A Meta-Design Approach to Collaborative Robotics to Achieve Sustainability Goals

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Abstract

This paper analyzes how collaborative robots can contribute to achieving some of the United Nations' Sustainability Development Goals and reflects on the advantages that a meta-design approach could bring to robot deployment in real settings. The paper highlights how true sustainability not only depends on technological innovation but also on considerations that pertain to the social sphere of the intervention, like the specific domain, the workplace, and the user community, which require infrastructures for customization, sharing, and collaboration.

Keywords

End-User Development, Collaborative Robot, Sustainability, Meta-Design

1. Introduction

The term *collaborative robots*, or *cobots*, refers to robots designed to work alongside humans in a shared workspace, unlike traditional industrial robots that operate independently or within restricted areas [1]. Cobots are equipped with advanced sensors and safety features, allowing them to collaborate directly with human workers without the need for safety cages, and are increasingly applied in various industries. In manufacturing, for example, cobots assist in assembly lines, where they handle repetitive tasks such as screwing, packaging, and sorting, helping human workers to focus on more complex activities [2]. Cobots also assist in rehabilitation by helping patients perform repetitive motion exercises, aiding in physical therapy recovery [3]. Additionally, in agriculture, cobots help in precision farming by planting seeds, picking fruits, and monitoring crop health [4].

Collaborative robotics plays a crucial role in advancing several Sustainable Development Goals (SDGs) [5]. For SDG 3, *Good Health and Well-Being*, cobots are employed in the medical field to support minimally invasive surgeries, telemedicine, rehabilitation, social assistance, health prevention, and improve working conditions, thereby contributing to health and well-being [6]. For SDG 9, *Industry, Innovation, and Infrastructure*, they drive innovation by automating tasks in various industries, improving efficiency, and enabling small and medium-sized enterprises to integrate advanced technology [7]. Cobots also contribute to SDG 12, *Responsible Production and Consumption*, by enhancing productivity while reducing material waste and energy consumption, as robots can optimize manufacturing processes and reduce errors [8]. Furthermore, cobots support SDG 8, *Decent Work and Economic Growth*, by assisting workers in repetitive and physically demanding tasks, allowing them to focus on more creative roles, thus enhancing job satisfaction and fostering economic growth through automation [9]. However, despite their promising potential, the widespread adoption of cobots is hindered by a significant barrier: programming complexity. Currently, the need for specialized knowledge in robot programming limits their deployment in many industries. Developing more intuitive programming interfaces that allow non-expert users to program and manage cobots is essential for unlocking their full potential and ensuring that these robots can be employed on a larger scale. Moreover, simplifying cobot programming can foster technological innovation, improve working conditions, and enhance educational opportunities, ultimately contributing to broader sustainability and economic development goals. To

Joint Proceedings of IS-EUD 2025: 10th International Symposium on End-User Development, 16-18 June 2025, Munich, Germany
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address this problem, the scientific literature proposes several approaches to end-user programming (EUP) in the robotics field [10]. However, considering the variety of domains where cobots can be applied, with the consequent diversity of end users, we claim that merely focusing on simplifying robot programming is not sufficient to make collaborative robotics really sustainable. Using our case study in the pharmaceutical sector, we thus reflect on the added value that a meta-design approach [11] can bring to the field. We analyze how the socio-technical perspective characterizing meta-design is fundamental to design end-user development (EUD) environments for collaborative robots tailored to the specific context, the users' needs, and the work community.

2. End-User Programming of Collaborative Robots

In their survey on end-user robot programming, Ajaykumar et al. [10] highlight how additional challenges with respect to traditional end-user programming emerge in this field: in fact, there is the need for programs to refer to locations and objects, and make the robot arm(s) interact with the physical environment by performing specific movements and actions. Furthermore, end users may have different backgrounds, skills, and capabilities to learn robot programming. Thus, it is important to design methods that allow people who are neither experts in robotics nor in programming to deal with robot programming complexity. The survey distinguishes between approaches that enable users to specify the structure of the program encompassing the steps the robot should perform to accomplish a given task (e.g. [12], [13], [14]) and approaches that are based on the demonstration by the users of the robot behavior (programming by demonstration [15, 16]).

