Therblig to Robot

Action Packages, Robot Motion and Human-Robot Collaboration in Domestic Environments

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Abstract

Industrial robotic arms commonly require specialist knowledge for machine functions. Specifically, training cobots for work sequences is time consuming and complex when task complexity increases, such as through differentiation in tool adaptations or work processes. This research explores robot versatility for a context of domestic environments (such as a kitchen/workshop), where work processes are approached as a hybrid scenario, with setup for integration of a tool variety whereby human-robot teams collaborate. The paper discusses a) novel workflows based on a palette of work tools adopted for robot tooling to translate manual human tasks to human-robot tasks; b) an initial script series for work processes that represents modelling, planning, simulation, and implementation; c) a framework for task division through action sets based on Therbligs that supports users; and d) an empirical evaluation of the approach through a series of user studies. In a post-carbon context, previously autonomous robots are required to become more versatile in terms of productivity, scalability, safety and skill criteria and environmental impact. This research extends beyond traditional kitchens to include workshop and fabrication scenarios characterised by the complexity and variability of task applications, guided by detailed action packages that explore robotic work for modular components or fluid and liquid materials; heat and assembly-based processing; and bridges from food preparation to fabrication and manufacturing tasks.

Keywords

Human-robot teaming, human-robot collaboration, robot programming, task allocation, Therbligs, kitchen, workshop

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1 Introduction

At present, industrial robotic arms in construction and manufacturing settings are commonly programmed to function autonomously, exhibiting precision, speed and accuracy (Javaid et al., 2021). To overcome work restrictions that arise by placing robots in secure settings, a shift to more customizable products, use of wider tool range or more intuitive work processes with robots and collaborative robots is desirable but challenging. The forthcoming advancement in both personal and industrial robotics involves transitioning robots from seclusion to cooperative engagements, where they can work alongside co-workers or users (Hjorth & Chrysostomou, 2022). Integrating robots into real-time scenarios and the unregulated and multi-criteria context of construction sites demands significant engineering to ensure that human operators can proficiently leverage the capabilities of robotic resources (Melenbrink et al., 2020).

Collaborative robots in contrast offer alternatives and novel pathways for work, collaborative work, manufacturing and interaction between man and machine beyond restricted environments (Michaelis et al., 2020). Yet despite advancements in skill acquisition and execution, robots applications are challenged in reaching their maximum potential when taken out of the usually well-regulated laboratory environment. Reprogramming industrial robotic arms is expensive as this requires specialist knowledge. Training cobots for work sequences is time consuming and complex when task complexity increases. However, improvements can be made by enabling untrained workers to operate within a framework of work sequences and robot action packages, such as by providing a basic set of work sequences and task sets that can be adopted.

This research explores a six-axis industrial robotic arm for collaborative task division and framework with personalised space of multiple users where sequences of preparation of food are considered, ingredients and menu set into shared workspace and processes. It focuses on interaction between human and industrial robotic arm and action packages for robotic work processes in a kitchen/workshop. A user study is performed to explore the adaptation for tools, robot programming and framework for differentiated tasks and a changing knowledge base. The domestic environment serves as a context for investigation into work processes, varied materials, tool applications, action sets and tasks, and movement sequences for production whereby standard domestic utensils are adopted from kitchen and workshop to test viability for subtractive, additive, forming and assembly methods. In workshop scenarios or construction sites, specialist knowledge must be translated to robotic processes; and actions defined for human or robot, or interaction between both. A series of production case studies (Figure 1) is presented that analyses manual cooking processes, establishes robotic programming and human-robot joint action planning, and uses Therbligs to refine subtasks for division of work between human and robot. The aim is here to go beyond robotic automation and instead better understand the potential of human-robot interaction; application of skills and best practice for man and machine; and providing a platform for innovation with tools and methods (work sequences and motions).

