Towards Recipe-driven Automation Concepts for Large-scale Food Production

Moritz Dorfer and Michael Rathmair
JOANNEUM RESEARCH ROBOTICS
Lakeside B13b
9020 Klagenfurt, Österreich
moritz.dorfer@joanneum.at, michael.rathmair@joanneum.at

Abstract

The hospitality sector is facing a severe shortage of skilled personnel, which results in a significant need of automation and digitalization. In particular, automation of professional kitchen processes poses significant challenges due to the variability of commodities, the mixed presence of humans and machines, and harsh environmental conditions. The introduced concepts integrates a recipe-driven approach including warehouse intralogistics and automation for food processor tending. The ongoing work presented in this extended abstract reflects initial results of an in-depth conceptualization phase supported by simulation-based validation.

1 Introduction and Motivation

In the context of large-scale catering (e.g. for high volume tourism regions having a high density of hotels and restaurants), the primary objective is to produce high-quality meals while maintaining cost-effectiveness. However, the shortage of skilled personnel in the hospitality sector makes this increasingly difficult, forcing the industry to look toward automation as a necessary solution [1]. While automation provides a method of maintaining output, the kitchen environment presents a number of challenges that differ considerably from those experienced in industrial settings [2].

In contradistinction to the assembly of automobiles, food preparation entails the management of biological materials (commodities) that exhibit variability in terms of shape, size, and ripeness [2]. Furthermore, the stringent hygiene standards and arduous conditions including elevated temperatures and moisture engender a challenging environment for sensitive sensors and robotics [1]. Maintaining consistent quality under such economic and physical pressures necessitates an approach that can handle the inherent unpredictability of food products and associated processing [2; 3].

The focus of current research is to concentrate on individual robotic tasks, such as automated frying or flipping, which remain disconnected from broader kitchen workflows [2]. The present paper discusses an alternative approach by integrating recipe-driven warehouse logistics with automation approaches for kitchen processes.

2 Related Research

Automation in food production has gained increasing attention due to labor shortages and the need for efficiency and consistent quality. Within Industry 4.0, robotics, AI, and IoT enable improved traceability, flexibility, and waste reduction in food systems [4]. However, these approaches are largely derived from structured industrial environments and do not directly address the variability and dynamic conditions of professional kitchens.

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Robotic food handling remains challenging due to the deformability, variability, and fragility of food products. Surveys highlight difficulties in perception, grasping, and manipulation, particularly under hygiene and environmental constraints. Recent work on deformable object manipulation and robot learning further emphasizes the need for advanced perception and adaptive control strategies [2]. Existing solutions, however, remain largely task-specific and lack integration across workflows.

Computer vision and deep learning have significantly advanced food quality assessment and process monitoring. Vision-based systems enable real-time inspection of attributes such as color, texture, and freshness, supporting adaptive process control [5].

3 Approaches for recipe-driven Kitchen Automation

The main objective is to ensure that the correct food ingredients are introduced into the food processing machines in the appropriate sequence and with precise timing. Currently, this step represents a highly resource-intensive manual process that requires significant human intervention and coordination. The concepts proposed in this work aim to automate this task, thereby improving process efficiency, reducing manual workload, and enabling more consistent and reliable production operations.

