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Low-Cost Design Proposal of a Modular Telescopic Autonomous Agricultural Robot

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Abstract

The application of autonomous robotics in food production is still in its infancy but bears significant potential, especially in the sector of precision farming. Here we present the results of a survey conducted during the years 2022–2023 with local farmers in Northern Germany to identify the challenges that are being faced by both conventional and organic farming practices due to climate change and increased food production regulations in the EU region. Additionally, a pilot study with a medium-sized (Demeter) farm is presented, identifying the real needs and problems organic farmers face during their food production chain from seeding, weeding, and maintaining the equipment till bringing in the harvest. The results indicate a strong demand for modular, autonomous, and digitized solutions to address key challenges in agricultural production. To address these challenges we propose a novel mechanical robotic platform design that has been developed in accordance with the Fab City principles of open and local production resulting in a low-cost open-source solution.

Keywords: autonomous robotics; digitized farming; organic farming; mechanical robotic platform; precision farming; sustainable farming; pilot study; local production; Northern Germany

1. Introduction

In agriculture, a distinction is made between conventional farms and organic farms. The difference in terms of farming is that weed killers such as pesticides and herbicides are used only in conventional farms, while in organic farms, weed control is done manually with various hoeing and brushing systems. Weed control and management is one of the most important tasks in agricultural production. Weeds compete with crops for water, nutrients, and sunlight and will have a significant negative effect on the yield when not properly managed [1]. The use of pesticides has been viewed critically [2] for decades. According to the 2022 Pesticide Atlas, approximately 385 million pesticide poisonings occur annually worldwide [3]. Stringent regulatory frameworks provide stronger protection for EU consumers than in most other regions worldwide, where pesticide use is subject to less comprehensive regulation or where regulatory enforcement is weaker. In addition, pesticide use is a cause of biodiversity loss [3,4]. However, the EU Commission published regulations called the “Sustainable Use of Pesticides Directive” [5]. According to these regulations, the risk and use of pesticides should be reduced by shifting to alternative

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approaches. The new regulations have put significant pressure on farmers, adding to the already existing challenges of finding skilled labor, rising operational costs, and dealing with uncertainties in the agricultural market. These challenges motivated the present study, which combines empirical insights from a farmer survey and a pilot study to inform the development of a modular, low-cost robotic platform aimed at reducing labor dependency while supporting compliance with evolving regulations.

In response to these regulatory and environmental challenges, technical solutions aimed at reducing pesticide use have gained increasing acceptance. Most notably, recent years have seen the development of autonomous mechanical weeders and precision chemical sprayers within academia and the private sector [6]. However, we identified that the majority of robots [7] or machines often have some limitations in their design due to their heavy structure that further contributes to soil compaction or makes them unsuitable to work in small to medium-scale organic farms as these types of farms grow the majority of their food in greenhouses and foiled tunnels [7]. We focused on these aspects after surveying German farmers and took them into account during the development of our modular platform. Additionally, with our design proposal, we aimed at eliminating the need for multiple machines for a range of tasks, operating only a single multi-purpose robot that can work with different crop types and conditions, such as row widths for maximum utilization in the field. Further, the development of this platform aims to promote open-source, locally distributed manufacturing systems fostering sustainable urban agricultural practices and builds upon the Fab City approach of producing as much as possible locally while collaborating on a global basis. This study is positioned as an exploratory and proof-of-concept investigation that combines empirical insights from farmers with early-stage engineering design. The objective is not to present a fully validated system but to establish a requirements-driven foundation for future development and validation.

1.1. Research Questions and Objectives

This study investigates how modular and low-cost robotic systems can address current challenges in agriculture, with a particular focus on small- to medium-scale farming in Northern Germany. These challenges include increasing labor shortages, regulatory pressure to reduce pesticide use, and the need for more sustainable and efficient production methods. To structure the analysis, the following research questions are addressed:

- RQ1: What are the most critical operational challenges and pain points faced by farmers in Northern Germany, particularly regarding labor, weed management, and sustainability requirements?
- RQ2: Which agricultural tasks and workflows are most suitable for support through modular robotic automation?
- RQ3: What functional and technical requirements can be derived from the farmer survey and the Demeter pilot study for the development of a modular robotic platform?
- RQ4: How can such a platform be conceptually designed in alignment with Fab City principles of local production, openness, and repairability?

These research questions guide both the empirical investigation and the subsequent conceptual design presented in this paper.

Contributions of This Study

The main contributions of this paper are as follows:

- Empirical insights from a farmer survey conducted in Northern Germany during 2022–2023, identifying key challenges, expectations, and priorities regarding agricultural robotics.

- Findings from a pilot study on a Demeter-certified farm, including observations on farm workflows, operational constraints, and practical needs in organic farming.
- A derived set of functional and technical requirements for the development of a modular agricultural robotic platform.
- A conceptual low-cost modular robotic platform architecture, interpreted through Fab City principles such as local manufacturability, openness, and repairability.

The literature review was conducted to establish the theoretical and technological background necessary for the assessment of the four outlined research questions (Section 2), later followed by our own survey (Section 3), where we discuss the novel design proposal (Section 6) and also its advantages followed by the results and discussions (Sections 4–7).

2. Literature Review

2.1. Agricultural Robotic Platforms: Limitations and Drawbacks

The increasing size and weight of modern agricultural machinery contribute significantly to soil compaction, which degrades soil structure and reduces crop productivity [8,9]. This compaction increases bulk density and impedes water infiltration, root growth, and nutrient absorption, especially in the subsoil, which may stay compacted for years. This phenomenon, referred to as "soil degradation syndrome," [8] includes other issues such as soil erosion and nutrient depletion, further harming agricultural sustainability [10].

