DESIGN AND MANUFACTURING OF SEED SOWING MECHANISM FOR AGRI-ROBOT

A Final Year Project Report

Presented to

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In Partial Fulfillment
of the Requirements for the Degree of
Bachelor's of Mechanical Engineering

by

Sulaymaan Ahmad
Ahmad Ureeb
Muhammad Aarij bin Nasir
Mahnoor Majid

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EXAMINATION COMMITTEE

We hereby recommend that final year project report prepared under our supervision by:

SULAYMAAN AHMAD	293413.
AHMAD UREEB	294907.
MUHAMMAD AARIJ BIN NASIR	283155.
MAHNOOR MAJID	301192.

Titled: "Design and Manufacturing of Seed Sowing Mechanism for Agri-Robot" be accepted in partial fulfillment of the requirements for the award of Bachelor's in Mechanical Engineering degree with grade ___

Supervisor: Dr. Sara Ali, Assistant Professor SMME	____________________ Dated:
Committee Member: Name, Title (faculty rank) Affiliation	____________________ Dated:
Committee Member: Name, Title (faculty rank) Affiliation	____________________ Dated:

____________________ (Head of Department)

__________ (Date)

COUNTERSIGNED

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ABSTRACT

The agricultural sector plays an important role in the economy of Pakistan in terms of GDP, employment, export earnings, and food security. However, the sector has remained largely underdeveloped in terms of technological advances. The Agri Rover 2023 aims to tackle this issue by automating the critical process of seed sowing. It will do this by moving continuously to create a furrow, dispense seeds, and cover them with soil. This will result in reduced seed wastage, costs, and time while increasing revenue and productivity. The design of the rover was adapted from the Mars Perseverance rover owing to its ability to traverse uneven terrain and the stability of its six-wheeled design. For the design of the seed-sowing components, an extensive literature review was conducted to decide the optimal method of furrowing, dispensing, and leveling. The initial design was then proposed and further built upon to make the device more accurate, reliable, easy to use, and adaptable for different crops. The final design used a furrowing wheel, a seed dispensing mechanism, and a leveling plate to carry out automatic seed sowing. Calculations and parametric studies were carried out to finalize the design and material selection. After a market survey, initial manufacturing was started. Once the working prototype has been constructed, it will be tested in phases. The rover has immense potential to disrupt the market and be developed further. Additional features can be implemented such as fully autonomous rover operation, obstacle detection, and solar-powered charging.

ACKNOWLEDGEMENTS

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This project would not have had the impact we wanted it to have without the support of the above-mentioned parties.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

FYP	Final Year Project
GDP	Gross Domestic Product
PLA	Polylactic Acid
ABS	Acrylonitrile Butadiene Styrene
PETG	Glycol-modified PET
TPU	Thermoplastic Polyurethane
FDM	Fused Deposition Modelling
COG	Centre of Gravity
CNC	Computer Numeric Control
CAD	Computer Aided Design
RC	Radio Controlled
PVC	Poly Vinyl Chloride
DC	Direct Current

NOMENCLATURE

L	Rover wheelbase (m)
T	Rover track width (m)
R	Turning radius (m)
V_{turn}	Velocity of rover during turning (m/s)
$V_{f,in}$	Velocity of inner front wheel during turning (m/s)
$V_{r,in}$	Velocity of inner rear wheel during turning (m/s)
$V_{f,out}$	Velocity of outer front wheel during turning (m/s)
$V_{r,out}$	Velocity of outer rear wheel during turning (m/s)
N	Number of revolutions per minute of motor
$\varphi_{f,in}$	Angle of rotation of inner front wheel for turning
$\varphi_{r,in}$	Angle of rotation of inner rear wheel for turning
$\varphi_{f,out}$	Angle of rotation of outer front wheel for turning
$\varphi_{r,out}$	Angle of rotation of outer rear wheel for turning
μ	Coefficient of friction between rover wheel and soil
θ	Banking angle
$v_{roll,h}$	Rover roll over velocity on horizontal track (m/s)
$v_{skid,h}$	Rover skid velocity on horizontal track (m/s)
$v_{roll,b}$	Rover roll over velocity on banked track (m/s)
$v_{skid,b}$	Rover skid velocity on banked track (m/s)

h	Furrow depth (cm)
r	Furrow opener disc cutting radius (cm)
λ	Kinetic parameter for rolling disc
δ	Friction angle
R_x	Cutting soil resistance (N)
N	Normal force cutting on unit segment of disc cutting edge (N)
u_0	Cutting soil resistance calculation parameter
u_1	Cutting soil resistance calculation parameter
u_2	Cutting soil resistance calculation parameter

