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Engineering Agricultural Robots for India: Mechanical Foundations, Contextual Challenges, and a Customised Design Approach

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Abstract
This research paper undertakes a comprehensive examination of the mechanical and scientific foundations of agricultural robots, highlighting their significance and challenges in the Indian agricultural context. It begins by examining locomotion systems, including wheeled and legged mechanisms. Sensor technologies, including vision systems, GNSS, LiDAR, and environmental sensors, are analyzed in terms of agricultural applicability. The study then explores robotic arms by categorizing them based on function, mechanical configuration, and deployment environment. India's pressing agricultural issues, including labor shortages, land pressure, and youth disengagement, are also discussed. Despite a rapidly growing agri-robotics market, barriers such as affordability, awareness, and infrastructure persist. To address these issues, the paper proposes a conceptual design of an agricultural robot tailored for India, incorporating rugged wheels, solar power, a modular arm, and multilingual interfaces, supported by policy recommendations to facilitate broader adoption.

Keywords: agricultural robotics, sensors, robotic arms, locomotion systems, India, rural technology adoption

Introduction

Agricultural robots are defined as any robotic device capable of improving agricultural processes by automating many of the tasks that farmers would otherwise perform manually, which are often slow or labor-intensive (Gomez, 2022). As a result, the use of robots in agriculture simplifies, speeds up, and enhances the effectiveness and efficiency of several tasks. According to research reports, the global agricultural robots market size was USD 4.9 billion in 2021, with an expectation to rise to USD 11.9 billion by 2026 (ReportLinker, 2021). Several mechanical and electrical components, as well as scientific engineering principles, enable the potential of agricultural robots. These entail locomotion systems, sensors, and robotic arms.

India has a significant agricultural sector. "Gross production value in the Indian Agriculture market is projected to amount to US$530.88bn in 2025. An annual growth rate of 3.05% is expected (CAGR 2025-2029), resulting in a gross production value of US$598.72bn in 2029" (Statista, 2025). While this sector is essential in ensuring the nation's food security and supporting the livelihoods of millions, it continues to rely heavily on manual labour, leading to inefficiencies in resource allocation and overall productivity. This may be limiting the sector's potential, particularly as younger generations are increasingly disinterested in pursuing agricultural careers due to its physically demanding and often low-tech nature. As India navigates these structural and generational challenges, innovation becomes increasingly essential.

This research paper aims to explore the mechanical and scientific principles underlying agricultural robots before examining the challenges associated with their deployment in the Indian context. It proposes both a conceptual design of an ideal robot and supportive policy measures to facilitate broader adoption.

Locomotion Systems in Mobile Robots

One of the crucial mechanical aspects of robots is locomotion, which refers to the method by which a robot moves from one place to another (Dam, 2025). Locomotion integrates principles from mechanics, control systems, and artificial intelligence to enable efficient, adaptive, and goal-oriented motion. There are several types of locomotion, with wheeled and legged locomotion being among the most common and widely used. Each of these has been further analyzed below.

Wheeled

Wheeled locomotion is one of the most widely adopted and efficient methods of mobility in mobile robots. In fact, "one of the first autonomous mobile robots was a wheeled mobile robot (WMR), built at Stanford University based on two driving wheels and a caster wheel as its guiding control actuator. This robot was designed based on Artificial Intelligence methods and it was able to perform planning, reasoning strategies, and motion control tasks autonomously in a complex environment" (Taheri and Zhao, 2020).

The popularity of this form of locomotion is a result of several factors, including mechanical simplicity, ease of control, high energy efficiency, and enhanced stability (Dubey, Prateek, and Saxena, 2015). Most commonly, such robots employ a minimum of three wheels (in rare cases, two wheels), often in a configuration that ensures balance and smooth operation during movement. Unlike leg systems, which will be analyzed next, wheel robots are not burdened with complex balancing mechanisms, contributing to their reliability and lower design complexity (Campion et al., 1996; Kamel and Yu, 2018).