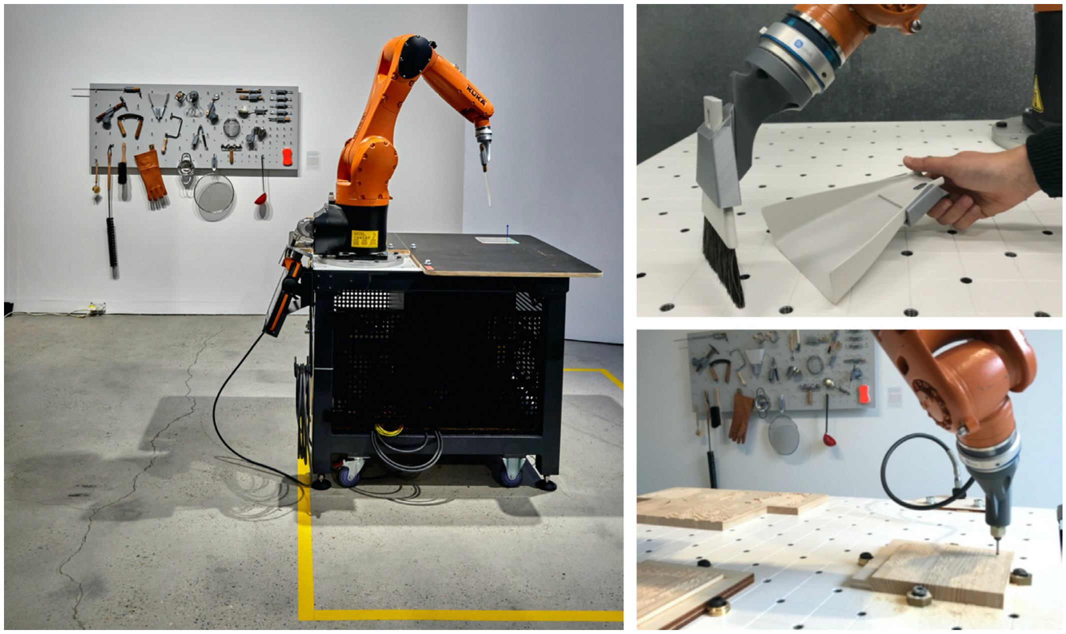


FIGURE 1 Collaborative robot programming with KUKA KR6 robot (left); Action sets in kitchen and workshop - swiping with a broom (left) and subtractive cutting/drilling with a Dremel (right top and bottom) at @SHErobots exhibition, Tin Sheds Gallery, Sydney 2022.

The research addresses a multifaceted set of questions aimed at advancing the field of robotic programming and human-robot collaboration. First and foremost, the study seeks to unravel the intricacies of process segmentation and work tasks, with a focus on delineating clear boundaries that enable efficient robotic programming. Investigating the domain of task division between human and robot, the research aims to establish a harmonious collaboration that optimizes the strengths of both entities. Furthermore, it aims to establish seamless linkages between motion and work movements across diverse task sets, emphasizing a holistic perspective in programming. Shifting from a product-oriented to a tool and motion library approach is a central query, intending to streamline the programming process and foster versatility. Creativity and serendipity, often overlooked in rigid programming structures, emerge as vital elements to be explored and incorporated. Additionally, the research seeks to enhance robot adaptability for non-skilled users, promoting accessibility and usability. Overcoming acceptance barriers constitutes a crucial aspect, acknowledging the need for societal integration of advanced robotic systems. In addressing these questions, the study aspires to contribute to the evolution of robotics, paving the way for more intuitive, adaptable, and widely accepted robotic technologies.

In the following, section 2 provides a summary of related work and gives a short introduction for principles, setup and framework. Section 3 introduces a case study for interaction and learning works and describes experiments, where the novel method of this work is tested in a user study. Section 4 discusses results and limitations. Section 5 offers a conclusion and outline of future work.

2 Background and Related Works

This section provides an overview of systems of cobots (2.1); current applications of kitchen robots (2.2); robot motion interfaces (2.3); and task allocation in Human-Robot teams: by using Therbligs to identify action sets and task division (2.4).

2.1 Collaborative Robots

Cobots are designed to allow humans and robots working together side-by-side, in direct physical interaction with a human user and within a shared workspace (Colgate et al., 1996). Cobots are often employed with the objective to increase workplace flexibility and productivity. A move from a manual to a flexible, robotic, human-involving workplace requires understanding and informed decision making on the side of the worker about what manual work can be handed over to a collaborative robot. In this context, the evolving role of robots as co-workers and collaborators, particularly with the introduction of collaborative robots, or cobots, is important. This introduction of robots in relationship to a human co-worker challenges established social, ethical, and cultural norms that either facilitate or impede their integration. Hence, this research seeks to explore methods of introducing cobots while respecting the significance of human presence in various contexts. For example, there exists a potential for cobots to mitigate musculoskeletal disorders (MSD) by assuming human movements such as lifting, pushing, pulling, and tugging, aiming to prevent MSD and reduce health-related compensation claims in fields like construction and fabrication. The research also delves into the development of training and engagement protocols for human-robot interaction (HRI), addressing the challenge of training robots for multiple movements in diverse settings, including construction. Additionally, the study explores the feasibility of cobots as collaborators in various contexts, ranging from construction sites to public or domestic applications, and evaluates the adaptation of hardware, particularly end effectors, to accommodate the diverse tool requirements of different work scenarios. Better insights are required into the effective integration of cobots, considering both the physical aspects of human-robot collaboration and the broader socio-cultural implications.

The collaborative nature, the ability to learn, and the guarantee of a safe co-existence of collaborative robots and humans in the shared workspace represent an essential change in the use of robots. The flexibility of decision-making between manual and robotic processing enables the technological upgrade of a manually managed workplace (Gajšek et al., 2020). Human-robot teaming, where humans and robots collaboratively perform parts of the task that they are best suited to perform, holds considerable promise for improving industrial work, but significant hurdles still remain in capitalizing on that promise (El Zaatari et al., 2019). While recent studies explore Semantic Recognition of Human Gestures for human-robot interaction (Lin et al., 2013), there remains a discrepancy between the traditional robot programming approaches used by developers and engineers who integrate robots into industrial environments and the needs of collaborative interaction design, the task of specifying collaborative tasks requires a different approach than what is afforded by standard non-interactive robot programming approaches. Schoen et al outlined four key technical challenges involved in human-robot teaming: (1) representation: representing work for both human interpretation and robot execution; (2) task-skill matching: creating human-robot plans that match task elements with worker skills while achieving task goals; (3) robot programming: implementing task elements for collaborative robots in a way that supports exploration of task plans across robot platforms; and (4) authoring pipeline: facilitating intuitive and effective translation of manual work into human-robot plans (Schoen et al., 2020).

