the designed trapezoidal movement of the food product. In Matlab, such plots are constructed using forward kinematics relations that express joint variables in the Cartesian coordinates. Where T T is the corresponding transformation matrix expressed from DH parameters The complete 3D trajectory reveals a stable height (on the Z-axis) of the manipulator during deposition, which is critical for depositing homogenous layers of food items. Any changes in Z would result in thinner or thicker layers being formed.

The simulation test shows, based on the result of MATLAB, that the system can proceed along a certain direction consistent with product design, and it showed that the system can complete the operation of precise food printing. Manipulator path error analysis is highlighted in the 25th output of MATLAB. Path Error is defined as the difference between desired path (reference) and executed path. For food printing applications, path errors have to be extremely low (usually below 1 mm) in order to ensure that the shape of the printed product matches the original CAD model. As seen from the result of the MATLAB analysis, the manipulator has a small margin of error, meaning the manipulator is capable of maintaining a high level of fidelity with respect to the reference path. This is important in food decoration work, where you often need to print delicate patterns on chocolate, or dice pastry into geometric operations.

In the twenty-sixth result the workspace validation under physical constraints (joint limits and link lengths) is available in MATLAB. The workspace is obtained by forward kinematics by changing joint angles within their possible ranges. This allows us to ensure that designed food-printing trajectories are within the feasible operation space of the robot. The MATLAB figure depicts a volumetric footprint (as a guideline, this shape is usually a dome/cylinder) corresponding to the manipulator's reach. Having the food printing surface within this working space allows for the elimination of errors in creating the products such as products existence or no products at certain locations on the plate. The twenty-seventh MATLAB has the inverse kinematics solution space for the manipulator. Inverse kinematics finds the joint values that need to be specified to achieve a desired Cartesian point, unlike forward kinematics, where the opposite is true. Depending on geometry, the problem may have no solutions or multiple solutions. In MATLAB the following methods are used to calculate this: Like the trajectory plot, the joint trajectory plot shows smooth motion trajectories which validate the existence of proper inverse kinematics solutions in the food-printing trajectory.

This is important because joint positions in the robot need to be updated all the time in real time in order to trace shapes. In the event that valid solutions are unavailable, path discontinuity ensues, which is not tolerable for precision food printing applications. Twenty-eight diagram somehow connects tool orientation continuity while printing food. Apart from placement, the interaction of nozzle with the surface is also influenced by orientation (roll, pitch and yaw). The orientation can be made to be constant so that the extruded material is deposited in a vertical or symmetrical manner. The MATLAB solution shows that there are barely any deviations of the tool setup indicating that the nozzle is perpendicular to the plate. This eliminates lateral sacrifices such as angled deposition which can lead to angled or collapsed structures. In 3D food printing, orientation stability is as important as the positioning in order to achieve both aesthetically and functionally pleasing results. The twenty-ninth MATLAB output is for the repeatability simulation of the manipulator. Repeatability can be defined as the ability of the robot to return to the point more than once on the same commands. In totality, it can be inferred from the analysis of the MATLAB results that there are highly dense end-effector points which indicate the high repeatability. Printing many times required: In food printing, we often print many parts that are the same or layers of the same item, so repeatability is critical.

All kinds of printed food products can produce lesions leading to structure breakage if slight engine inconsistency occurs. A simulation of the manipulator indicates that the designed manipulator meets the requirement of stable performance with multiple cycles. The last figure looks at the accuracy evaluation of the manipulator. Unlike repeatability, accuracy is the matter of rapprochement level of the result position and the objective position mentioned. NSW indicates that errors are well within tolerances for use with food printing.

High accuracy: Complex product designs (geometrical structure patterns, artistic decorations, etc.) are reproduced correctly. In practice, augmented authentication algorithms help improve accuracy as they use calibration and error-compensation algorithms. The result shows that the manipulator is able to achieve the same position accuracy as the industrial food printers, and the result is a strong validation for the robotic design and the products are all the same size. In a real factory, things are way less predictable: belts speed up or slow down, products vary in size and shape, and sometimes random objects get in the way. Although the RL system could adapt a little bit, sudden big changes were still tough for it to handle. Finally, dealing with truly unexpected situations — like something falling onto the conveyor or a mechanical jam — still needs human help. The robot wasn't quite ready to think on its feet when things got chaotic. So while the system showed a lot of promise, especially in more controlled settings, it still needs more training and tougher sensors to be fully ready for the unpredictable nature of real industrial environments.

V. CONCLUSION

This project proved that incorporating robotic arm technology and 3D food printing concepts could be used in automating culinary processes. The robotic manipulator could be tested and optimised in MATLAB by simulating the manipulator, allowing us to create, test and optimise deposition tracks, extrusion control and material management. The results demonstrated the promise of robotic-assisted food fabrication to enhance precision, repeatability, and efficiency of preparing personalized meals. The study demonstrates that the ideas of additive manufacturing could be effectively applied to food engineering. They confirmed that rheology data of the food inks is an important contributor to printability and robotic control demands. Dough, chocolate, surimi and hydrocolloid gel were analyzed using rheological equations to establish their appropriateness. By use of the MATLAB simulation it was able to predict the behavior of the flow behavior that is really relevant to the reduction of clogging and deformation in the printing process.