Wheel robots can be categorized based on the type of wheels and drive mechanisms they employ. These include standard wheels, which offer two degrees of freedom of rotation - around the center shaft and at the point of contact. Caster wheels, commonly seen in trolleys, allow for passive directional rotation through an off-center pivot. Lastly, omni wheels provide three degrees of freedom, enabling holonomic motion, which is more ideal for tight and dynamic environments.

While it is true that wheeled locomotion systems are traditionally favoured for flat and predictable surfaces, they are not inherently unsuitable for uneven terrain. Specific types of wheels, including rugged or even specialised wheel designs, can significantly enhance performance on uneven surfaces.

Legged

Legged locomotion refers to robots that are legged and built to tackle terrains where wheels might fall short. These types of robots can typically cross wide gaps, climb stairs, and navigate irregular surfaces with ease. This is usually made possible by having each leg with at least two degrees of freedom, meaning one server motor per joint.

One Legged

The least legged a robot can be is a one-legged robot, also commonly referred to as a hopper, because it can conduct only one motion: hopping, due to having only one point of contact between the foot and the ground (Huang and Zhang, 2023). According to research, hoppers can maneuver through rough terrains and obstacles. Still, dynamic stability remains a significant concern, as the robot must actively balance its center of gravity by shifting its mass.

Two-legged/Bipedal

Two-legged, bipedal, or humanoid robots also exist and are the most common types of robots observed over the last decade, as they are capable of imitating many human actions, including walking, running, dancing, jumping, and navigating stairs (Rubio, Valero, and Llopis-Albert, 2019). There are many examples of such robots, including the well-known and successful Honda ASIMO. This is a humanoid robot that is 130 cm tall and weighs around 50 kg. It boasts a walking speed of 2.7 KPH and a running speed of 9 KPH, and is rather complex, with 57 degrees of freedom distributed throughout its body (Honda, 2011). Another very popular humanoid is the TOPIO 3.0, a ping-pong-playing robot featured at the international robot exhibition in Tokyo. A Vietnamese company developed this humanoid robot, utilizing a processor and artificial neural networks, along with a 200 frames per second camera, for its operation (Tabrizi, Pashazadeh, and Javani, 2020).

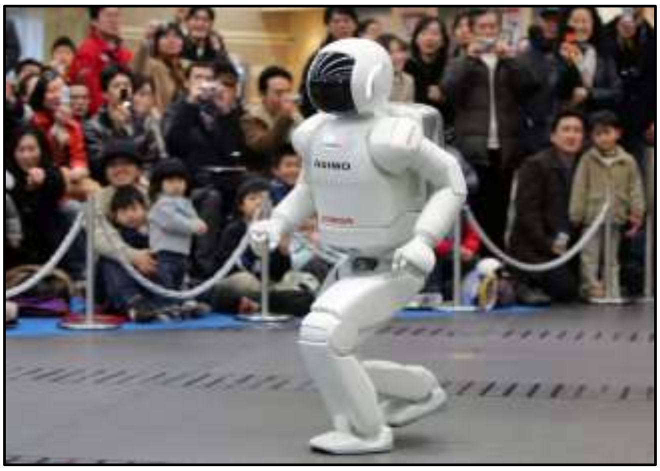

Image 1: Asimo (Furukawa, 2018)

Image 2: TOPIO 3.0 (Reuters, 2015)

However, once again, dynamic stability is an issue in such bipeds because walking on two legs is inherently unstable and requires constant adjustments to maintain balance, unlike in wheel or quadruped robots, which have a much more stable basis of support (Jánoš et al., 2022). To address this challenge, researchers have made several attempts to explore different control strategies and modeling techniques aimed at achieving more reliable and stable walking, as well as enhancing the performance of robots. F. Plestan et al. (2003) proposed a theoretical control law and demonstrated its viability by achieving asymptotically stable walking in an underactuated planar five-link biped robot. Their approach modeled rigid contact and considered the impact of the swing leg as well as an instantaneous double support phase, highlighting how stability could be achieved even in simplified and underactuated systems. Furthermore, a widely adopted framework for evaluating dynamic stability is the concept of the Zero Moment Point (ZMP). This defines the point on the ground where the sum of all active force moments equals zero. Maintaining the ZMP within the support polygon is a standard method for ensuring balance during locomotion. Building on this, K. Mitobe et al. (2000) implemented the ZMP control line in real-time on two different robots, and the experiment showed that stable and smooth motion could be achieved by supplying a reference trajectory for the trunk position, affirming the practicality of ZMP-based control in physical systems. Even S. Kajita et al. (2003) introduced an advanced method of biped locomotion using preview control of the ZMP, employing a simplified cart-table model to predict and adjust for future instability. This method was tested through stimulation of walking on spiral stairs, demonstrating that predictive control could effectively manage dynamic balance even in complex and non-planar environments. Collectively, the studies have made significant contributions to our understanding of how dynamic stability can be achieved in bipedal robots, whether through theoretical modeling, real-time strategies, or predictive planning methods.