In the first category, visual programming languages are often proposed. They may be based on computer-oriented notations, such as flowcharts in RoboFlow [12] or hierarchical trees in CoSTAR [13], or inspired by more intuitive metaphors, like the block-based one where program statements are puzzle pieces to be combined together. For instance, Code3 [14] and CoBlox [17] allow the user to compose programs through the drag-and-drop of blocks on a canvas. A further visual programming language is the skill-based one proposed in [18]: *skills* are high-level concepts that describe robot actions, such as "pick object" or "place object in the location", which can be parameterized and combined in linear sequences to define complex behaviors, which however cannot include loops or conditionals.

An alternative approach to robot program specification is the use of natural language. For instance, in [19], a web-based natural language interface is presented that supports occupational and rehabilitation therapists in defining tasks for interacting with a NAO humanoid robot. As underlined in the survey by Villani et al. [20], due to the complexity and safety-critical issues of the robot tasks, natural language programming is difficult to deploy in the manufacturing and industrial contexts.

Other approaches combine in a unique environment different paradigms, like the block-based interaction with natural language programming [21][22] or verbal commands with sketches that provide context and logic for the robot program [23].

Artificial Intelligence (AI) is increasingly being leveraged to simplify robot programming, making it more accessible to non-experts. Among AI-driven approaches, Large Language Models (LLMs) are emerging as powerful tools for EUP in robotics due to their ability to interpret natural language commands and generate executable code. By bridging the gap between human intent and machine execution, LLMs enable users to define robotic tasks without requiring deep programming knowledge. However, their adoption introduces critical challenges, particularly regarding code reliability, error prevention, and user validation. A key issue in LLM-based robot programming is code verification. As explored in [24], errors in LLM-generated code typically occur in the interpretation and execution phases, with a notable tendency for LLMs to overlook crucial details from user prompts. The authors propose prompt engineering techniques, such as reinforcing task constraints and structuring numerical task contexts, to reduce execution errors. Their study underscores the necessity of dedicated verification tools, including custom scripts and simulation environments, to enhance the reliability of LLM-assisted programming.

A similar concern arises in human-in-the-loop approaches where users must refine LLM-generated code. For example, the tool presented in [25] allows users to assess and modify Python or C++ code produced by ChatGPT. However, this approach assumes a certain level of programming expertise, as users must evaluate and correct the generated code. To overcome this limitation, hybrid approaches have emerged to further integrate LLMs into EUP for robotics. In [26], a system is introduced for programming pick-and-place tasks via a natural language interface. The LLM interprets user commands, translates them into structured data, and visualizes the results using Google Blockly[1], enabling non-technical users to validate and refine the robot's task flow. This study highlights the issue of LLM non-determinism and the necessity for user oversight in verifying task execution. In [27], an LLM-driven interface assists in automating chemistry laboratory workflows. The system provides a 3D robot model alongside a chat panel where the LLM generates Python scripts for execution. However, this approach still requires users to have programming knowledge to validate correctness.

Beyond industrial and professional applications, LLMs also play a growing role in social robotics, particularly in dialogue management for human-robot interaction [28] [29]. LLMs enhance conversational fluency by contributing to more natural and engaging human-robot interactions.

These developments illustrate the potential and challenges of AI-based EUP for collaborative robotics. While LLMs offer a promising avenue for democratizing robot programming, issues related to reliability, interpretability, and non-determinism must be addressed. Furthermore, all the mentioned approaches to EUP in robotics are focused on facilitating coding and rarely consider other aspects related to the specific application domain, users' profiles, or social issues that may hinder participation in end-user robot programming.

3. A Socio-Technical Perspective based on Meta-design

Our recent effort to improve cobot programming is represented by PRAISE (Pharmaceutical Robotic and AI System for End Users) [30]. This system has been developed to assist pharmacists in defining robot programs for the preparation of *galenic formulations*, which are medicinal preparations made in pharmacies to meet specific patients' needs (e.g., in cases of allergies to certain excipients or when specific dosages are not commercially available). Such robot programs allow guiding cobots in performing some of the steps included in the galenic production process, like mixing different ingredients, filling capsules with the obtained galenic preparation, and transferring capsules into suitable containers. Unlike adopting a traditional EUP perspective, which primarily focuses on enabling non-expert users to write simplified code, we followed a meta-design approach. As underlined in [31], meta-design encompasses a socio-technical perspective that extends beyond merely providing simplified programming tools. On the technical side, we designed PRAISE as an EUD environment that empowers users to design, modify, and validate robot programs through intuitive interfaces able to manipulate user-defined items. On the social side, we observed and interviewed representatives of the target population and designed mechanisms to foster rich ecologies of participation and user-system co-evolution [11], with the purpose of achieving a truly sustainable integration of cobots in pharmaceutical settings. PRAISE exemplifies this approach by integrating a hybrid interaction paradigm that combines a natural language interface powered by an LLM (see Figure 1) with a domain-oriented graphical interface (Figure 2) for task verification and modification. This allows pharmacists, who lack formal programming expertise, to define robot tasks while maintaining full control over the final execution.