Agricultural robots and machinery [11], while offering advanced solutions, often lack adaptability and modularity, particularly in environments like greenhouses or polytunnels, which are essential in organic and general farming [12]. These controlled environments require equipment that can perform various tasks with precision and flexibility. However, many heavy machines, such as the Fendt Xaver [13], Naïo Dino [14], FarmDroid FD20 [15], Ecorobotix Avo [16], AgBots by AgXeed [17], John Deere R8 [18], and others [19], are primarily designed for specific functions like seeding and weeding, limiting their application in smaller spaces. Their significant weight contributes to soil compaction, which can adversely affect soil health and plant growth, making them unsuitable for the delicate ecosystems within greenhouses and polytunnels. Moreover, the lack of modularity complicates maintenance and operational efficiency as these machines often require specialized knowledge and tools for repairs, leading to increased downtime. In organic farming, where sustainability and soil health are paramount, the inability of these machines to operate effectively in confined spaces, combined with maintenance challenges [20], poses significant barriers for small to medium-scale farming operations. Although robots like the Thorvald II agrobot [20] address some of these issues, some factors that remain to be addressed in the robot setup are improved farm tool versatility and automatically maneuvering the robot with a telescopic structure over height and width for a single robot and also considering the cost of the entire system. However the Thorvald II robot fits well for vineyards and strawberry fields laid at a certain height above form the ground but not all other cropping structures inside polytunnels such as lettuce.

The use of fossil fuels in agricultural machinery contributes significantly to carbon emissions, exacerbating climate change and undermining sustainable farming practices [21]. In this context, transitioning to regenerative or clean power sources presents a compelling solution. By harnessing renewable energy, such as solar, wind, or bioenergy, agricultural robotic platforms can operate with minimal environmental impact, reducing CO_2 emissions and promoting eco-friendly farming methods [19]. Implementing clean energy systems not only aligns with the principles of organic farming but also enhances energy security and resilience in rural areas, where access to conventional power sources may be limited. Ultimately, the integration of renewable energy into agricultural robotics fosters a more sustainable agricultural ecosystem, supporting both crop productivity and environmental stewardship.

While several existing agricultural robotic systems address specific tasks such as seeding or weeding, most platforms remain task-specific, relatively expensive, and limited in adaptability to small- to medium-scale organic farming environments. In particular, many commercial systems lack modularity, are difficult to repair in rural contexts, and rely on centralized manufacturing and proprietary components.

In contrast, the approach proposed in this study emphasizes a modular, low-cost robotic platform designed for flexibility across multiple tasks and crop types. The mechanical structure of the platform is intended to be locally manufacturable using widely available fabrication methods, while the overall system is designed to be locally assemblable from standard, commercially available components such as motors, sensors, and control units. This approach supports repairability, adaptability, and reduced dependency on centralized supply chains.

This is particularly relevant for organic farming systems, where diverse crop structures and smaller field conditions require flexible and lightweight solutions. Furthermore, the proposed system addresses gaps related to implement compatibility, maintenance simplicity, and integration into decentralized production systems aligned with Fab City principles. A comparative overview of representative agricultural robotic systems and the proposed platform is provided in Table 1.

Table 1. Comparison of existing agricultural robotic systems and proposed platform.

System	Modular	Target Farm Size	Production Approach	Flexibility
Naïo Dino	Low	Medium–large	Industrial manufacturing	Task-specific
FarmDroid FD20	Medium	Large	Industrial manufacturing	Limited
Thorvald II	Medium	Specialized	Industrial manufacturing	Moderate
Proposed platform	High	Small–medium	Local manufacturing (structure) + system assembly	Multi-purpose

2.2. Economic and Environmental Aspects of Conventional and Modern Agricultural Machines

Conventional agricultural machinery often involves significant operational costs due to fuel consumption, maintenance, and labor. These machines typically require more frequent repairs and are less energy-efficient, leading to higher greenhouse gas emissions [22]. In general, the reliance on fossil fuels not only raises operational expenses but also indirectly contributes to environmental degradation through soil compaction [22,23], erosion, and water pollution from runoff. In contrast, automated farming solutions, including precision agriculture technologies, offer improved efficiency by optimizing resource use (like water and fertilizers) and reducing the frequency of machinery use. While the initial investment in agricultural robotic platforms and systems can be substantial, the long-term reduction in operational costs and the accrued environmental benefits make these technologies a viable and sustainable solution over time [19]. Modern automated solutions also enhance productivity and sustainability by enabling real-time monitoring and data analysis, which can lead to more informed decision-making in crop management. These technologies can facilitate practices like variable rate application and integrated pest management, reducing chemical usage and minimizing adverse ecological impacts. By decreasing reliance on large, conventional machines, automated systems can mitigate soil compaction and improve overall soil health, fostering a more sustainable agricultural ecosystem. As global pressures for sustainable food production increase, the transition towards automated farming solutions is becoming increasingly important for both economic viability and environmental conservation [22,24,25].