CHAPTER 1: INTRODUCTION

Motivation

With a strong grasp of engineering principles, proficiency in important software, and a view of the industrial landscape of the country through multiple internships, the members of this group wanted their FYP to incorporate different disciplines and create a novel engineering device that would tackle real-world problems and therefore have the potential to create an impact on a large scale. This drove the group to brainstorm and develop its own ideas for potential innovations that could be pitched to the department.

The group consensus favored the disciplines of robotics and automation in conjunction with control systems, recognizing the combination to be a powerful way of bringing technology into existing processes along with the associated benefits of increased quality and reliability of work and reduced time and costs. Additionally, the importance of mechanical design was also clear as a necessary component of any applied solution. Previous experience in the form of projects within this field, particularly in the design and implementation of control systems using microcontrollers, also provided some confidence to the group and furthered its willingness to use similar principles on a larger scale.

In terms of potential sectors for which the project could be positioned, the agricultural sector stood out for two major reasons:

1. The sector was immensely important in the context of Pakistan, incorporating a large portion of the population and having a direct impact on the economy of the country.
2. The sector had remained neglected in terms of technology, with very little innovation and progress being seen in recent years.

These factors presented a huge opportunity for us to pitch a solution that could have an impact in this ever-important field.

Problem Statement

Agriculture plays a vital role in Pakistan's economy, providing employment to almost 37.4% of the workforce and contributing 22.7% to the country's GDP [1]. The agricultural sector is the largest source of foreign exchange earnings, with up to 70% of the country's total export earnings coming from agricultural products [2]. Agriculture is critical to Pakistan's food security, as it provides food for domestic consumption. Hence, the development and modernization of the agricultural sector is essential to ensure sustainable economic growth and improve the livelihoods of Pakistan's people.

However, the sector has remained largely underdeveloped in terms of technology and automation, with the latter only visible in the form of heavy machinery on large areas of land, and manual labor still taking precedence in most settings. This is something that we wanted to address with our FYP, which aimed to automate a very crucial agricultural process: seed-sowing.

Currently, seed sowing is done largely through manual labor. Farmers either disperse handfuls of seed on their land or sow a few at a time at designated spots with their hands. Both methods have major drawbacks in the form of time consumption and labor costs. More importantly, a significant portion of these seeds fail to germinate. In fact, sowing seeds through traditional methods can result in 25-30% seed wastage [3]. Moreover, improper seed depth and spacing can reduce yields by 21-24%, and soil compaction caused by heavy machinery can reduce yields by up to 17-20% [4], [5]. All of these losses mean increased costs and reduced revenue for the farmer, which also decreases the agricultural output from the sector as a whole.

We knew that with the technology at our disposal today, there had to be a better solution.

Objectives

The project will meet four distinct deliverables:

1. **Design of Agri Rover**: design and fabrication of a wheeled rover that can easily traverse agricultural land while being reasonably stable and able to bear the weight of itself, the seed sowing modules, and the seeds that it will carry.
2. **Design of seed sowing mechanism**: conceptualization, design, and fabrication of attachable components for furrowing, seed dispensing, and soil leveling.
3. **Implementation of a control architecture for seed sowing module**: design, coding, and circuitry of a suitable control system that dispenses seeds at the correct rate based on the speed of the rover and the required inter-seed spacing.
4. **Integration of all three systems into a working prototype**: physical attachment and control system integration for all seed-sowing modules with the rover.

In addition, the group established some base principles which it wanted to use to guide future efforts in the design of the rover. They are as follows:

1. **Accuracy**: the rover should have great accuracy in terms of the sowing location and the depth of the seed. These factors have a direct impact on the germination rate of seeds and therefore will have the greatest effect on the success of the project.
2. **Adaptability**: the rover should be able to accommodate different types of seeds while ensuring that they are sown at their optimal depths and with the desired spacing. This will make the product more versatile and hence provide more value to the end user.
3. **Ease of use**: considering that the expected userbase of the rover is farmers, it should be easy to use and require minimal training to operate. This means that the rover should minimize dependency on the farmer, which will speed up market adoption.
4. **Reliability**: the rover should be of a rugged and robust design that can sustain the use conditions of agricultural land. It should also not be unnecessarily complex in terms of its design and operation. This will ensure that the rover provides longevity to the user and requires less maintenance.