Four-legged/Quadruped

While three-legged or tripod locomotion methods do exist, they are not commonly used in robotic design. Instead, four-legged or quadruped robots have been extensively researched due to their inherent stability and adaptability to various environments. One of the earliest well-known quadruped robots was the Sony-developed AIBO, released in 1999. AIBO was primarily designed as a robotic pet combining entertainment features with basic autonomy and limited artificial intelligence (Pransky, 2001). Although AIBO was not the first quadruped robot ever developed, it was one of the first commercially successful quadruped robots, marking a significant breakthrough in consumer robotics and human-robot interaction.

Image 3: AIBO (Sony, 1999)

One of the most advanced and widely recognized quadruped robots in modern robotics research is Big Dog, developed by Boston Dynamics in the mid-2000s and funded by the Defense Advanced Research

Projects Agency (DARPA) (Davies, 2013). Big Dog is a multi-terrain quadruped robot approximately 3 feet long, 2.5 feet tall, and weighing around 240 lbs. It is equipped with over 50 sensors, including inertial sensors, joint sensors, accelerometers, and altimeters, and features an onboard computer for real-time processing (Wooden et al., 2010). Big Dog is typically controlled by a human operator using an Operator Control Unit (OCU) via IP radios. It maintains balance using estimates of its lateral velocity and acceleration derived from the sensed behaviour of its legs. Unlike one-legged and biped robots that struggle with dynamic stability, quadruped robots, such as Big Dog, exhibit inherent dynamic stability, making them highly suitable for rough terrain.

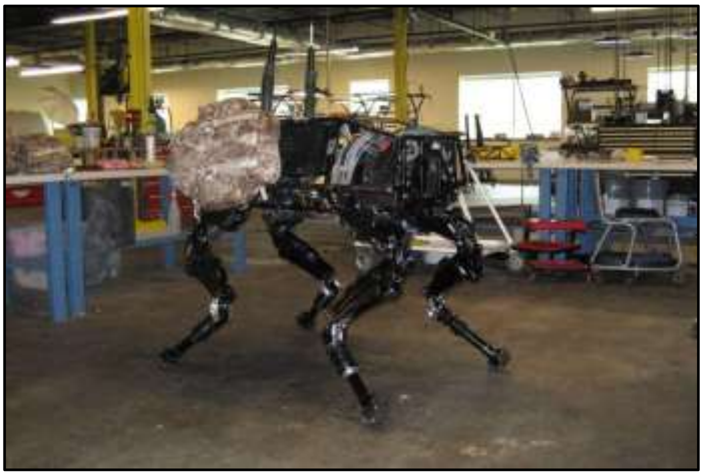

Image 4: BigDog (BostonDynamics, 2023)

According to C. Queiroz et al. (2000), in quadruped robots, at least three legs must remain in contact with the ground at any given time during the static gait. They studied this principle using a 2D+1 model, which imposed certain restrictions on the robot's body configuration and leg movement. Although this model did not provide information about body posture or leg height during phases, it allowed the researchers to develop exhaustive gait sequences and propose an algorithm to determine a stable walking sequence based on foot placement relative to the body.