2.3. Modular Design Principles

Modular hardware design principles offer several advantages that enhance product development and manufacturing efficiency. One significant benefit is the reusability of components, which allows manufacturers to leverage existing modules across various products [26]. This not only reduces costs associated with design and production but also promotes sustainability by minimizing waste through efficient resource use. Additionally, the modular approach facilitates easier testing and maintenance; individual modules can be tested separately, enabling quick identification and replacement of faulty components, which ultimately reduces downtime and maintenance costs. The scalability of modular systems allows for rapid adaptation to market demands, making it easier for manufacturers to respond to changing requirements and incorporate new technologies without necessitating a complete redesign [27–30]. However, modular design also presents certain challenges that must be navigated carefully. The complexity of designing a modular system can lead to increased development time and the need for thorough architectural understanding, which can complicate the integration of various modules [27,28]. Furthermore, striking the right balance between standardization and customization can be difficult; excessive standardization may limit product uniqueness, while too much customization can inflate production costs and undermine the benefits of modularity. Integration issues can also arise when dealing with multiple suppliers, where poorly designed interfaces may lead to compatibility challenges and performance degradation [31,32].

2.4. Fab City Principles and the Idea of Openness

The paradigm shift from the traditional linear economic model to a more circular approach is the core idea envisioned by the Fab City Global Initiative for cities around the globe [33]. This shift involves creating cities that are locally productive yet globally connected, leveraging advanced manufacturing technologies and digital fabrication aiming to build self-sufficient urban areas that reduce waste and carbon emissions while fostering innovation, economic growth, and social cohesion [33]. This vision became more tangible through the development of a framework, the Fab City Full Stack, highlighting the need for interventions on multiple levels to relocate and restore the production of energy, food, and other products [34]. The Fab City Full Stack consists of multiple layers, each playing a crucial role in the ecosystem and involves the integration of local production facilities, such as Fab Labs and makerspaces, with global supply chains. The foundation layer is based on the development of infrastructure and technologies for local production and the application of thorough scientific knowledge in order to implement sustainable or even regenerative practices. The development of an open-source, modular robotic platform for agriculture addresses these aspects on multiple levels. It represents a practical application of advanced manufacturing, distributed knowledge, and open-source hardware, contributing to sustainable urban agriculture and local food production.

Openness is a cornerstone of the Fab City movement. The open-source paradigm originated in the software engineering community and mainly focuses on open-source software with prominent examples such as Linux [35], software with "source code that anyone can inspect, modify, and enhance." Open-source hardware is an adaption of the open-source software concept. According to the Open Source Hardware Association (OSHWA), "Open source hardware is hardware whose design is made publicly available so that anyone can study, modify, distribute, make, and sell the design or hardware based on that design." The benefits of open-source hardware are manifold. They range from a rapid innovation process due to the involvement of the community, to the customization opportunities to meet specific needs and the educational characteristics for students and hobbyists, to the overall transparency that builds trust with the customer or user. However, the challenges businesses face when implementing an open-source project or product should not be neglected, especially since the legal framework and regulatory background are still unclear. Businesses might face competition that copies and sells their designs. Ensuring sufficient quality control and legal liability are challenges that should not be ignored. Finally, finding and developing business models and ways of monetization that are sustainable while maintaining openness is a crucial part.

3. Methodology

3.1. Survey Design and Data Collection

We conducted a survey using a questionnaire to better understand the current market situation and to be able to take farmers' customer wishes into consideration for product development. We came up with a total of 26 statements as a team, which we divided into four different sections. In the first section, the questions included some aspects of the agricultural robot, which the respondents rated according to their importance. In the second section, we set up short and general statements for respondents to agree or disagree with. The third section of our survey contained two questions about the efficiency of the robot. The last section of our survey included economic questions. For example, here respondents were asked to select the desired profit gain they would seek if they were to operate an autonomous robot in their fields in the future and the likelihood of investing in such a robot altogether in the near future.

The questionnaire design was informed by preliminary discussions with farmers and domain knowledge of agricultural practices, focusing on key operational challenges such as labor demand, weed management, and economic constraints. Open-ended responses were further analyzed to identify recurring themes that informed the technical requirements.

We presented our statements in a single-choice format using Microsoft Forms, which facilitates both distributing the survey to multiple respondents and analyzing the results in Microsoft Excel. The questionnaire was administered online and required approximately 10–15 min to complete.

Respondents rated each aspect on the following scale:

- 1—Very unimportant;
- 2—Unimportant;
- 3—Undecided;
- 4—Important;
- 5—Very important.

Each statement is briefly described in the following tables (Tables 2–6), followed by the aspects it addresses and the corresponding survey results. The statements in Table 2 asked respondents to rate various aspects of the robot according to their perceived importance.

Statements in Tables 3 and 4 address general and efficiency-related aspects evaluated by the respondents. The rating scale in this part is as follows: 1 = strongly disagree, 2 = disagree, 3 = undecided, 4 = agree, 5 = strongly agree.

Table 5 contains two questions concerning the efficiency of the robots. The rating scale in this part ranges in steps of five from 0% to more than 20%.

Table 6 presents the realistic best-case scenario of our survey. The rating scale in this part ranges from 0% to 100% in steps of twenty. Respondents were asked to evaluate the following aspects.

Table 2. Survey statements regarding autonomous agricultural robot features.