CHAPTER 2: LITERATURE REVIEW

The literature review conducted focuses on the development, design, and implementation of autonomous seed-sowing robots, as well as on the selection and performance evaluation of different mechanisms for different steps involved in the seed-sowing process.

The act of sowing seeds can be broken down into three steps: digging or creating a furrow in the soil for the seed, dropping the seed in that space, and, finally, covering the seed with soil. For each of these steps, different potential mechanisms were studied to shortlist the optimum designs for our agricultural rover based on currently available research.

Rover

Agricultural fields are usually uneven, with remnants of crop residue from the previous harvest as well as rocks and hardened clusters of soil, hence, the rover needs to be capable of traversing through such uneven ground. Moreover, since the farmlands in Pakistan are irregularly shaped, the rover needs to have high maneuverability so it can cut sharp corners. It also needs to have a small turning radius to optimize land usage and increase yield with the minimum required inter-row distance for the particular crop.

Since the rover needs to be all-terrain, the Mars rovers developed by NASA are the prime example of such a vehicle as it has been designed to move on the rugged surface of Mars. The design of a Mars rover was discussed in a paper that described the various challenges of designing a roust rover for the harsh environment of Mars [6]. The authors proposed a design for a rover that would use solar panels to generate electricity, and a six-wheeled drive system for mobility (Figure 1). The study showed that the stability, mobility, and terrain adaptability of a vehicle depend mainly on its wheelbase.

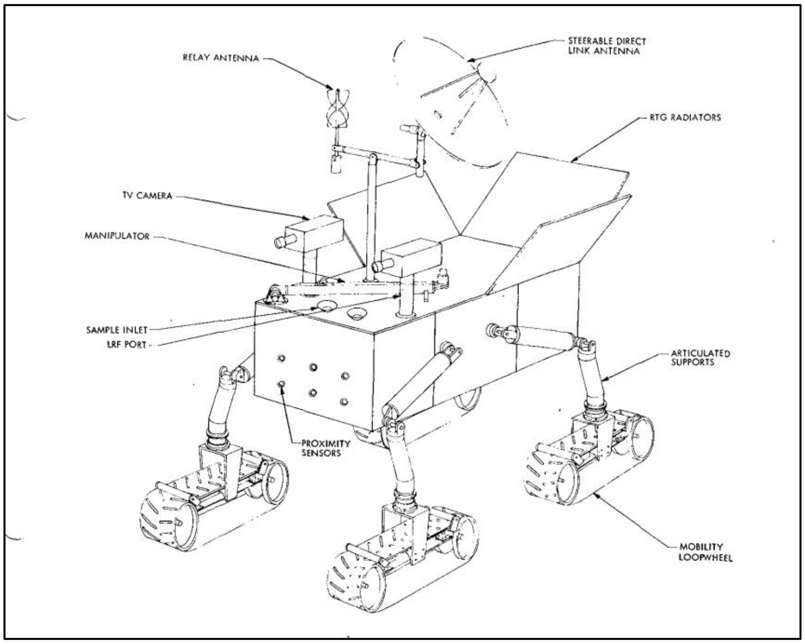


Figure 1: Proposed Mars rover design [6]

Another study that was conducted reinforced the influence of the wheelbase on vehicle maneuverability and steering performance by holding a comparison of a six-wheel drive vehicle to a conventional four-wheel drive vehicle [7]. Two different arrangements of six wheels were used for the experiment: one with the third pair of wheels placed at the rear and the other with the third pair of wheels placed in the middle of the wheelbase. The study aimed to compare the turning radius, stability, and control of the six-wheel drive vehicle with the four-wheel drive vehicle under different steering conditions. The results showed that the six-wheel drive vehicle with two pairs of wheels at the rear had the largest turning radius (5.03 m), followed by the six-wheel drive vehicle with a pair of wheels in the middle (4.96 m) and the four-wheel drive vehicle (4.81 m). However, the six-wheel drive vehicle with wheels in the middle had better stability and control in challenging terrain conditions. Additionally, the six-wheel drive vehicle exhibited better maneuverability and traction performance than the four-wheel drive vehicle. The study concluded that a six-wheel drive vehicle could be a better alternative to a conventional four-wheel drive vehicle in challenging off-road conditions.