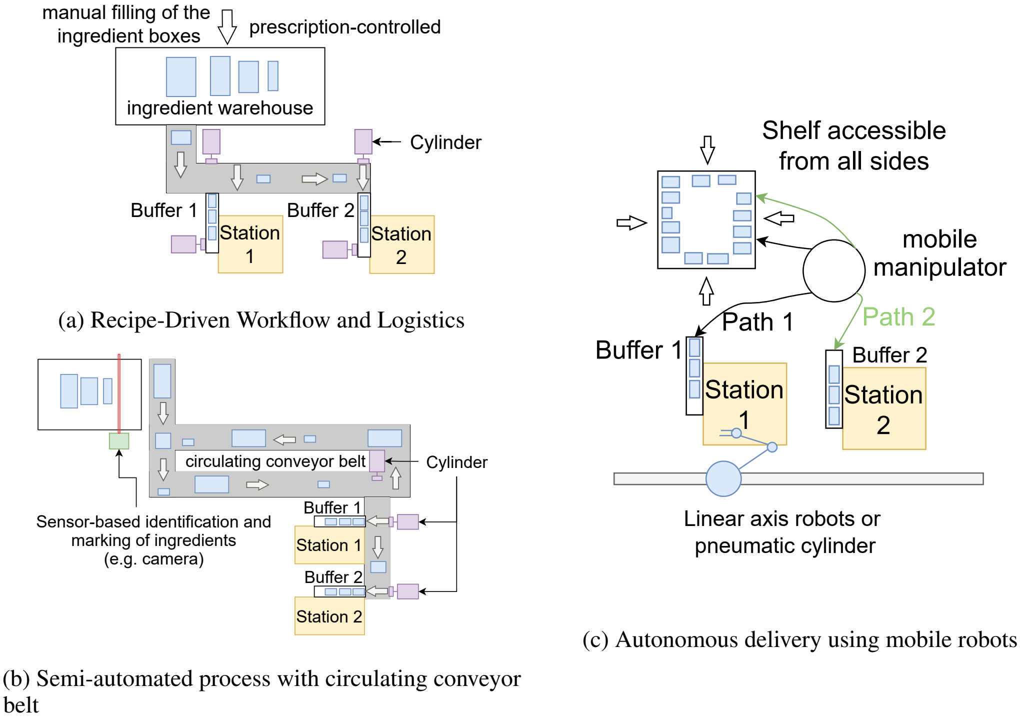
In order to address the complexities of commercial kitchens, the following technologies combine kitchen digitalization with flexible intralogistics and sensor feedback-based optimization. Technologies are focused on the establishment of a resilient production flow by means of the connection of automated storage, transport, and cooking stations (professional food processing machines) through a central digital recipe-based repository.

Workflow Automation and Intralogistics The approaches presented in this paper are based on the results of a design thinking workshop. The main goal of the workshop was to discuss and design concepts for ingredient transport from a central storage to various cooking stations. Main outcome of the workshop were the following three approaches:

1. **Recipe-Driven material supply:** The concept illustrated in Figure 1a is based on a manual compilation of food commodities at an in-house storage/warehouse. A production station (Station 1 or 2) may trigger this manual process and a worker arranges the single commodities on a conveyor belt. This is instructed by a monitor directly placed at the warehouse output. Sensors and pneumatic cylinders are used to sort the boxes into dedicated station buffers. Hence, ingredients for a dish arrive the cooking station at the recipe-correct buffered order. Cylinders at the station triggered by the recipe-based timing plan implement the correct submission of each ingredient into the food processing machine.
2. **Semi-automated process with circulating conveyor belt:** The concept illustrated in Figure 1c is similar to the approach presented above but boxes subsequently circulate along a primary conveyor loop that traverses all stations. When a cooking station signalizes a demand, the system identifies the matching box and a pneumatic diverter pushes it onto a local feed line. This results in a just-in-time commodities supply with predictable smaller buffer sizes at the cooking stations.
3. **Autonomous delivery using mobile robots:** The approach illustrated in Figure 1b integrates a potential fleet of mobile robots. These mobile robots implement a high flexibility commodities supply between the storage and the cooking stations. In this approach tending the food processing machines is implemented using a serial robot arm that is mounted on a linear axes. This fully robot-based approach provides maximum flexibility under high-mix low volume production conditions where potential process adaptions and reprogramming of automation equipment is required.

All three concepts realize a recipe-driven request logic implementing the overall goal of supporting the food processing machines with the correct ingredients sequence and timing. Coordination between storage, transport system, and cooking units is significantly important to enable the system's scalability while maintaining effectiveness and quality.