Statement No.	Question/Statement	Description
S1	The robot works autonomously, so the farmer can work on other tasks	Importance of autonomy in agriculture, allowing farmers to focus on other tasks.
S2	The weed is identified and removed at an early stage	Significance of early-stage weed identification and removal.
S3	The weed is uprooted rather than just cut off	Importance of uprooting weeds to prevent regrowth.
S4	The robot is solar-powered and works environmentally friendly	Evaluation of the robot's environmental friendliness and use of solar power.
S5	The robot has a low working speed	Preference for accuracy over speed in weed destruction.
S6	Some characteristics of the robot can be adjusted manually by the farmer	Importance of manual adjustability of robot features.
S7	The robot weighs around 1000 kg and is much lighter than a tractor	Significance of the robot's light weight in reducing soil compaction.
S8	The robot is much smaller than a tractor	Advantages and disadvantages of the robot's smaller size compared to a tractor.
S9	The robot is easy to set up	Importance of ease of assembly and setup.
S10	The robot can work with various cultures	Ability of the robot to distinguish and work with different crops.
S11	The pricing of the robot	Economic consideration of the robot's purchase price and payback period.
S12	If we missed an important aspect, you would like the robot to have, you can insert your idea below	Open-ended input for additional important aspects not covered in the survey.

Table 3. Survey statements regarding agricultural policy and robotic impact.

Statement No.	Question/Statement	Description
S13	Less pesticide should be used in agriculture	The goal of this robot is to reduce future pesticide use, seeking farmers' perspectives on pesticide application
S14	Policymakers should tighten legal controls on the use of pesticides	Respondents should indicate their agreement that protecting the environment, biodiversity, and human health requires stricter laws and regulations from politicians
S15	Saving time through the use of robotics on the fields	The evaluation of whether autonomous robots independently removing weeds saves time highlights its importance for farmers
S16	Reducing costs through the use of robotics on the fields	The evaluation of whether robotics can save time and reduce costs, including wages and insurance for agricultural workers, illustrates the importance of cost savings

Table 4. Survey statements regarding expected impacts of agricultural robotics.

Statement No.	Question/Statement	Description
S17	Increasing the yield through the use of robotics on the fields	Evaluating the use of robotics in weed control demonstrates that time and cost savings can lead to increased net profits
S18	Decreasing the working hours through the use of robotics on the fields	Autonomous robots eliminate the need for constant supervision, allowing farmers to pursue other tasks or work fewer hours
S19	Increasing the harvest through the use of robotics on the fields	Robots assist with weed control and sowing, enabling precise planting and potentially leading to a better and larger harvest

Table 5. Survey statements regarding acceptable performance thresholds of agricultural robots.

Statement No.	Question/Statement	Description
S20	Acceptable percentage of damaged crop	Participants were asked to select the maximum acceptable percentage of plants that may be damaged by robots during weed cutting or uprooting
S21	Acceptable percentage of missed weeds	Respondents were asked to decide the maximum acceptable percentage of weeds that robots may miss during cutting or uprooting

Table 6. Survey statements regarding expected economic and operational outcomes of agricultural robots.

Statement No.	Question/Statement	Description
S22	Desired percentage of cost reduction	Respondents were asked to indicate the percentage by which their costs should be reduced if they operate robots on their fields
S23	Desired percentage of yield increase	Respondents were asked to indicate the percentage by which profits should increase if they operated robots on their fields
S24	Desired percentage of reduced working hours	Respondents were asked to indicate the percentage by which working hours should decrease if robots were used on their fields
S25	Desired percentage of harvest increase	Participants were asked to indicate the percentage by which their harvest should increase if robots were to operate on their fields
S26	Probability to have an autonomous weeding robot on your farm in the next five years	Respondents were asked to indicate the likelihood of acquiring at least one of our robots in the next five years for autonomous weed control on their fields

3.2. Sample and Study Context

The survey was conducted during the period 2022–2023 and targeted farmers across Germany. A total of 117 questionnaires were distributed via email to farming businesses and professional contacts within the agricultural sector, from which 20 valid responses were received, resulting in a response rate of approximately 17%.

The sample included a mix of organic and conventional farms as well as other agricultural businesses; however, due to anonymization and the limited sample size, detailed subgroup distributions are not reported. The results are therefore presented in aggregated form.

Participants were selected based on their active involvement in agricultural production. Both organic and conventional farms were included to capture a broader range of perspectives on agricultural robotics and sustainability practices.

In addition to the survey, a pilot study was conducted on a Demeter-certified organic farm located in Northern Germany. This case study provided context-specific insights into operational workflows and challenges in organic farming, which complement the broader survey results.

3.3. Pilot Study: Demeter Farm Case Study

In addition to the survey, a pilot study was conducted on a Demeter-certified organic farm located in Northern Germany in Hamburg. The farm represents a small- to medium-scale organic agricultural operation, cultivating crops such as lettuce and coriander under field and/or controlled environments (e.g., greenhouses or polytunnels). The farm relies primarily on manual labor for tasks such as weeding and crop maintenance, with a relatively low level of mechanization compared to larger conventional farming systems.

The pilot study was carried out through 2–3 site visits and informal interviews with farm operators and workers. Observations focused on key stages of the agricultural workflow, including seeding, weeding, crop maintenance, and harvesting.

Needs and problems were identified through a combination of semi-structured interviews with farmers, direct observation of daily operations, and informal workflow analysis of key tasks such as weeding, seeding, and crop maintenance. This approach enabled the identification of labor-intensive processes, operational bottlenecks, and limitations of existing tools and machinery.

The insights obtained from the pilot study were used to complement the survey findings and to inform the derivation of functional and technical requirements for the proposed modular robotic platform. The relationship between observed challenges, derived requirements, and resulting design features is summarized in Table 7.

Table 7. Traceability from observed farm challenges to system requirements and design features.