Rover Motion and Digging Mechanism

Digging to a certain depth to sow seeds for optimum seed germination is the first step in the seed-sowing process. Upon our research, we discovered that there are two possible mechanisms of achieving this; through drilling individual holes at set intervals or by creating a continuous furrow in the soil.

Two separate experiments had been conducted on the former type of digging mechanism on a seed-sowing agricultural rover. One of the rovers designed used a drill-like mechanism along with a motor to move the drill bit up and down, thereby creating a hole in the soil [8]. The other rover used a rack-and-pinion mechanism coupled with a plunger to create a hole as shown below in Figure 2 [9].

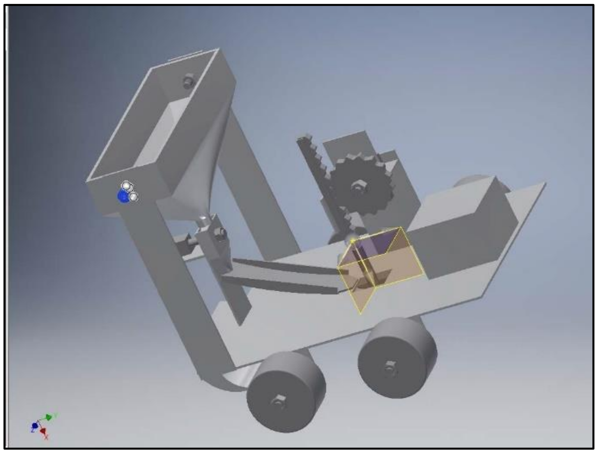


Figure 2: Agricultural rover with rack-and-pinion digging mechanism [9]

Both of the rovers described exhibited step-wise motion as they stop after a predetermined distance to dig the hole and then drop the seed before moving ahead to repeat the same procedure for the next seed. Due to this motion, such a design offers higher accuracy and precision, but it is a very time-consuming process. On the other hand, furrow-creating mechanisms as described in several other literatures (elaborated under Furrow Openers) create a continuous narrow line in the soil at a constant depth. Since their motion is continuous, they result in a faster seed-sowing process, however, they offer lower accuracy and precision compared to the rovers with step-wise motion. Despite this decrease, they still offer the accuracy and precision that is required in agriculture and the variation is still much lower than the manual methods or seed drill machines currently used to sow seeds.

Based on the advantages and disadvantages of both designs, the furrow opener mechanism seemed to be the optimum choice for our seed-sowing agricultural rover as it offers good precision and accuracy in less time.

Furrow Opener

Currently, the most commonly used planting machinery in modern agriculture is the tractor-drawn seed drill. According to a report, the key components of these machines include planting units, seed meters, seed hoppers, and fertilizer applicators [10]. The report also covered the different types of furrowing mechanisms. These furrow openers can be classified into two major categories, namely wedge and disc types, each of which is further divided into different types based on their shape as can be seen in Figure 3.

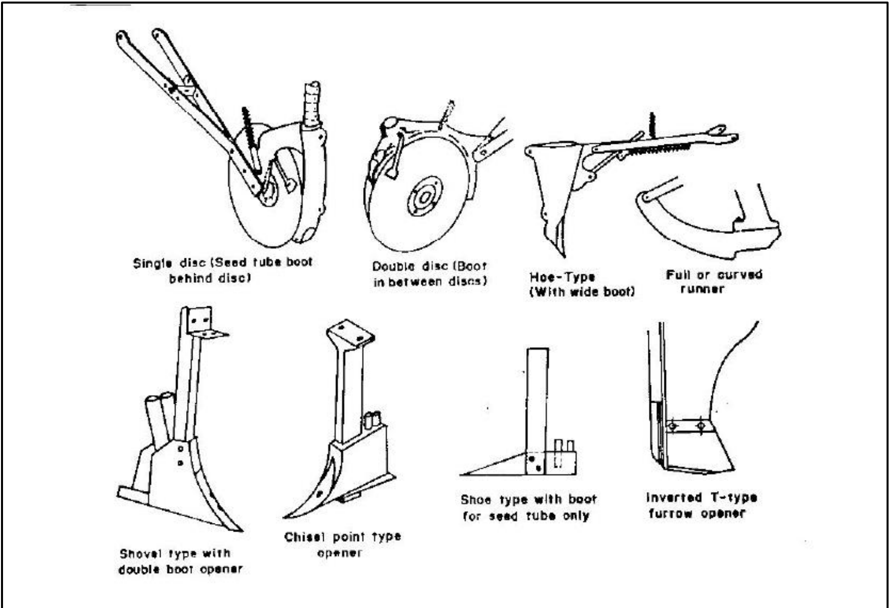


Figure 3: Different types of furrow openers [10]