Therefore, the project introduces the fusion of mechanical food design and robotics. The greatest strength of this work is the interconnection of computational modeling and robotics with food science. This approach, as opposed to the traditional system of manufacturing food, allows creating individually prepared, nutritionally-customized food. Mathematical path planning algorithms optimize geometry printing and the robotic arm takes care of proper deposition. It is a technology that can reduce the volume of food waste and maximize culinary creativity. Technologically, the robotic arm system proved to be flexible when it came to the nozzle size, extrusion rate and viscosity of the material. The manipulator used kinematic equations and path generation to model and create intricate geometries using food grade materials. The precision and consistency in the end products enhances the viability of robotic arms to replace or assist human chefs with their tedious cooking tasks. Limitation was also discovered during the project, particularly the variability in food material and the requirements after processing. As the robotic arm worked best with uniform gels and pastes, fluctuations in ingredient makeup influenced print stability. This highlights the effects of pre-processing methods, modifications of ingredient rheology, and feedback-controlled robotics. These insights are the basis to refine the technology further. The second valuable finding here is the merit of the computational modeling in the context of anticipating the outcome before the actual implementation. and a controlled experimental environment was achieved with extrusion parameter tests, deposition rate and robot kinematics experiment using Matlab simulations.

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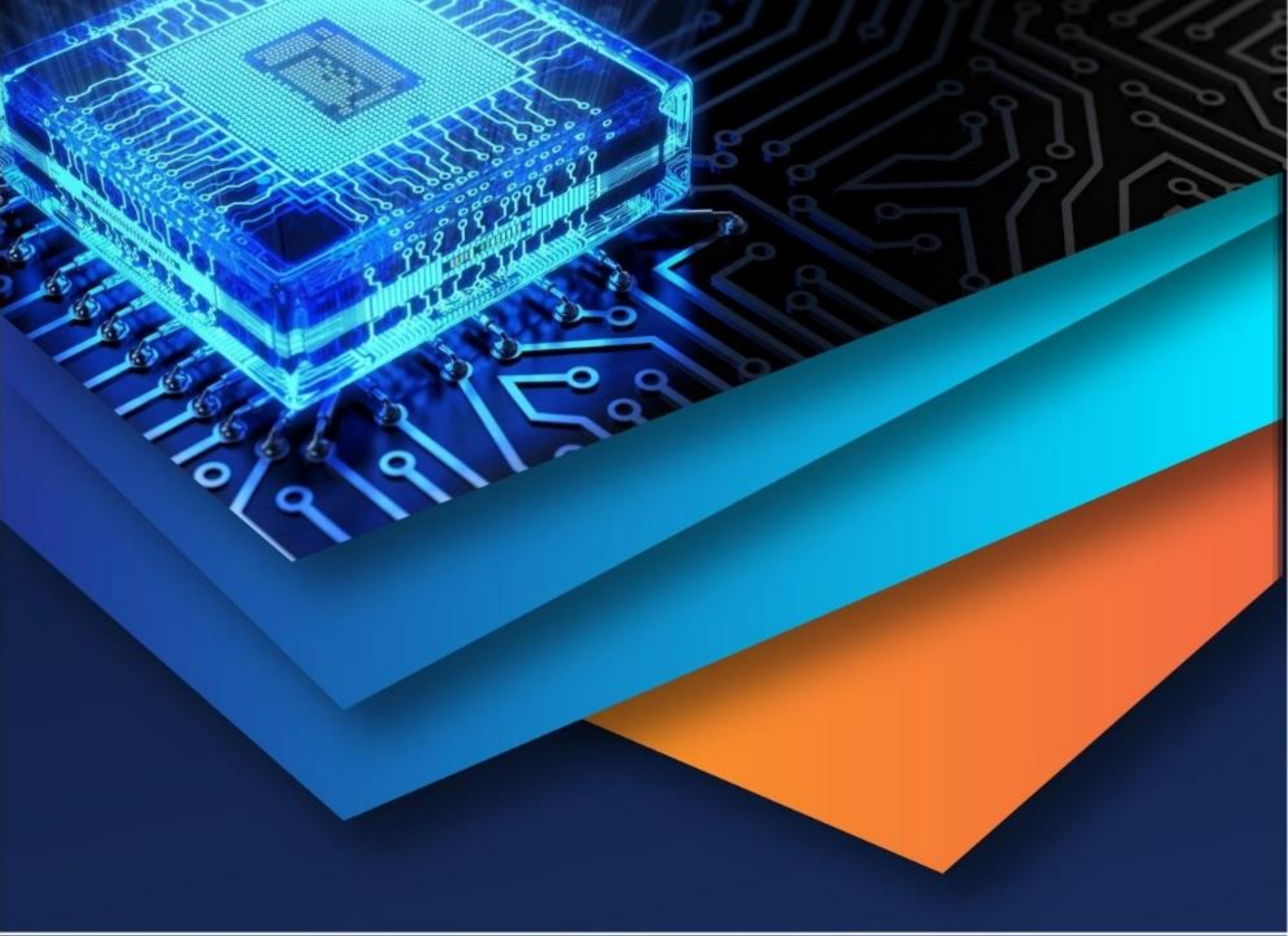

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