Observed Pain Point	Derived Requirement	Design Feature
Labor-intensive manual weeding	Reduce manual labor through automation	Autonomous navigation and weeding module
Difficulty adapting tools to different crops	Flexible system adaptable to multiple crops	Modular architecture with adjustable working width and height
Soil compaction from heavy machinery	Lightweight system to minimize soil impact	Telescopic lightweight frame structure
High maintenance effort of existing machinery	Simple and maintainable system design	Modular components for easy replacement and repair
Limited operation time (daytime constraints)	Ability to operate continuously	Support for extended or autonomous operation (e.g., night operation)

3.4. Data Analysis

Quantitative survey data were analyzed using descriptive statistical methods, including frequency distributions and percentage-based summaries. The results are presented in aggregated form using bar charts and percentage plots.

Qualitative responses, such as open-ended feedback from participants, were analyzed using a thematic coding approach to identify recurring themes, including maintenance concerns, operational flexibility, and additional feature requests. Due to the exploratory nature of the study and the limited sample size, no formal inter-rater reliability assessment was conducted.

3.5. Limitations

Several limitations should be considered when interpreting the results of this study. First, the relatively small sample size ($N = 20$) limits the generalizability of the findings. Second, the recruitment method (email distribution) may introduce self-selection bias as respondents may have a higher interest in technological innovation than the general farming population.

Additionally, the sample may not fully represent the diversity of farm sizes, production types, or regional conditions across Germany. Furthermore, the survey does not explicitly control for farm size distribution, which may influence the relevance and prioritization of robotic solutions. The findings should therefore be interpreted as exploratory insights rather than statistically representative results.

The study is exploratory in nature and aims to identify trends and requirements rather than provide statistically generalizable conclusions.

Despite these limitations, the survey provides valuable initial insights into farmer needs and expectations, which are further complemented by the pilot study described in this paper.

4. Results

This section presents the questionnaire results and conclusions are summarized in Section 5. In this study, challenges are considered “urgent” if they were rated as “important” or “very important” by more than 60% of respondents. In the following figures, the y-axis denotes the frequency of responses per statement and per choice, plotted against the x-axis representing the rating scale. The top-ranked requirements based on the survey responses are summarized in Table 8.

Table 8. Top-ranked requirements based on survey responses ($N = 20$).

Requirement	Important + Very Important (Count)
Autonomous operation (S1)	11
Early weed detection (S2)	15
Uprooting weeds (S3)	13
Manual adjustability (S6)	14
Lightweight system (S7)	12

As shown in Figure 1, several key requirements exceed the defined urgency threshold of 60%, indicating strong agreement among respondents.

The twelfth point of our survey was for farmers to tell us their issues and wishes. The following topics are important according to the farmers and should be considered during product development: transportation, anti-theft devices, the robot being able to also work at night, requiring little maintenance, maintenance costs, running costs, and swarm intelligence.