Six-legged/Hexapod

Lastly, six-legged or hexapod robots represent some of the most stable and widely adopted forms of legged locomotion in robotics. Their static stability is primarily attributed to the use of the tripod gait, in which at least three legs remain in contact with the ground at any given time, ensuring balance, even when the robot is in motion (Nez, Thompson, and Troyer, 2025). While the supports reduce the complexity associated with balance control compared to bipeds or quadrupeds, one of the most significant challenges is in limb coordination, resulting from the high number of possible leg configurations. One notable example of a hexagon robot is RiSE (Robots in Scansorial Environments), a biologically inspired six-legged climbing robot developed by Boston Dynamics in collaboration with several academic institutions and once again funded by DARPA (Saunders et al., 2006). RiSE is designed to climb vertical and horizontal surfaces, including walls and trees. Its design draws inspiration from insect locomotion; the foot and control mechanisms of the robot allow it to grip and adapt to various textures, making it incredibly versatile and suitable for complex environments.

Image 5: RiSE (BostonDynamics, 2023)

To manage the complexity of limb coordination in such robots, researchers have explored decentralized control architectures. As part of this, instead of relying on a single centralized control, the control system is distributed across the robot. Joint controllers are responsible for controlling the rotation angles of individual joints. These are integrated by leg controllers, which determine the overall movement and footprint of each leg. Finally, a gait controller coordinates the output of the individual leg controllers to generate synchronised movement. This modular control hierarchy simplifies the overall control problem by dividing it into manageable subsets, enhancing the robot's adaptability and operational efficiency.

Sensors in Agricultural Robots

While not a mechanical component, sensors are a vital part of mobile robots, working alongside mechanical and control systems to enable autonomy and interaction with the environment. Sensors are devices that detect various environmental properties, including position, distance, motion, and visual data, and then convert them into signals that a robotic system can process (Javaid et al., 2021). By integrating sensor input with control and navigation systems, robots can achieve efficient and intelligent locomotion across diverse terrains and applications. The remainder of the section outlines key categories of sensors used on mobile robots, particularly those relevant to the agricultural industry.

Vision Sensors

Vision sensors enable robots to acquire and process visual information from the environment (Herberger, 2024). The sensors typically consist of a camera lens system, image processing hardware, and software algorithms for interpretation. Vision sensors are capable of identifying objects, determining their orientation and position, and assessing their physical characteristics, such as size, color, and shape. There are two primary types of vision sensors: monochrome and colour vision sensors. Monochrome vision sensors analyse images based on greyscale contrast, making them suitable for detecting object edges, shapes, and lightning variations. Colour vision sensors, on the other hand, separate incoming light into red, green, and blue components, enabling fine distinction between objects based on colour differences even when these are subtle.

GNSS

GNSS, or Global Navigation Satellite System, is a positioning sensor system widely used for outdoor localization, offering accurate real-time position tracking by referencing satellite signals. This system plays a crucial role in guiding robots along predefined paths or uncovering target zones efficiently. Due to its characteristics, GNSS-based machinery guidance has become one of the most widely applied navigation strategies for agricultural robots (dos Santos et al., 2019). When agricultural robots operate in open environments, GNSS can effectively improve the efficiency of resource utilisation and real-time information acquisition (Rovira-Más et al., 2015). That being said, one of the main drawbacks of GNSS-based navigation systems is that they are susceptible to changes in environmental factors, including the physical structure of the environment, obstruction by obstacles, bad weather, and signal interruptions (de Ponte Müller, 2017). Therefore, it is difficult for such systems to provide long-term, robust, and reliable navigation information in an unstructured agricultural environment.

LiDAR

Light detection and ranging (LiDAR) sensors emit laser pulses and measure the time it takes for them to reflect off surrounding objects, thereby creating detailed 3-D maps of the environment (Becher, 2024). This capability allows for precise distance measurement, object detection, and terrain mapping even in low light or variable lighting conditions, making it useful when adopted in agricultural robots. Compared to GNSS, LiDAR provides greater stability in agricultural settings where the GNSS signal is unreliable, weak, or completely obstructed (Wen, Zhang, and Hsu, 2020). This typically occurs in environments with dense vegetation, physical obstructions, or covered areas, such as orchards, vineyards, and covered farms. However, the high cost of the LiDAR sensors currently limits their application in large-scale configuration of agricultural robots (Higuti et al., 2019; Iqbal et al., 2020).