Actions required for work processes can be ordered in a Hierarchical Task Analysis (HTA), including a) top-level actions which refer to object handling or the order in which objects are to be manipulated, and b) bottom-level actions that focus on which actions are required (Winter). Identifying hierarchical structures of work processes including tool requirements, material affordances, and motions by both human and robot agents can be exploited to reduce the total solution space. Consequently, a better understanding of robot actions, task sets and sub-tasks for actions is required for collaborating with a cobot or industrial robotic arm, whereby the potential function is defined over all composite tasks across top-level and bottom level work. It is essential to recognize that a robot's genuine value within household settings extends beyond mere companionship to encompass aspects of "workmanship," as underscored in a survey on the general acceptance of robots (Arras & Cerqui, 2005). Additionally, robots are then also contextualised in atypical environments and tasks (Ito & Nakamura, 2022). This implies that in the context of human-robot collaborations, factors such as interaction, communication, and reciprocal exchange need to be given additional consideration. Is a robot merely an object or perhaps a tool? A tool that itself wields another tool? A mechanical device? Or can it be regarded as a genuine companion? Identifying the distinguishing features that transform a robot into a companion rather than a mere tool poses a pertinent question in this exploration.

2.2 Applications of kitchen robots

While a fully automated yet not fully comprehensive kitchen in the film 'Mon Oncle' (Tati, 1958) delivered surprising effects, recent studies into introducing robots in a domestic or industrial kitchen environment have been developed, with the focus on retrieval of recipes and task automation, often with the limitations of programming robots for specific recipes and high affordances in time and expertise. While early studies consider assistive technologies (Boyer, 2004), industrial domestic robots are often programmed for automation (Junge et al., 2020); provide a consumer robotic kitchen with dual arm system by Moley (Hansman, 2015) or ; or the Samsung robot arm duo 'Botchef' (Techable, 2019), based on chef's methods and techniques captured through a 3D motion tracking system and translated into movement using bespoke algorithms. Both approaches assume automation of processes rather than human-robot interaction or collaboration. Further studies expand these limitations to enable a larger range of production, with a focus on natural or textural language for robot programming and motion planning. 'BakeBot' demonstrates application of textual recipes in a kitchen environment that were prepared by a robotic chef, whereby a dual-arm robot collects recipes online, parses them into a sequence of low-level actions and executes different recipes, within a set scenario with workstation and ingredients laid out, and a repertoire of primitive actions, such as pouring ingredients into a bowl and mixing them (Bollini et al., 2013). Integrating the robot into domestic environments includes research into robotic kitchen counters can be equipped with sensors and actuator for action-adapted assistance (Morishita et al., 2003; Yamazaki et al., 2010), ubiquitous sensing and actuation for Robotics and Autonomous Systems (Rusu et al., 2008), or evaluating the usability and users' acceptance of a kitchen assistant robot in household environments (Pham et al., 2017).

While a sequence of tasks was successfully carried out in real space, and the system's performance was simulated to adhere to a broader array of recipes, 'Bakebot' predominantly operates with the primary aim of aiding a human partner who intervenes when faced with unsupported task primitives. These are instances where the robot system requires assistance in executing instructions. Similarly, an exploration of robot motion planning, based on the analysis of online recipes, demonstrated the feasibility of 25 out of 50 recipes by scrutinizing and scripting cooking procedures and cross-referencing them with a motion code database (Inagawa et al., 2021). However, the generation of robot motion through offline teaching using a cooking robot simulator, while successful in reproducing defined motions, relied on fixed action protocols and stationary positions of cookware and ingredients. This approach neglected human interaction, thereby limiting the solution space and hindering the advancement of work process applications or adaptations to material changes. In contrast, the present research delves into the collaborative performance of work processes by human-robot teams, emphasizing the development of a tool archive, action sequences, and task sets to facilitate open-ended applications in the realm of cooking (see Figure 2).

Humans naturally categorize items for storage and handling, and the use of classification techniques employing object features can replicate this organizational process. In the context of human-robot interaction, kitchen objects serve as classification system and a database for investigating danger perception (Leusmann et al., 2023). An additional dimension refers to non-finite materials, such as liquids (Elbrechter et al., 2015). At the core remain user and skill adaptability (Wang et al., 2021), which may include human advice to robots (De Winter et al., 2019). An organizational study on robots' adaptation to domestic environments (Cha et al., 2015) outlines key challenges. Firstly, regarding object-related features, robots need to return items to specific locations without constant detailed instructions from users. Secondly, for effective user adaptation, robots must learn user-related features, including instructions about object locations, spatial arrangements, and user habits. This adaptability is crucial for seamless household operation and assimilating new information. Lastly, in dynamic environments like kitchens, robots must register and implement new data about the surroundings, agents, and objects to adapt their behaviour, necessitating both sensing capacity and machine learning capabilities.