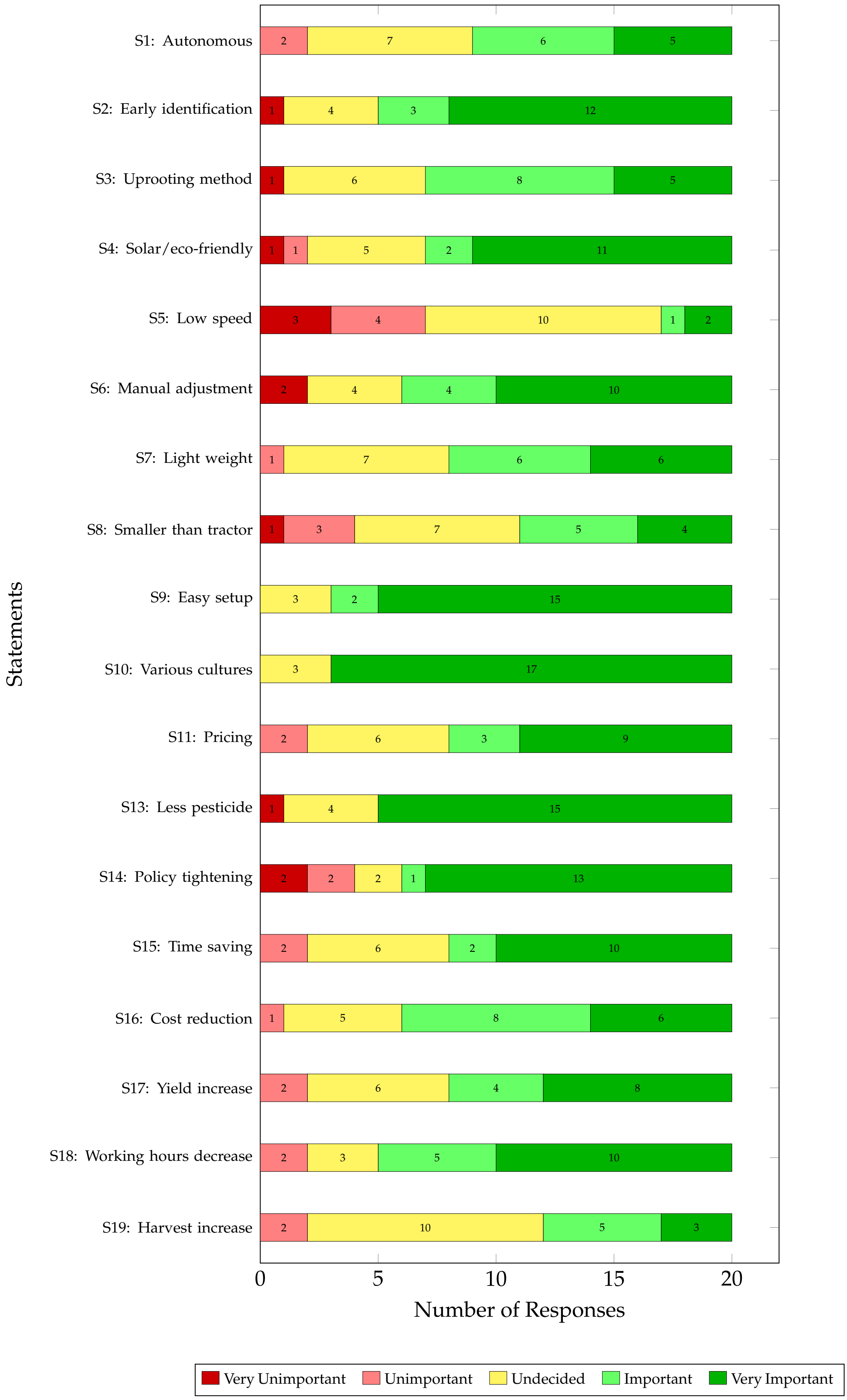

Figure 1. Survey responses for all 16 statements regarding agricultural weeding robot features and benefits ($N = 20$). Statements S1–S11 use the importance scale; S13–S19 use the agreement scale.

Figures 2 and 3 present the combined survey outcomes for statements S20–S21 and S22–S26, respectively.

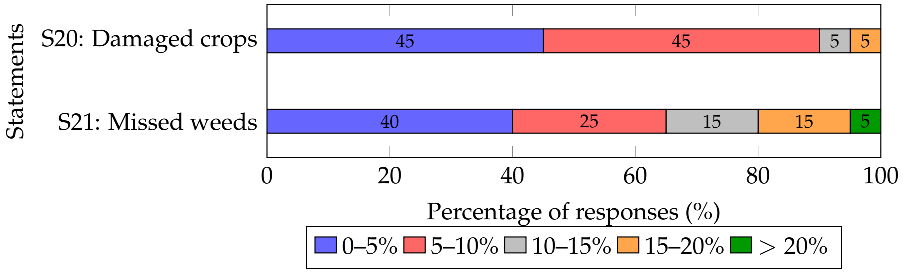

Figure 2. Combined outcomes of S20 and S21.

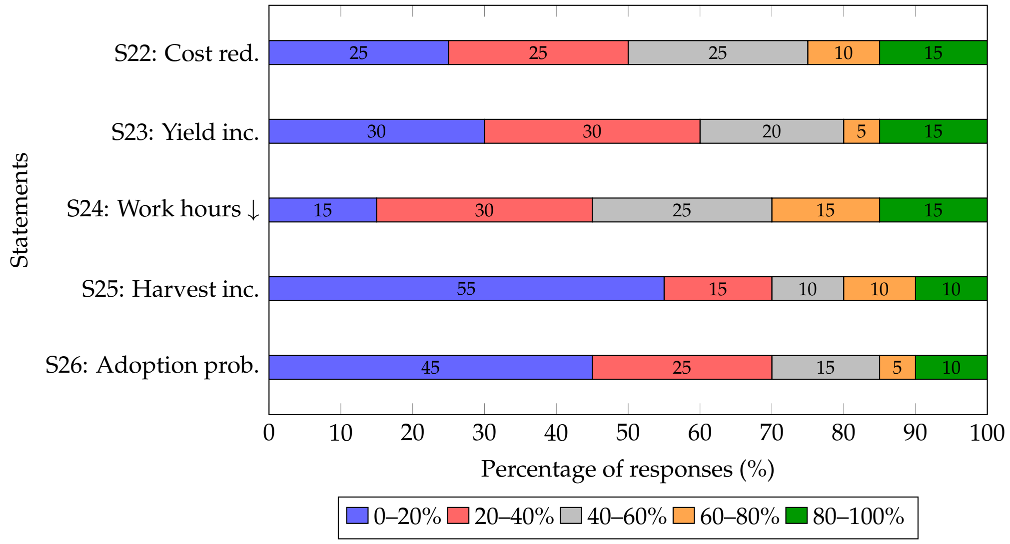

Figure 3. Combined outcomes of statements S22–S26.

The answers show that it is realistically possible to increase the harvest with the work of autonomous robots on farms. Therefore 30% of the responses desire an increase of 40% to 100% as a best case. The last question of our survey shows some mixed feelings about robotics in the future. While 45% of the respondents are not planning to acquire an autonomous robot for their farm in the near future, 15% are thinking of operating a robot, with a probability of more than 60%, on their fields.

The survey results highlight strong demand for lightweight, modular, and easy-to-use robotic systems, which directly informed the platform design presented in the following section.

5. General Technical Requirements and Specifications

The technical requirements for the proposed weeding robot are derived from the survey results and a comparison with existing agricultural robotic systems (Section 2.1). A key requirement is precise weed detection and removal, which necessitates the integration of vision-based systems and advanced algorithms to distinguish between crops and weeds while minimizing crop damage.

The platform is intended to operate autonomously and adapt to different farming conditions through adjustable working width and height. A lightweight structure is essential to reducing soil compaction, particularly in organic farming environments. Furthermore, energy-efficient operation, ease of transport, and low maintenance requirements were identified as critical factors for adoption.

To address these needs, the system is designed as a modular platform with user-friendly components that can be easily configured, maintained, and adapted to different farm sizes and use cases.

6. Initial Platform Design

Based on the derived technical requirements, an initial prototype of the robotic platform was developed and tested in field conditions. The design features a modular telescopic leg structure replicated on all four sides, enabling omni-directional movement and adaptability to different field geometries.