Environmental Sensors

In addition to navigation and positioning systems, agricultural robots may also rely heavily on environmental sensors, which are specifically tailored to meet the needs of certain crops and soils. As part of this, one such category may include Dielectric Soil Moisture Sensors, which are vital for monitoring water content in the soil, as it is a key factor affecting plant health and yield. These sensors detect changes in the dielectric constant of the soil, which correlates with moisture levels. Closely related to this are Soil Temperature and Humidity Sensors, which help manage microclimate in open fields or controlled environments like greenhouses (Cavallo, 2023). These sensors track ambient air conditions, water temperature, and soil heat levels, all parameters that directly influence irrigation decisions and crop growth cycles.

Robotic Arms in Agricultural Robots

Robotic arms are one of the most fundamental mechanical components in the engineering of agricultural robots. These are essentially designed to mimic the motion and function of human arms (Pawar et al., 2018), thereby playing a critical role in automating tasks that are traditionally performed by manual labor (Sun et al., 2022). Through years of technological advancements, robotic arms have become essential for improving operational efficiency, minimising human effort, and enhancing the speed and precision of agricultural processes (Chahal et al., 2023).

In the context of precision farming, specifically, numerous agricultural robotic arms have been developed to meet diverse needs. Their classification depends on application scenarios or operational characteristics. For instance, based on their functional role in the field, robotic arms may be classified as harvesting, weeding, seeding, disease and pest detection, spraying, or plan management arms (Fountas et al., 2020).

Alternatively, classification by mechanical configuration and degree of freedom is also possible, including Descartes robotic arms, joint robotic arms, high-degree-of-freedom combined robotic arms, and multiple robotic arms (Barnett et al., 2020). Another common characterisation is based on the deployment environment, for instance, greenhouse arms, orchard-specific arms, dryland arms, and those designed for paddy fields. Each of these categories reflects design adaptations made to accommodate varied terrains, crop types, and climate conditions.
To meet the highly variable and unpredictable nature of agricultural environments, robotic arms must demonstrate superior adaptability, accurate manipulation, and reliable obstacle navigation. Modern agriculture robotic arms are therefore typically developed using integrated systems that combine advanced hardware with intelligent software. The core hardware structure typically consists of manipulators (Dam, 2024), which can be rigid or soft, as well as various actuators, including electric motors, hydraulic systems, and pneumatics (Baker, 2019). It also includes diverse end-effectors, including grippers, cutters, sprayers, and suction tools, along with an array of sensors for perception and feedback. The software architecture encompasses algorithms for perception, motion planning, and control, all of which are coordinated by a central controller to ensure seamless interaction between the robot and its environment (Lytridis et al., 2021).
Despite rapid progress, several technical challenges persist in deploying robotic arms for precision agriculture (Maffezzoli et al., 2022). One of the significant issues is the inability to adapt to dynamic and unpredictable conditions in real-time. Variability in crop morphology, environmental disturbances, and uncertain terrain conditions can introduce errors in perception and decision-making. Safety is another concern, especially when robotic arms are operating in close proximity to human workers. Addressing these challenges requires a holistic approach consisting of refining the mechanical design and software logic, conducting detailed system analysis, and performing cost-benefit evaluations to ensure practicality, reliability, and field deployment.

Agricultural Robots for India

India has a vast agricultural sector and a growing population. The country, therefore, faces mounting pressure to maintain and enhance food productivity. According to land use statistics, the nation's land area has decreased from its peak of 184.8 million hectares in 1975 to 179.9 million hectares in 2022-2023, despite rising demographic demands (Mordor Intelligence, 2025). This decline, coupled with the adverse impact of climate change and a noticeable decline in youth participation due to the labour-intensive nature of agriculture, has intensified the urgency to adopt innovative and resource-efficient agricultural technologies. In this context, agricultural robots have emerged as a promising solution to address key productivity challenges. These technologies can reduce manual effort, enhance precision, and attract a new generation to farming through smart-tech-enabled approaches.
India’s agricultural robotics market is witnessing rapid growth, projected to expand at a CAGR of 20.99% from 2022 to 2028, potentially generating over 555 million in revenue by 2028 (INKWOOD RESEARCH, 2024). Many innovations have been introduced, including autonomous tractors, robotic harvesters, unmanned aerial vehicles (UAVs), and automated milking systems. Despite these advancements, several barriers continue to limit the widespread adoption of agricultural robots in the country (Sahoo et al., 2023). Firstly, cost and affordability remain major issues for small and marginal farmers, who make up the majority of India’s agrarian workforce, as they are often unable to access this technology due to higher upfront investment costs. Limited awareness and technical knowledge about the utility operation and