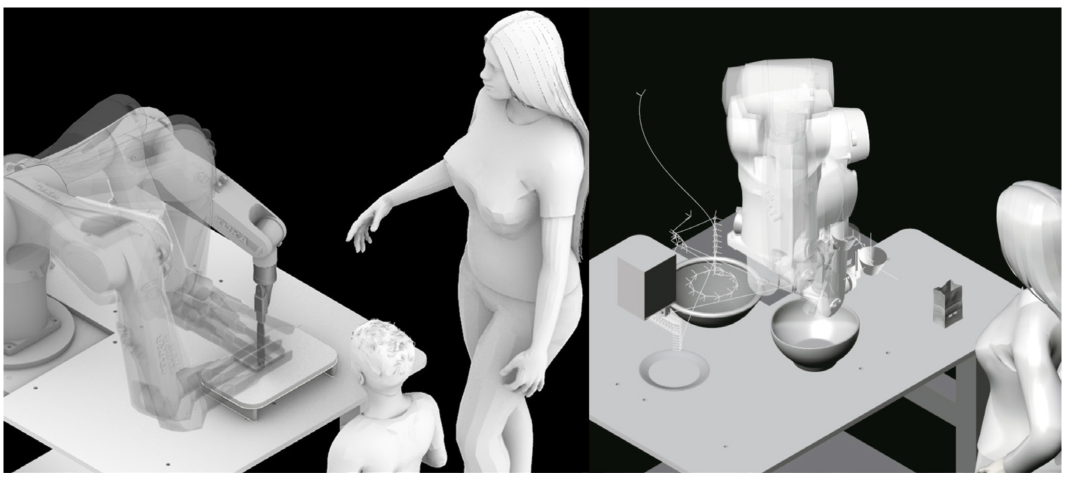


FIGURE 2 Detail of RobotKitchen environment with adapted tools for intuitive human-robot interaction, including cutting (left) and mixing(right), with multiple interactants – collaborative robot arm, two humans – within one workzone.

2.3 Access Points: Robot Motion and Interface(s)

Robot motion programming often demands significant expertise in robotics or coding, presenting a challenge for users and creating barriers to spontaneous or intuitive human-robot collaboration. Effective work processes rely on the ability to plan and visualize robot motion, emphasizing the importance of simple and accessible user interfaces. Common methods include robot motion programming through tools like KUKA prc and ROS, while alternatives involve using a teaching pendant to establish a sequence of points and corresponding angles for the robot arm or employing motion capture systems for hands and arm motions. This research specifically examines robot motion planning within the context of recipe procedures, encompassing operations related to ingredients, movements, tools, and utensils. Human-robot interaction intricately involves explicit information on tool use, toolpath angles, robot trajectory, destination points for material deposition, work plane, and workspace. This complex setup is interconnected through tasks and action sets, requiring differentiation into subsets. To enhance capacities for both the robot and the human, each actant is considered for best practices, with the robot emphasizing precision, consistent quality, repeatability, and handling potentially hazardous tasks, while the human brings advantages such as an unlimited movement range, sensing and locating ability, tolerance compensation, flexible availability, handling complexity, and innovative capacity.

The nature of the tool is questioned—is it an object with associations, or is it an integral part of the robot? Recent research on human-robot collaboration advances the understanding of measures like trust, safety, and effectiveness, predominantly focusing on optimization. However, Leusmann et al. (2023) observe that objects shared in a work process influence these measures and impact human perceptions of danger and safety levels during handling. Their online survey of 153 kitchen objects reveals significant variations in how humans perceive kitchen objects. The object-holder plays a role in danger perception, and prior user knowledge increases the perceived danger when robots handle those objects.

2.4 Task Allocation in Human-Robot Teams

To understand the actions and tasks shared between humans and robots, the study utilizes Therbligs to identify action sets and task allocation, employing Hierarchical Task Analysis (HTA) to model human-robot tasks and pinpoint action sets and sub-tasks distributed between the two entities.

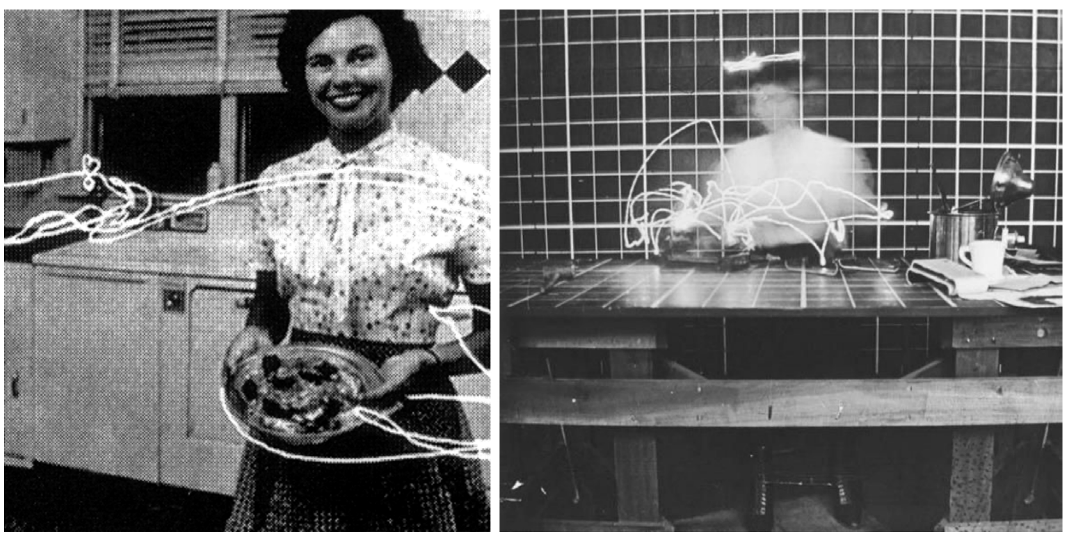


FIGURE 3 Optimisation for kitchen processes around 1960/70 (left), Motion efficiency study by Frank Gilbreth, c. 1914. Collection: National Museum of American History.