Vision-Based Sensor Data Feedback to Enhance Process Quality:
The use of biological ingredients poses challenges to automation, primarily due to the lack of consistency, quality and uniformity of commodities [6]. To maintain solid standards, the concepts presented above may integrate a camera-based vision system directly into the workflow.



(a) Recipe-Driven Workflow and Logistics

(b) Semi-automated process with circulating conveyor belt

(c) Autonomous delivery using mobile robots

Figure 1: Concepts for the automation of large-scale kitchen environments with the goal of supporting cooking stations with ingredients at the recipe -defined correct sequence and timing.

These cameras and associated classification trough deep learning approaches, may assess the quality of raw material, verify pre-processing steps, and track the movement of batches. Reliable image processing in a kitchen requires beside of significant computing power to process, reliable hardware and optics protected from heat, moisture and potential deposits. Furthermore, high-quality cameras may enable analyzing color patterns and surface textures which can be used as a quantitative freshens indicator [7]. To close this sensor feedback loop quality data and in particular variations from reference ingredients are transmitted to the cooking station, which automatically adjusts thermal processing parameters for compensation. Beyond inspection of quality and freshness, a camera may monitor the completeness of pre-processing tasks like peeling, cutting or slicing. If an ingredient fails to meet geometric specifications, the system may identify this inadequacy before it reaches the cooking station.

4 Discussion and Next Steps

The state of the ongoing work presented in this extended abstract is in a focused concept-phase supported with prototypes and kitchen automation concepts operated in a digital twin simulation environment.

The transition from manual kitchen operations to an integrated, recipe-driven automated system poses several multi-dimensional challenges. While the technical capabilities of the presented approaches are strong in theory and simulation, their practical implementation has to consider specific operational limitations and further requirements, such as:

- **Recipe database and management:** The presented approaches form a heterogeneous systems, requiring seamless communication between a central digital recipe database, physical transport units, and control of cooking stations. The full process shall be connected to a demand driven ERP system handling customer orders and triggering customer orders.

- **Process resilience:** Sensors and robotic components have to function reliably in environments with high humidity, fluctuating temperatures, and the presence of fats or oils. Process stability has an equal importance as in classical production environments since insufficient delivery of meals to hotels, restaurant, etc. can affect the reliability and reputation of a production kitchen. However, seamless integration has the goal to react highly flexible to demand variations without getting troubles by missing workforce or resource bottlenecks.
- **Hygiene and regulatory requirements:** Hygiene is a core requirement rather than a secondary consideration in food industry. The main goal is to prevent the accumulation of organic material on surfaces and in crevices in order to prevent bacterial growth and meet according standards and regulations. There is a significant difference between components that come into direct contact with the product and those that do not. Within the presented concepts it is planned that direct food contact is avoided as much as possible. Hence, ingredients are transported in food-industry qualified boxes that can be cleaned independently and separately from automation equipment after usage.
- **Economic aspects:** Economic viability of the system depends on its scalability and according ROI estimations. The modular nature of the recipe-driven approach facilitates this but requires a basic digital infrastructure in terms of a central recipe-database, communication and computation infrastructure, etc. Beyond labor savings, the system aims to reduce food waste by better planning capabilities and demand driven production features enhanced by flexible automation concepts. This may directly contribute to cost-effectiveness and a simultaneously improvement in sustainability.

Future work will focus on enhanced simulation to facilitate pre-evaluation and step-by-step experimental prototyping and testing of automation modules in lab environment (goal TRL of 4). These tests are significant to refine system concepts, enhance reliability and prove compliance with strict hygiene standards in the domain of professional food processing. The future goal within upcoming research projects is to design a functional demonstrator for the purpose of conducting real-world trials and present efficiency and impact of modern large-scale kitchen automation to potential stakeholders and customers.

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