maintenance of agricultural robots, especially in rural and similar communities, further hampers adoption. Customisation for diverse crops is another issue, with India's agricultural diversity spanning multiple regions, crop types, and cultivation methods requiring region-specific robotic adaptations. Integration with traditional practices may also present barriers, and many farmers may also be hesitant to replace long-standing methods with unfamiliar technologies, especially if they require significant operational changes. Power supply and energy efficiency constraints also affect robot functionality in off-grid regions. The need for solar-powered or energy-efficient designs is essential for broader implementation.

The custom-designed agricultural robot below, tailored explicitly for India, directly addresses many of the barriers currently hindering widespread adoption. Wheels should be the chosen form of locomotion. While they are not the usual choice for uneven terrains, which is what much of India's farmland has, rugged wheels can offer good maneuverability, better traction, and stability. Indian farms also experience a wide range of weather patterns, from dry, cracked soil to wet, flooded fields during the monsoon. Once again, these wheels can adapt to these changing conditions far better than smooth or light-duty wheels. There is also a cost-benefit of selecting rugged wheels. Firstly, they are cheaper than legged locomotion. Secondly, although they may be more expensive initially than basic wheels, rugged wheels can reduce downtime and damage, making them more economical in the long run, which is quite important for the target audience of such robots. Affordability can be further enhanced by incorporating modular competence and locally sourced, low-cost materials, which can reduce production and maintenance costs.

Furthermore, the solar-powered energy system ensures functionality in rural areas where unreliable electricity might otherwise hinder operations. The offline compatible control system and basic touchscreen interface with regional language support can be integrated to overcome digital literacy and connectivity issues. Lastly, the interchangeable end-effectors on the robotic arm, ranging from weeders to seeders and sprayers, enable customization for diverse crops and farming practices, thereby enhancing its adaptability across India's agricultural regions and reducing the cost of investing in multiple robots for various functions.