Initial tests demonstrated the feasibility of the concept but also revealed challenges related to soil porosity and high torque requirements for movement on uneven terrain. These findings indicate the need for further improvements in traction, stability, and mechanical efficiency in future iterations.

6.1. Operationalization of Fab City Principles in the Platform Design

The platform implements Fab City principles through a combination of local manufacturing of structural components and local assembly of the overall system. The mechanical frame is designed for fabrication using accessible methods such as CNC machining and welding, while key components (e.g., motors, sensors, and control units) are sourced and integrated modularly.

To support replication and adaptation, the system is intended to be documented through CAD models, bills of materials, and assembly guidelines. The modular architecture enables straightforward repair, replacement, and upgrading of components, supporting long-term usability in decentralized and rural contexts. The mechanical components of the locomotion system are shown in Figure 4, illustrating the four robotic legs with integrated actuators. Based on this design, a first telescopic lightweight modular robotic platform prototype was developed, as shown in Figure 5.

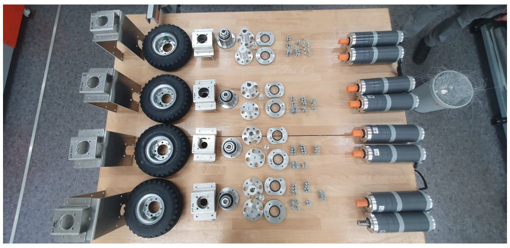

Figure 4. Four identical legs with actuators.

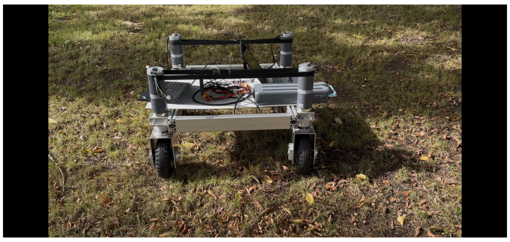

Figure 5. First telescopic lightweight modular robotic platform prototype.

6.2. Conceptual Technical Specifications

Based on the derived requirements, the platform is designed as a modular robotic system for row crops and bed-based agricultural environments, including open fields, greenhouses, and polytunnels. It supports tasks such as mechanical weeding, crop monitoring, and integration of interchangeable implements. The lightweight adjustable frame, combined with a high-torque drivetrain, enables an estimated payload capacity of 80–150 kg for low-speed operations. The estimated total system weight (excluding payload) is approximately 80–120 kg, depending on configuration. The system is intended for semi-autonomous operation with planned integration of GNSS (RTK) and/or vision-based navigation. It is electrically driven with battery-based operation targeting several hours of runtime. Safety features include emergency stop and controlled operating speeds, with advanced capabilities such as obstacle detection planned. The platform is designed as a low-cost solution through modularity, use of off-the-shelf components, and local manufacturing of structural elements combined with local assembly. A breakdown of the prototype platform components and their approximate cost estimation is provided in Table 9.

Table 9. Prototype platform components and approximate cost estimation.

Component	Specification	Approximate Cost (€)
Drive system	24V BLDC motors with encoders (×8), ∼120 Nm each	7200–8000
Motor control	ODrive S1 (×8)	1120
Power supply	48 V, 15 Ah Li-ion battery	400–600
Computation	Raspberry Pi	80–120
Navigation (planned)	GNSS RTK module	300–800
Mobility	Pneumatic wheels (×4, ∼260 mm)	200–400
Structure	Aluminum T-slot frame	300–500
Sensors	Limit switches, basic electronics	50–100
Total (platform only)		9800–11,600

Compared to existing commercial agricultural robotic systems, which often exceed €20,000–€50,000, the proposed platform demonstrates a significantly lower entry cost for small- to medium-scale farms.

The presented configuration represents an early-stage prototype of the robotic platform and does not include perception systems or advanced autonomy components. The system is intended as a first step toward field evaluation and iterative development.

Due to the high-torque drivetrain configuration, the platform uses four primary drive actuators for ground propulsion, each providing approximately 120 Nm torque with a gear ratio of 192:1. Additional actuators are used for leg articulation and structural adjustment, enabling omni-directional movement and adaptability to varying field conditions.

Based on this configuration, a practical payload capacity in the range of approximately 80–150 kg is considered feasible for low-speed agricultural operations. Higher loads may be mechanically possible due to the high-torque drivetrain; however, structural limits, terrain conditions and system stability define the practical operating range.

However, the high gear ratio results in reduced traversal speed, which may limit efficiency for time-critical operations such as large-scale weeding. This trade-off between torque and speed will be addressed in future design iterations.

At this stage, detailed structural analysis such as finite element modeling of the telescopic structure has not yet been performed. However, preliminary design considerations include the use of rigid aluminum profiles and symmetric load distribution across the four-leg configuration to minimize deflection in extended states.

Stability on uneven terrain is addressed through the multi-leg configuration, which allows adaptive contact with the ground and improved load distribution. Further structural validation and optimization will be part of future work.

7. Discussion

This section discusses the results of some statements from our questionnaire and tries to address some of the points mentioned. The answers from our questionnaire provide information on what farmers value when it concerns robotics in agriculture.

As shown in outcome of S26 statement, the majority of surveyed farmers rated key aspects of the weeding robot, such as autonomous operation and early weed identification, as important or very important. This result aligns with our expectations, given that these features were prioritized during the development of the prototype. Specifically, 64% of respondents rated autonomous operation highly important, while some remain uncertain about automation, and 60% considered early weed destruction as very important for preventing reproduction and protecting soil and crops.

