**Innovative food manufacturing by robotic technology**

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The aim of this PhD thesis research project is to extend the application of the Industry 4.0 in the food sector through the application of robotic technology. The activities will firstly focus on one of the main unit operations, kneading/mixing, to explore possible benefits of robotics in this context. In addition, the research activities will be dedicated to the integration of robotics into the 3D printing technology, attempting to maximize the benefits offered by these industrial innovations impacting on the process efficiency and efficacy and on the quality of the end-products.

**Processi alimentari innovativi attraverso la tecnologia robotica**

Questo progetto di tesi di dottorato è dedicato allo studio ed estensione delle applicazioni dell’Industria 4.0 nel settore alimentare attraverso l’impiego della robotica in alcune fasi dei processi di produzione degli alimenti. Le attività si focalizzeranno su una delle principali operazioni unitarie, la miscelazione/impastamento, per esplorare i potenziali miglioramenti qualitativi conferiti dalla robotica in questa fase di processo. Inoltre, le attività di ricerca studieranno la possibilità di integrare la robotica con la tecnologia di stampa 3D per impiegare i maggiori gradi di libertà garantiti dalla robotica per la creazione di prodotti alimentari innovativi per forma, dimensione, proprietà interne e funzionalità chimico-fisiche.

# **1. State-of-the-Art**

During the last years, several events such as the pandemic, the climate change and the recent Russia-Ukrainian war have caused economic, societal and environmental changes. Due to these events, we are witnessing an exceptional evolution of all those sectors that fall within the global economic sector. An extraordinary innovative approach that is fuelling the interest of academia and industries is the application of precision manufacturing. Such approach can be defined as the creation of a single objects by tailoring the process to the specific properties of both the raw materials and desired functionalities. These objects are produced with a precision impracticable by the traditional manufacturing processes. The robotic technology is one of the most important candidates to make reliable the ambitions of the precision manufacturing in the food sector because it is very flexible and with an extreme adaptability to the high variance of food properties. Many benefits could be reached by robots since they ensure more efficient processes, improved health, safety, security, reduced waste and environmental effects as well as mitigating labour-intensive tasks, as reported in Table 1 (EU, 2021). Despite these opportunities, while in different sector (i.e., the automotive and electronic sector) robots are already integrated in the production system, it is not realized and implemented with only few applications such as considering food handling, food packaging or the phase of cutting/peeling of food (Wang et al., 2021; Kanegae et al., 2020; Mu et al., 2019). However, there are still many other challenges to be faced for the practical and wide implementation of the robotic in foods industry such as the needs of detailed information regarding the main physical, mechanical and morphological features of food to be submitted to robotic food processing. Also, a large number of unit operations requiring for high level of standardization and precision as well as high level of hygiene have not been investigated in detail.

For instance, during the mixing/kneading operation of liquid-to-liquid, liquid-to-solid compounds and dry ingredients, different issues are faced due to the large variety of chemical and physical properties of materials. Many food applications require high spatial homogeneity of ingredients and additives, and a precise temperature control during heating and cooling processes to avoid segregated portion of the mixture. These questions combined with the high energy consumption make the mixing industry one of the less efficient (Ye & Chau, 2007). The use of robotic unconstrained movements during mixing could enhance the efficacy and efficiency of this operation.

Another potential interesting application of robots is in the field of Additive Manufacturing of food which is subjected to the growing interest of academia and food industries due to its ambitions of personalized manufacturing, on-demand production, high flexibility, etc. The introduction of robotics in 3D food printing would allow to obtain unparallel improvements due to the hundreds of degrees of freedom at disposal for unconstrained movements and precision dosing of food materials (Prashar et al., 2022). In fact, robotic movements open to the possibility to precisely control food composition and nutritional content creating customized foods based on individual dietary needs.

***Table 1*** - Potential benefits and capabilities of robotic technology in food manufacturing (from EU, 2021)

|  |  |  |
| --- | --- | --- |
| **Industrial robot capabilities** | | **Benefits** |
| **DECREASE** | PRODUCTION COST | Reduced costs associated to manual labour and utility expenses; |
|  | MATERIAL WASTE | Increased efficiency for reduction of material waste and less scrap from rejects; |
|  | FLOOR SPACE | Compact systems with mounting versatility; |
|  | PRODUCTION TIME | Higher speed and efficiency, fast re-configurability; |
| **IMPROVE** | PRODUCT QUALITY | More efficient process control, high repeatability, and accurate task execution; |
|  | PRODUCT UNIFORMITY | Errors caused by human error and fatigue eliminated; |
|  | WORKING ENVIRONMENT | Existing labour upgraded, removes human from unfavourable conditions and tedious tasks; |
| **INCREASE** | PRODUCTION RATES | Ability to produce 24/7 without disruptions; |
|  | FLEXIBILITY | Reconfigurable and easy to apply to a variety of tasks; |
|  | SAFETY COMPLIANCE | Works in hazardous environments, made of hygienic materials; |
|  | COMPETITIVE ADVANTAGE | Faster response to market demands, allows for product customization and personalization; |
|  | EFFICIENCY | Optimized processes, increased yield (reduces production material waste, scrap from rejects). |

# **2. PhD Thesis Objectives and Milestones**

This PhD project aims to explore the integration of robotics into the food system improving the efficacy and efficiency of the food manufacturing sector. Specifically, the research activities will focus on two possible applications, mixing/kneading and additive manufacturing technology, according to the Specific Objectives (SO) listed in the Gantt diagram given in Table 2:

**SO1. Develop, test and validate of a robotic kneading system with spatula or kneading hooks as end-effector**: T1.1. will be focused on mixing test with model system and T1.2 with complex food formulation by modulating the main robotic variables (velocity, acceleration, temperature, time, mixing paths in the 3D space) and studying the effect of the main techno-functional properties of the samples.

**SO2. Robotic 3D printing**: during T2.1 some common and new variables of the 3D robotic arms will be modulated and their effect on several attributes (rheological, nutritional, physical, etc.) of the end-products will be analyzed. Research activity T2.2 will be dedicated to the development of uncommon geometries with more complex food formula.

**SO3. Writing and Editing** of the PhD thesis, scientific papers and oral and/or poster communications.

***Table 2*** *–* Gantt diagram

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Activity Months | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** | **21** | **22** | **23** | **24** |
| SO1) | ***Robotic Mixing/Kneading*** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | ***T1.1 Kneading: model systems*** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | ***T1.2 Kneading: complex formulation*** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| SO2) | ***Robotic 3D Printi ng*** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | ***T2.1 Process study and optimization*** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | ***T2.2 Product development*** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| SO3) | ***Thesis and Paper Preparation*** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |

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