The Therbligs, originally developed by industrial analysts Frank and Lillian Gilbreth in 1911, constitute a task assessment system designed for industrial work. This classification system, named after the Gilbreths (spelled backward as "Therbligs"), was created to capture, analyze, and categorize motions that capture human activities during a work task (Gilbreth, 1930). Such motion studies situated in factory environments were later also adopted for optmising space efficiency for kitchen work (Figure 3). Gilbreths' Therbligs can be used to describe any task (Ferguson, 2000), including elemental motions of human-related physical actions, cognitive processes, and behaviours. In turn, these further reverse-engineered to categorize actions and subdivide tasks to achieve results in a work process (Yen, 2011, S. 20). Therbligs contain both data on action and information (Oyekan et al., 2020), as a work agent observes the environment, obtains information, evaluates against an action, and then continues to implement that action as next step. Importantly, the agent in this context can be human or robot, depending on task allocation -and so, full work processes can be segmented in work tasks that are collaboratively shared between human and robot. Recent research (Chen et al., 2021) used Therbligs to analyse user behavior in a kitchen context with observation of actions by the elderly via video documentation, with the aim to optimise kitchen layouts. Their decomposition of continuous actions focuses primarily on spatial setups and movement across U or L shaped kitchen layouts. In addition, an excerpt of seven Therbligs has been adopted as rule-based, compositional, and hierarchical modelling of action used by Dessalen et al. (2023) in a kitchen context.

	Therblig	Description	Agent*
1	Search:	Begins when the eyes and/or the hand start to seek the part and ends when the part is located.	H, C
2	Find:	Momentary mental reaction at end of the search cycle.	H, C
3	Select:	Choosing a particular object among a group of similar objects.	H, C
4	Grasp:	Starts when the active hand grabs the object and ends when the next opera-tion (use or transport loaded) starts.	H, R, C
5	Hold:	Retention of a part after it has been grasped, with no other movement or manipulation of this part taking place.	H, R, C
6	Transport loaded:	Moving a part using a hand motion.	H, R, C
7	Transport Empty:	Moving the unloaded hand.	H, R, C
8	Position:	Placing the part in the proper orienta-tion for performing the motion “use”.	H, R, C
9	Assemble:	Joining two parts together.	H, R, C
10	Use:	Manipulating an object in a way it is intended to be manipulated.	H, R, C
11	Disassemble:	Separating parts that where joined.	H, R, C
12	Inspect:	Comparing the object with a predetermined standard.	H, C
13	Preposition:	Replacing an object in the proper orientation for its next “use” (position is performed after).	H, C
14	Release Load:	Releasing the object when it has reached its destination.	H, R, C
15	Unavoidable delay:	Period from the point when a hand is inactive to the point when it becomes active again.	H, R, C
16	Avoidable delay:	Waiting within the agent’s control which causes idleness that is not included in the regular work cycle.	H
17	Plan:	Mental function which may occur before one action (deciding which part is going next) or prior to “inspect”.	H
18	Rest:	A lack of motion which is only found when the rest is prescribed by the job or taken by the worker.	H

TABLE 1 An overview of the Therbligs and descriptions, and further offers a categorisation for potential human/robot action. Significantly, some Therbligs refer to physical actions are available to both human or robot (as an industrial robotic arms devoid sensors), such as Grasp (4), Transport Loaded (6) or empty (7), Release (14), or Position (8). Others describe cognitive processes that require sensors, such as Search (1), Find (2) or Select (3), or human-focused actions such as Un/Avoidable Delay (15, 16), Plan (17) or Rest (18).

*H (human), R (industrial robotic arm), C (collaborative robot)

3 Case Study: A Robot Kitchen for Reverse Engineering Recipes

The following sections presents integral components of the robotic system, specifically focusing on the Robot Toolbox, Robot Toolpath Library, and Human-Robot Action Sets. The Robot Toolbox serves as a critical aspect, providing endeffector access to industrial robotic arms by employing custom-designed toolholders (Figure 4). These toolholders facilitate the mounting of various work tools, ranging from typical kitchen utensils to workshop tools, offering a versatile foundation for scripting, tooling, and calibrating robot motion sequences. The design includes adaptable features, accommodating a wide array of tools and end effectors, fostering a customizable base that can readily evolve with further additions.