A meta-design approach is essential because EUD systems must be usable, adaptable, and capable of supporting the different needs of different users and work environments. In the case of PRAISE, this means not only enabling pharmacists to create robot tasks but also providing mechanisms for defining new task items and sharing them within the community. The pharmacist can define the items required for a specific task or, alternatively, reuse previously created items. Furthermore, more experienced users can define and share the different task items with less experienced users. This shared repository facilitates collective improvements, ensuring that workflows evolve in response to individual and community-driven insights. As an example, Figure 3 shows the page used to describe the data

[1] https://developers.google.com/blockly

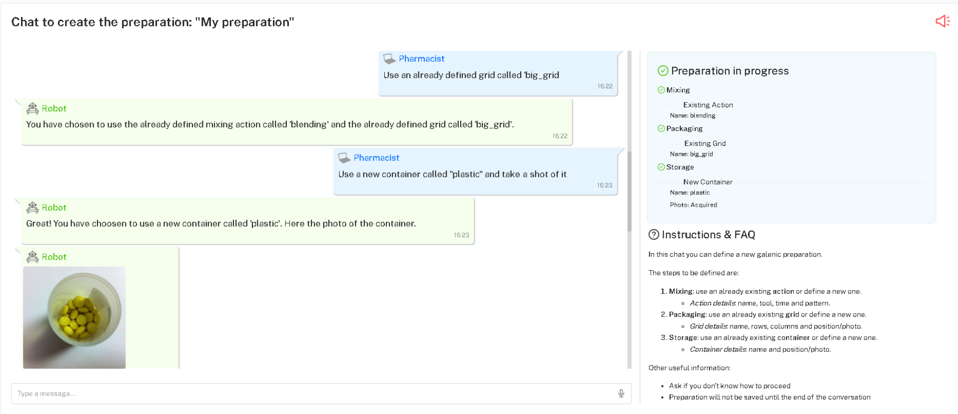

Figure 1: The definition of a preparation through the chat interface in PRAISE

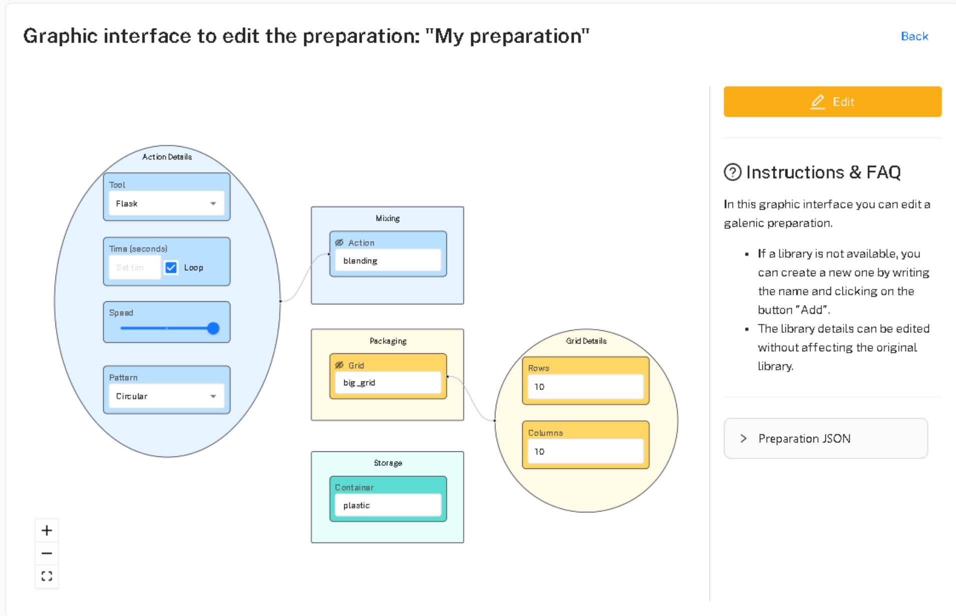

Figure 2: The graphical visualization of a preparation in PRAISE

characterizing a container: they include the *Name*, the *Shared* attribute, the *Keywords* (i.e., alternative names to call the same item according to users' preference), and the definition of how the robot must reach the container to fill it with capsules. The latter can be a fixed *Position* acquired through robot teaching (*Get position* feature), or a shape obtained after processing the container photos captured through the robot camera (*Get photo* feature).