Another notable finding is that 65% of farmers rated uprooting weeds, rather than simply cutting them, as important or very important, while 30% were undecided and 5% found it unimportant. This may reflect limited experience with complete weed removal. Additionally, 55% of respondents rated solar-powered robots as very important, highlighting the agricultural shift towards reducing fossil fuel reliance and adopting environmentally friendly, battery-powered solutions. The robot's low working speed seems relatively unimportant, with 35% rating it as unimportant and 50% undecided from statement S5. This may be due to its perceived link to low productivity, though in our opinion, greater accuracy in weed removal is often tied to slower operation.

Statement S6, which highlights the ability to manually adjust properties such as working width and height, was rated as important or very important by 70% of respondents. This is understandable as field rows often vary in width, making such customization valuable for farmers. Statements S7 and S8, concerning the robot's size and weight, were rated as important, supporting our expectation that smaller, lighter robots will be widely adopted due to reduced soil impact, easier transport, and convenient storage compared to tractors. The statement S11, addressing the robot's price, highlights its economic importance. As agricultural businesses prioritize financial considerations, both the purchase price and potential running costs are crucial factors.

The survey results show strong support for reducing pesticide use, with 75% of respondents in favor and 65% agreeing that stricter political regulation is needed to control pesticide usage. Farmers also anticipate time savings from automated weed removal and hope that robots will reduce costs by cutting the need for labor, pesticides, and fuel. While 60% expect increased yields from robots, opinions are mixed on profitability, with 40% undecided or disagreeing. The results regarding time savings are reinforced by statement S18, with 75% of respondents agreeing that reduced working hours can be redirected to other operational tasks. However, statement S19 highlights farmers' skepticism about the potential for robotics to increase harvests, with 50% undecided and only 40% expressing optimism. The study acknowledges limitations, including a low survey participation rate, which may have restricted the depth of insights gained. A larger sample could have provided more nuanced perspectives on weed robots, particularly in statement S12. In the rapidly evolving information age, both opportunities and challenges arise. Significant advancements in technology and the economy necessitate ongoing market research to identify new trends and innovations. Future studies should aim to develop and implement unique technological features for robots to remain competitive, gathering data through online surveys, expert interviews, or digital research.

Implications for Urban Farming and the Fab City Vision

The survey results highlight the growing demand for sustainable, efficient, and customizable agricultural technologies. One of the key takeaways from the survey is the necessity for solutions that address labor shortages, reduce the reliance on chemical herbicides, and enhance the precision of agricultural practices. Our prototype of an autonomous weeding robot offers a promising response to these challenges.

A unique aspect of the robot's design is its modularity. Farmers, developers, and researchers can easily upgrade and customize the robot to meet specific agricultural needs. For instance, soil monitoring sensors or irrigation systems can be integrated to enhance the robot's functionality, making it adaptable to diverse agricultural environments. This modular design also allows for scalability, meaning the robot can be utilized in small community gardens as well as large-scale farms. As a result, farmers can benefit from this technology, supporting the robot's broader applicability and accessibility.

Another key characteristic of our robot is its open-source nature. By making the robot's mechanical and electronic components available under an open-source license, innovators worldwide can build, modify, and improve the robot according to their specific requirements. This open-source approach fosters community collaboration, encouraging knowledge-sharing and collective problem-solving among developers, farmers, and researchers. The open-source nature of the robot also facilitates local production as users can produce and customize the robot based on local needs and resources, fostering economic activity and reducing dependency on external suppliers [34]. This decentralized model of production aligns with the goals of sustainable urban agriculture and the Fab City framework, which seeks to create closed-loop, sustainable food systems. The replicability and ease of maintenance of the robot makes it therefore an attractive option for small and large-scale farmers alike. The robot's integration into the Fab City framework not only contributes to more sustainable food systems but also stimulates economic opportunities within urban and rural communities. Local entrepreneurs and small businesses can develop and sell customized versions of the robot, thus creating new job opportunities.

The survey results further emphasize the importance of cost reduction and efficiency. Farmers are increasingly drawn to technologies that reduce operational costs, and the autonomous weeding robot addresses this by reducing labor costs while aiming at high precision of weed control. Furthermore, the robot's ability to operate without chemical herbicides contributes to healthier soils, which in turn benefits long-term crop production and addresses environmental concerns.

Additionally, the development and deployment of the robot provide significant educational value, offering hands-on learning experiences for students, hobbyists, and even farmers themselves. These practical experiences demonstrate how digital fabrication and open-source principles can be applied to solve real-world agricultural problems [34].

8. Conclusions

In conclusion, the exploration of modular robotic platforms in agriculture offers a multifaceted approach to addressing the dynamic challenges faced by farmers of all scales. By conducting a qualitative survey among German farmers, the research identifies specific demands and obstacles, ensuring that the development of these platforms aligns with real-world needs. Evaluating their adaptability and versatility highlights their potential to perform diverse agricultural tasks, from planting to harvesting, with enhanced precision and efficiency. Furthermore, analyzing the economic and environmental benefits underscores the sustainability of transitioning to modular mobile robotics, contributing to reduced resource usage and operational costs. Lastly, integrating the development of these platforms within the Fab City concept emphasizes the role of localized, circular production systems in fostering innovation and sustainability in agriculture. Together, these insights lay a strong foundation for advancing agricultural practices through modular robotics, paving the way for more resilient and sustainable farming ecosystems.

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