The choice of furrow opener depends on the specific soil conditions and planting requirements. The two main categories of furrow openers were compared in a study that investigated the effects of a hoe furrow opener with a double disc furrow opener on the soil disturbance of a sandy loam Ultisol soil under a no-tillage system [11]. These furrow openers were tested on seed drills under different coulter combinations i.e. no coulter, smooth coulter, and fluted coulter (Figure 4). Field experiments were conducted in southern Brazil by observing the soil displacement and compaction caused by the opening of a furrow along with the soil structure and density. Soil displacement and compaction impede seed germination, hence, a design that results in less soil displacement and compaction is deemed as the better design. The study found that the disturbed area was affected by the type of furrow opener. The hoe opener resulted in greater soil disturbance and furrow width (0.26 m) as compared to the double disc opener (0.24 m). The study also showed that the use of coulters resulted in a reduction of soil swelling by approximately 8% in the case of the smooth and 20% for the fluted coulter, however, they increased the furrow width.

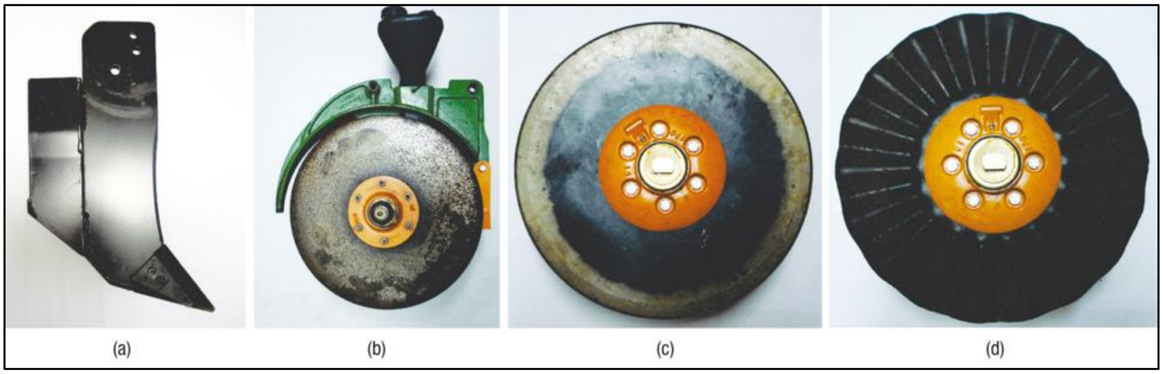


Figure 4: Hoe furrow opener (a), mismatched double-disc furrow opener (b), smooth coulter (c), offset fluted coulter (d) [11]

Similarly, another experiment conducted a comparison between an inverted T-type furrow opener with a smooth rolling coulter, a single disc furrow opener, a double disc furrow opener, and a double disc furrow opener with a smooth rolling coulter at different speeds [12]. The study also measured the levels of moisture retained by the soil before and after furrowing for any losses as adequate moisture promotes seed germination. According to the paper, the initial soil moisture content in the soil was 12% and after 24 hours of furrowing, the remaining moisture was 11.2% for the double disk furrow opener with smooth rolling coulter, 10.61% for the double disk furrow opener, 10.18% for single disc furrow opener, and 9.35% for the inverted T-type furrow opener with smooth rolling coulter. Moreover, the highest soil penetration resistance was experienced by the double disk furrow opener with smooth rolling coulter (1.36 MPa), compared to double disk furrow opener (1.3 MPa), single disk furrow opener (1.21 MPa) and inverted T-type furrow opener with smooth rolling coulter. Furthermore, the widest furrow was produced by the inverted T-type furrow opener with smooth rolling coulter (30 mm) followed by single disk furrow opener (25 mm), double disk furrow opener (20 mm), and double disk furrow opener with plain rolling coulter (16 mm). It is evident from these experiments that disc type furrow openers perform better than wedge type openers with or without coulters as they cause less soil displacement and swelling, less moisture loss, and experience less resistance although they do not penetrate as deep as wedge type furrow openers.