4. Achieving Sustainability through Meta-Design

Following a meta-design approach in the domain of collaborative robotics requires considering the technical issues inherent to the robot itself, encompassing aspects such as programming and task execution. In addition to these intrinsic factors, the broader environmental context must be considered, including the perspectives of end users, the specific application domain, and the related context.

As reported in Section 1, collaborative robotics, on its own, can contribute to several SDGs. Adopting a meta-design approach allows one to be even more sustainable, by reinforcing the achievement of those SDGs and satisfying further SDGs. As previously mentioned, cobots may contribute to achieving SDG 3, *Good Health and Well-Being*, but meta-design can enhance this aspect by promoting an ecologically valid

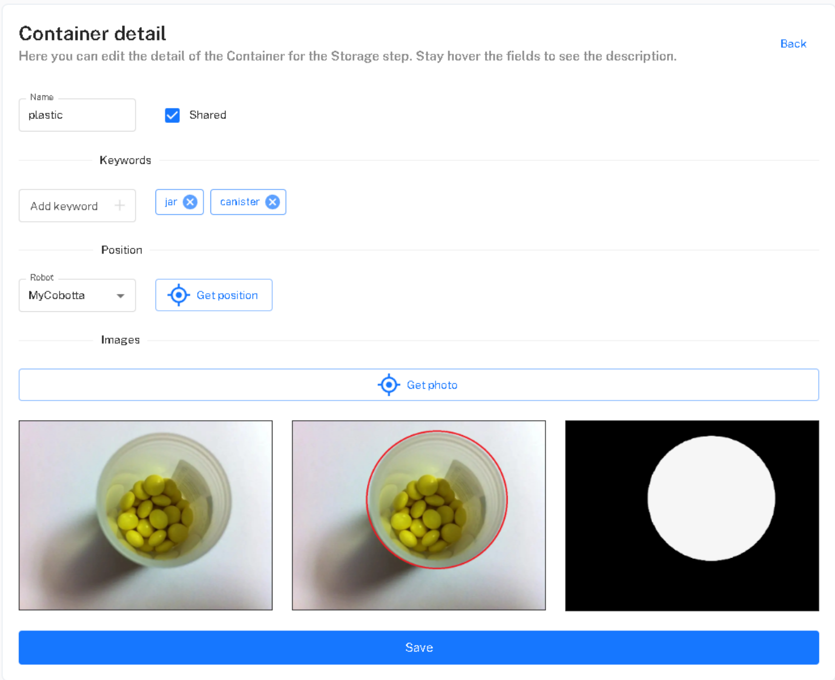

Figure 3: The definition of a container in PRAISE

approach [32]: issues related to ergonomics, tasks, and workers' needs can be analyzed to assign cobots the most repetitive, error-prone, and tiresome activities, leaving human workers time for high-value and creative activities, thus improving their well-being. Meta-design may also reinforce the achievement of SDG 9, *Industry, Innovation, and Infrastructure* by favoring cobot technology appropriation through EUD tools and infrastructures for sharing and collaboration. Similarly, achieving SDG 12, *Responsible Production and Consumption*, is one of the objectives of collaborative robotics: indeed, cobots are particularly suitable for small batch and customized productions. Since this kind of production often pertains to local and handcrafted work — as in our PRAISE project with pharmacists —, meta-design can play a crucial role in tailoring the technology to the specific context and workers' needs.

As to other SDGs not mentioned before, SDG 4, *Quality Education* can be achieved by taking into account the level of expertise of end users and leveraging appropriate EUD techniques and social mechanisms to foster community knowledge development. In PRAISE, this objective is reached through the integration of a system of shared items (objects, actions, locations, and robot tasks), enabling users to access and reuse predefined elements created by others. This feature is particularly valuable for novice users, who can benefit from existing user-created programs and gradually build their expertise in robot programming without having to start from scratch. By facilitating knowledge transfer and enabling incremental learning, PRAISE lowers the barriers to entry for pharmacists and other healthcare professionals, ensuring that they not only use the system effectively but also progressively develop a deeper understanding of automation and robotics principles. SDG 5, *Gender Equality*, and SDG 10, *Reduced Inequalities*, can be pursued thanks to the customization of robotic applications to align them with the specific competencies and literacy of the target community. By minimizing the required knowledge to operate cobots, expertise in programming is not mandatory, which helps reduce the risk of job displacement. As to SDG 5, it is well-known that the female percentage in STEM faculties is significantly lower than that of males, and this is especially true for computer science curricula. The democratization of programming and interaction with cobots can not only streamline the work of existing employees but also create job opportunities that do not require expertise in programming or robotics, helping to address the challenges faced by those without these qualifications. Cobots may also contribute to SDG 11, *Sustainable cities and communities*, in that they can be more affordable than industrial robots in the least developed countries and small work communities. However, their use must