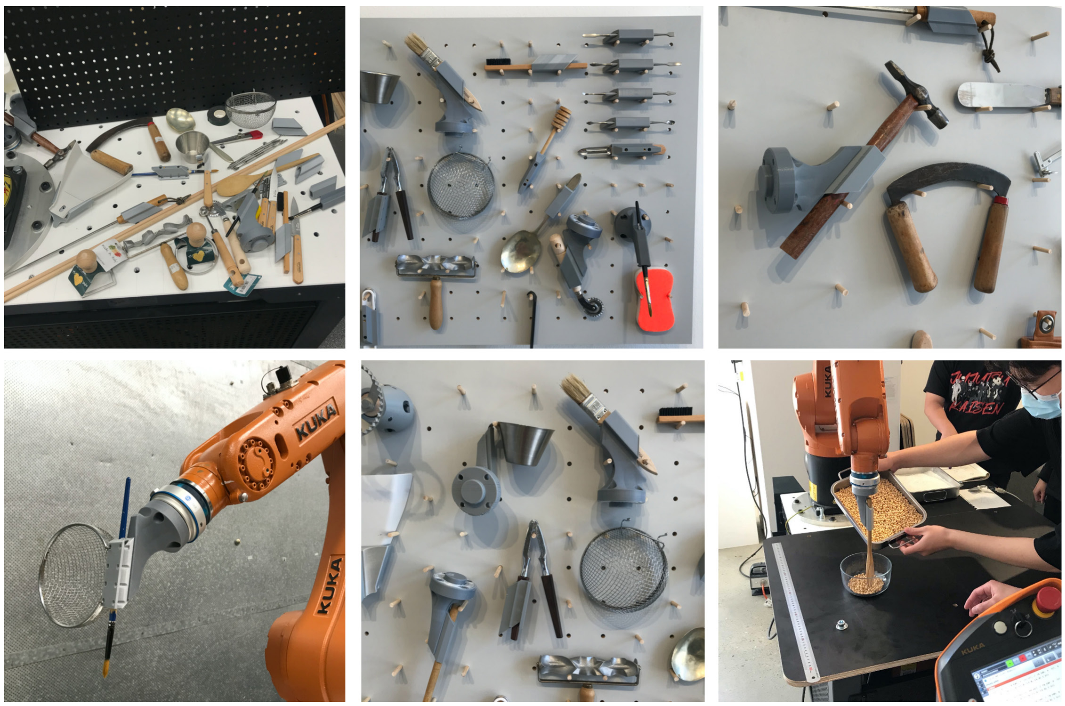


FIGURE 4 Tools adapted as robotic end-effectors across kitchen and workshop, including hammer, stamps, carving knifes, heat resistant glove, measuring cups, or brush, etc. While commonly used in only one context, tools share attributes and can be adopted across applications.

The Robot Toolpath Library is introduced as a pivotal element, enabling users with varying computational design knowledge to program and simulate original motion sequences with chosen tools from the Robot Toolbox. Script Bites, designed for users with a range of expertise from 3D modeling to introductory-level robot programming, offer a user-friendly interface to create and simulate motion sequences for diverse applications. This library encompasses various motions, tools, and robot types, facilitating accessible robot programming without specialized knowledge.

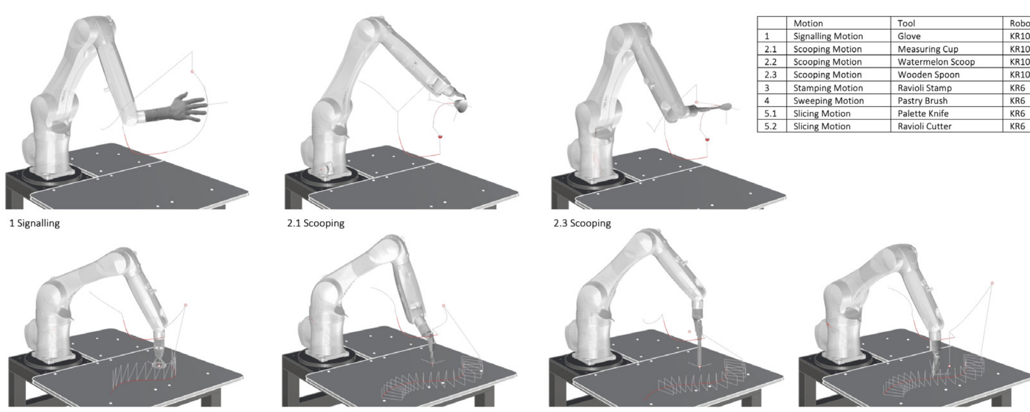
Transitioning to Human-Robot Action Sets, participants are guided to adopt the Therblig framework for food production tasks. The focus is on defining actionable tasks for both the robot (considering factors like toolsets, workplace definition, and reach) and the human (factoring in age, dexterity, and skillsets), along with detailed descriptions of crossovers between both agents. The Therbligs serve as anchor points, facilitating the identification of task divisions, shared tasks, and considerations for interaction and handovers. This framework allows for effective planning of tasks, sequences, and interactions that align with the capacities and restrictions of each agent. The subsequent sections explore these elements in further detail, providing insights into the development and implementation of our integrated human-robot system.

3.1 Robot Toolbox: Providing Endeffector Access

Physical tools were matched with custom designed toolholders as a series of work tools that can be mounted on two industrial six axis robotic arms used for the test series. Figure 4 illustrates an overview of the toolbox that includes typical kitchen utensils and workshop tools, with the aim to provide a departure point for initial scripting and tooling, including robot motion sequences and calibration. The toolholder is adapted for the robotic toolplate and secured with 4 screws, with a 3D printed base geometry, and a) variable additions that lock-in as quick adaptation with shared profile or diameters (spoon, ladle, knife, paintbrush, honey ladle); or b) larger dimension tools or bespoke profiles (stamping tool, measuring cup, sieve, skewer, glove); and c) end effectors that adapt typical workshop tools (saw, hammer, broom, palette knife, or carving tools). This toolholder design provides a customisable base that can be readily modified to hold further additions to the toolbox.

3.2 Robot Toolpath Library: Enabling Robot MOTIONS

Users with varying knowledge in computational design, scripting and robot programming (min 3D modelling -max introductory level robot programming) used Script Bites, with the objective to program and simulate an original motion sequence with a chosen tool of the robot toolbox, with a motion relative to their chosen dish. Scripts were simulated and then physically tested on a KUKA KR 10 or KR 6, relative to tool setup. Figure 5 shows an overview of available motions, tools and robot types.



	Motion	Tool	Robot
1	Signalling Motion	Glove	KR10
2.1	Scooping Motion	Measuring Cup	KR10
2.2	Scooping Motion	Watermelon Scoop	KR10
2.3	Scooping Motion	Wooden Spoon	KR10
3	Stamping Motion	Ravioli Stamp	KR6
4	Sweeping Motion	Pastry Brush	KR6
5.1	Slicing Motion	Palette Knife	KR6
5.2	Slicing Motion	Ravioli Cutter	KR6

FIGURE 5 A toolpath library that enables Script Bites (robot programming) for users without specialist knowledge, developed for action sets and tools, including signalling, scooping, stamping, sweeping and slicing motions.