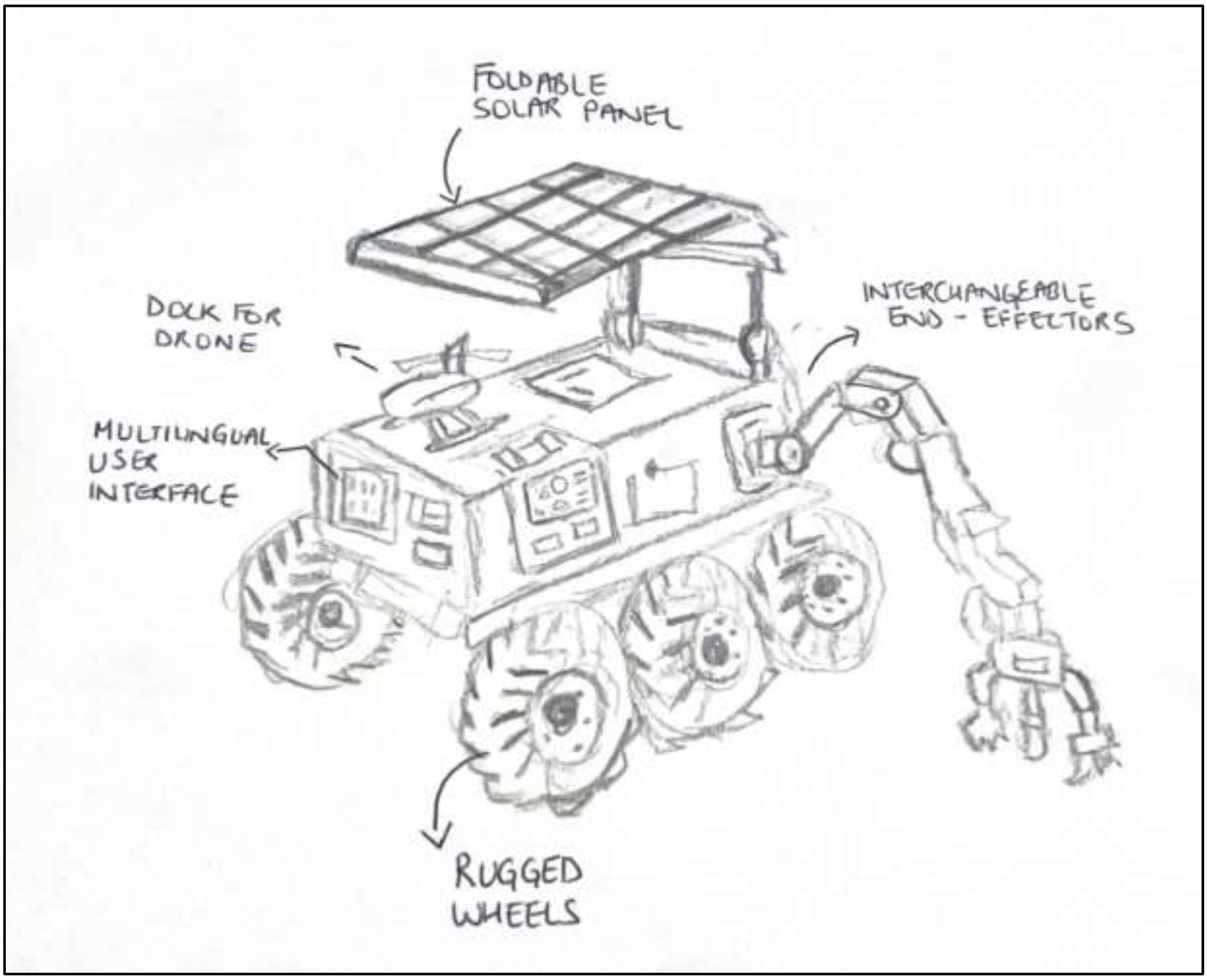

Image 6: Sketch of an agricultural robot for India

It is vital for such design elements to be well executed as part of a multi-pronged strategy, also integrating education, accessibility, and support. Government agencies, agri-tech companies, and local cooperatives should collaborate on extensive training and capacity-building programs tailored to rural contexts. These should include hands-on demonstrations, multilingual support materials, and mobile advisory units. Furthermore, subsidies and low-interest financing may also be made available to farmers to make the robots more accessible. Lastly, involving the local youth in the operation and servicing of agricultural robots can not only generate employment but also encourage community ownership. Establishing rural tech hubs that provide technical support, repair services, and spare parts can ensure reliability and long-term usability.

Conclusion

This paper explored the core mechanical and scientific principles that underpin agricultural robotics, including locomotion, sensor integration, and robotic arms, while contextualizing these components within India's unique agricultural landscape.

India's agricultural sector is at a crossroads, grappling with decreasing cultivable land, climate unpredictability, and a declining rural labor force. While agri-robots offer a viable solution, widespread deployment is hindered by affordability, lack of technical know-how, limited infrastructure, and low perception of value among farmers. This paper responds by proposing a conceptual robot tailored for India, designed with rugged wheels, solar-powered functionality, multilingual interfaces, and modular robotic arms capable of switching end-effectors. This model directly addresses key adoption barriers through thoughtful mechanical design.

However, technology alone is not sufficient. The proposed solution must be supported by robust policies, ranging from subsidies and public-private partnerships to rural training programs and regulatory frameworks that ensure accessibility, data security, and long-term sustainability.

In conclusion, agricultural robots, when engineered with contextual relevance and supported by inclusive policy, can help India's farming sector transition into a more efficient, resilient, and future-ready industry.

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