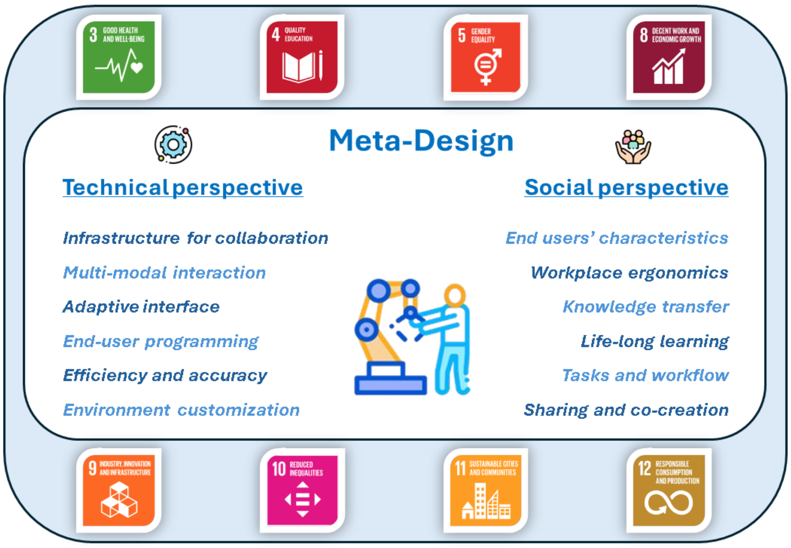

Figure 4: The role of meta-design in achieving sustainability goals through collaborative robotics

be sustainable in the long run, when experts are no longer present to help customize the technology to that specific community and needs. Meta-design, in this case, is fundamental to consider the variety of end users, including their age, skills, and backgrounds, and create solutions favoring a rich ecology of participation [11] and promote spaces for co-creation [32]. SDG 8, *Decent Work and Economic Growth*, can be supported not only by the intrinsic characteristics of cobots but also by a meta-design approach that foresees the integration of adaptive features in the EUD environment, enabling the creation of robot programs. In the context of natural language interaction, such as the one in PRAISE, how the user interacts with the system must evolve according to its use. Achieving this objective requires the development of an interface capable of learning the language of the users within their respective domains and cultural contexts. When an LLM is used, this goal can be achieved by providing the model with initial information about the user, the domain, and the context. In addition, the model can update this information dynamically, interaction after interaction.

Figure 4 illustrates how meta-design applied to collaborative robots can contribute to achieving some of the SDGs defined by the United Nations.

5. Conclusion

In this position paper, we have explored the role that collaborative robots can play in achieving sustainability goals and how a meta-design approach to their programming and their deployment in real contexts is useful to keep a socio-technical perspective that can make the intervention really sustainable. Further aspects can be more deeply investigated to understand the impact of a meta-design approach in the considered field. For instance, the choice of a specific AI system, such as an LLM, to be integrated into the EUD environment for robot programming can become critical for sustainability, as it is essential to assess the limitations imposed by LLM providers in terms of cost, latency, transparency, and accuracy. Moreover, one must acknowledge that LLMs and current AI systems are far from being sustainable, given their substantial resource consumption, including energy and computational power, which raises concerns about their environmental impact. In summary, the long-term success and sustainability of collaborative robotics may leverage a meta-design framework that ensures flexibility, user control, and alignment with ethical and environmental considerations. This perspective reinforces the idea that technological advancements in robotics should not merely replace human labor but rather augment human expertise, fostering more efficient, adaptable, and sustainable work environments.

Declaration on Generative AI

During the preparation of this work, the authors used ChatGPT and Grammarly in order to: grammar and spelling check, paraphrase, and reword. After using these services, the authors reviewed and edited the content as needed, thus, they take full responsibility for the publication's content.

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