Participants programmed two robot actions; first on a general level and then adopted as robot motion integrated into a human-robot interaction as part of a food production sequence. This means that participants were programming in a constraint knowledge space – effectively inhabiting a pre-set robot program) while exploring the potential solution space for their individual task set, with focus on constraints that are physically possible.

3.3 Human-Robot Action Sets: Allocating Therbligs

Each participant group was tasked with adopting the Therblig framework for their food production scenarios. The emphasis was placed on identifying actionable tasks suitable for robots (considering factors such as the absence of sensors, diverse toolsets, workplace definition, and reach) and/or humans (considering age, dexterity, and skillsets). Additionally, participants provided detailed descriptions of crossovers between both agents. The Therbligs served as pivotal reference points for discerning task divisions or sub-tasks that could be executed by either agent, determining which tasks could be shared, and specifying instances where interactions and handovers should be considered. Consequently, the allocation of Therbligs facilitated the planning of tasks, consecutive sequences, and interactions, considering the capabilities and restrictions of both agents (Figure 6 provides a concrete example of this process).

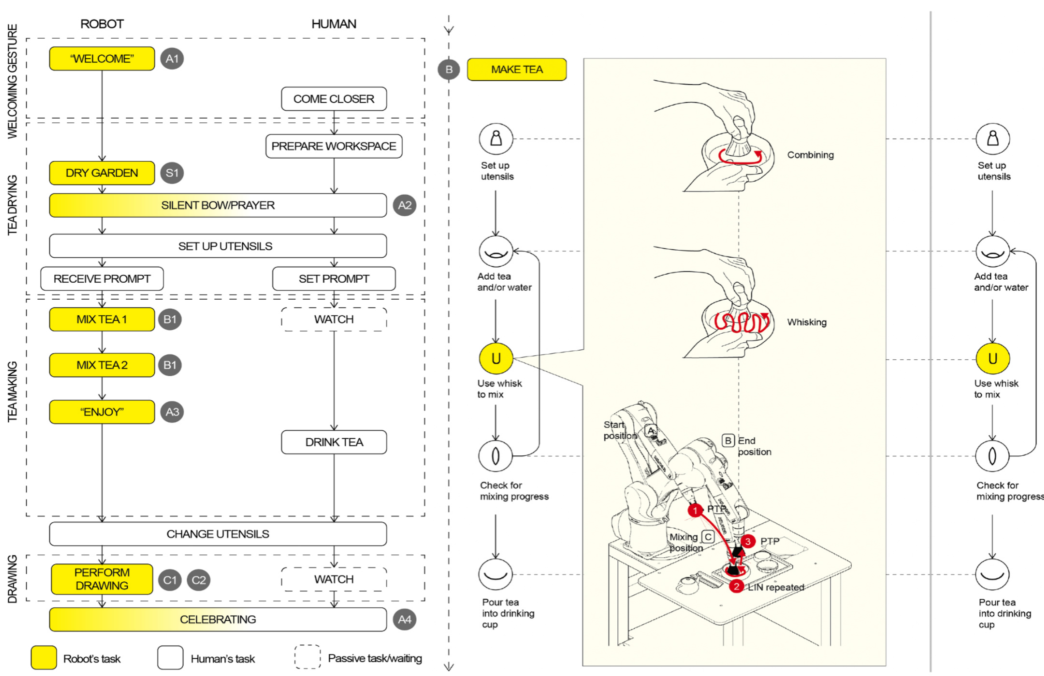


FIGURE 6 Diagrammatic analysis of shared action sets shared for human- robot team (left), and discrete sequences with Therbligs identified, here for tea making (right).

3.4 Demonstrators and Prototypes

Across a diverse range of food production scenarios that encompassed various cultural and social backgrounds, users demonstrated a remarkable capacity for adaptation and innovation. The incorporation of tools and ScriptBites was not merely limited to their intended purposes; rather, users expanded the boundaries of work processes by employing combinatorial logic to devise novel robot protocols, material applications, and tools. The spectrum of food concepts explored was extensive, spanning procedural tea-making, meat tenderization, pouring and mixing for jelly and no-bake cake preparation, as well as the construction of intricate desserts such as croquembouche and mille-feuille, as illustrated in Figure 7.

FIGURE 7 Overview of Case studies with six user groups, ranging from gestural and communication tasks for a robot (left, top) to precise and customised food gradients (right, bottom).

Significantly, the robot action protocols enable explorations with multiple materials and multiple tools. Similar to workshop, manufacturing or fabrication environments, this includes subtraction processes (cutting, slicing), production of finely tuned outcomes in ranges and gradients, additive processes such as mixing of various fluid materials (or granulates), changing textures and densities, handling temperature-based substances (hot/cold), and exerting directional force, pressure or repeated punching. While these actions take place in a kitchen environment here, there exists the potential to transfer these processes to more traditional fabrication and workshop domains. Tools and processes can be quickly and precisely adapted and adjusted to material constraints and variations.

The innovation extended beyond conceptualization, involving the development and 3D printing of new tools and tool adaptors. Users engaged in scripting iterative variations for robot motions, and an initial analysis of Therbligs played a pivotal role in human-robot task allocation. The results demonstrated the versatility and applicability of the framework across diverse knowledge sets of users. Moreover, it proved effective in task planning within a series of objectives (dishes), effectively accommodating new constraints introduced by the users and the specific task set. This multifaceted approach showcased the potential for creativity, intuitive handling and problem-solving within the context of human-robot collaboration in food production.

4 Discussion

Results are reported in the following. Participants quickly understood how to act within the given framework and system. The constrained solution space was useful for most participants in focusing on robot actions and workability in production of food segment. Executing the recipes on the robot shows a functioning open-ended system (as opposed to automated, end-to-end systems). While the set of motion primitives enable a variety of simple recipes to be executed with the industrial robot arms, several recipes could be successfully demonstrated. More significantly, the setup showed a high function of user acceptance, whereby participants were able to confidently use and riff off provided robot codes. A significant benefit is here the human capacity for innovation and intervention, with significant ability to assess, correct and control ongoing robot programs, constellation of material and utensil positions, and intervention in case of errors of the robot system. The Therbligs enabled participants to structure the workflows between human-robot teams; adjust according to agent capabilities; evaluate and control sub-tasks within the motion protocols, which enabled a much higher degree of precision planning.

However, several limitations should be noted. Limitation of the system stem from the lack of robustness, whereby failure in any of the robot's systems leads to a failure to successfully follow the recipe. Another limitation stems from the fact that materials are non-finite, ie consumables, with undetermined shrinkage, segmentation, change of gravity center, or changes from liquid to solid states. Real-time data feedback that continuously informs robot protocols; Machine-learning systems (ML) would enable increased response of the robot. Future potentials can offer another level of adjustment by expanding to Human-cobot collaboration, which is sensor based, offers continued data feedback, and allows integrating Graphical user interfaces, language processing, object recognition, task planning, and manipulation.

Significantly, the contributions of this research are in; a) a novel workflow based on a palette of work tools adopted for robot tooling to translate manual human tasks to human-robot tasks; b) an initial script series for work processes that represents modelling, planning, simulation, and implementation; c) a framework for task division through action sets based on Therbligs that supports users; and d) an empirical evaluation of the approach through a series of user studies. This can be of particular importance in a context of postcarbon, where architecture and construction industries need to respind to resource scarcity, circular materiality and careful considerations of embodied carbon. The robotic test studies serve here as departure point for embedding gradient conditions, working with non-finite and indeterminate substances and materials, and allow precise and versatile machining beyond automation.

5 Conclusion and Future Work

This research has introduced an innovative workflow cantered around a diverse set of work tools adapted for robot tooling, facilitating the translation of manual human tasks into human-robot tasks. It encompasses an initial script series that covers modelling, planning, simulation, and implementation of work processes, along with a task division framework based on Therbligs, supporting users in their interactions with robots. The empirical evaluation of this approach was conducted through a series of user studies. Future research directions may include three key dimensions: the reverse engineering of skill sets and process knowledge, facilitating the transfer and adaptation of the developed framework to other work processes and tasks, and extending its application to other cyberphysical systems for enhanced sustainability. The restructuring of human-robot interactions is envisaged, where robot/cobot systems can impart process knowledge and transfer skill sets for tasks related to food preparation and production.

Cooking, being a domain that necessitates physical, kinematic expertise in tool and utensil usage, heat source and hot material handling, temperature control, and understanding the chemistry of different ingredients, provides a context where a robot can be trained for actions and, reciprocally, teach and demonstrate process knowledge. While this research has primarily focused on kitchen scenarios as a distinctive robot work environment, the actions, tasks, analytical studies, framework, and workflows developed can be readily adapted for applications and contexts where collaboration and interaction between robots and humans are essential. This extends beyond traditional kitchens to include workshop and fabrication scenarios characterized by the complexity and variability of task applications. Additionally, in a robot-supported domestic environment, integration with big data can address issues related to reverse speed, homogeny, expediency, and globalization. This connection can align with initiatives such as the Slow Food and Farm-to-Fork movements, integrate with community gardens, embrace communal values associated with regional context and supply and assist individuals in adapting methods for sustainable resource utilization, waste and recycling strategies, and the promotion of circular economies in various domains, including food, architecture, design, fabrication, and manufacturing.

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INDEX/Definitions

- *Authoring pipeline:* refers to facilitating intuitive and effective translation of manual work into human-robot planning and programming of interactions and collaborations (Schoen et al, 2020).
- *Collaborative task execution (CTE):* an agent autonomously performing a task either collaboratively with or in the presence of other agents, while respecting any associated social roles and divisions of responsibility.
- *Learning from Demonstration (LfD):* refers to a robot control system that is capable of engaging in collaborative behaviors, including the capability for safe operations, physical manipulation, speech recognition, and even non-verbal communication, and intention detection.
- *Skill:* Refers here to either human or robot and is defined as a temporally extended action similarly to options in reinforcement learning, and is assumed to minimally include a set of known preconditions, expected post-conditions, and known goal states.
- *Trace observation:* a method of investigation in spatial planning and design for observing user movement in space, results of trace observation support design applications across all stages and are commonly used in the planning and evaluation of design solutions.
- *Task Allocation:* describes the division of tasks in Human-Robot Teams. Human-robot tasks can be derived from Hierarchical Task Analysis (HTA) and hierarchical learning. Interactions are then planned and managed by use of Therbligs, which support identifying action sets and task division.
- *Therbligs:* are basic actions required to complete a task and include effective, auxiliary and ineffective motifs (Chen). The analysis of kitchen behavior Therbligs focuses on the observation of actions in the kitchen of the elderly and the decomposition of continuous actions. The actions are categorised according to 18 kinematic factors and the process is optimised through ESRS (Eliminate, Combine, Rearrange, Simplify).

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