So far the comparisons had been with smooth disc furrow openers but these can have several variations as well. A study compared the performance of different disc-type furrow openers for no-till paddy field conditions [13]. The study was conducted in China and involved testing four different types of furrow openers: notched, toothed, smooth-edge single disc, and double disc at three different speeds (Figure 5). The study showed that the type of furrow opener, its operating depth, and its speed affect the forces acting on it and its cutting ability. The highest vertical force was observed on the double disc opener followed by notched-type, toothed-type, and smooth single disc furrow openers. Moreover, the experiment showed mean straw-cutting efficiencies of the notched, toothed, smooth single disc and double disc furrow openers to be 12.4, 46.2, 11.4, and 78.5%, respectively. Therefore, this study concluded that the double disc furrow opener had the best performance in comparison with other furrow openers as it offered a significantly higher cutting efficiency than the other types.

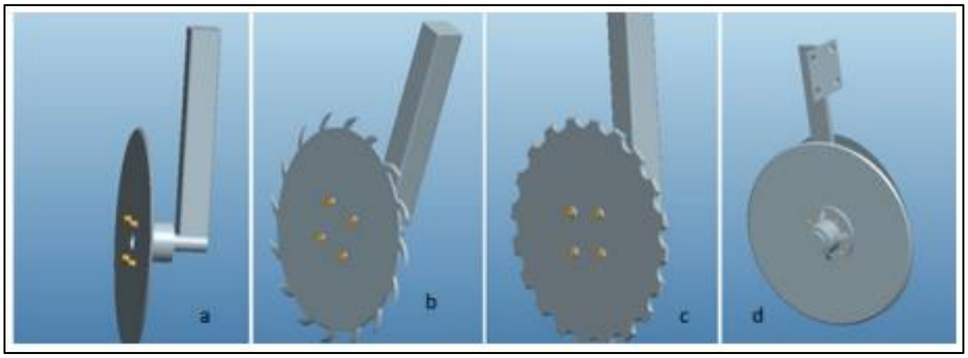


Figure 5: 3D view of furrow openers: (a) smooth-edge single disc; (b) tooth-type; (c) notched-type; (d) smooth-edge double disc [13]

Seed Metering

Seed metering is used to separate individual or a set number of seeds from the container they are stored in and drop them to be planted into the soil. Several different mechanisms can be used for this purpose. A certain study used two separate plates placed horizontally, one on top of the other, inside a conical flask as can be seen in Figure 6 [14]. The bottom plate is stationary while the top plate is connected to a motor. Both plates have a hole punched in them and are placed under the seed tank. As the upper plate rotates and the holes align, a seed is dropped through the hole at the location for planting. The results showed that the robot was able to accurately identify the planting locations and deposit seeds in the soil with high accuracy. It also reduced sowing times to one-third of the time taken to sow a similar field area manually.

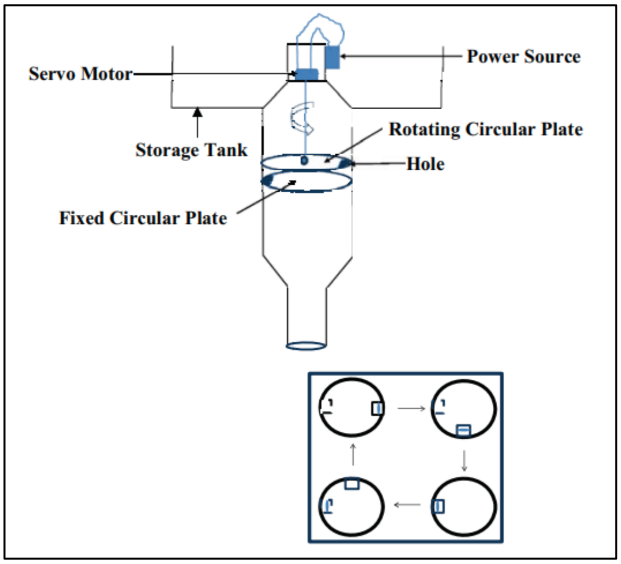


Figure 6: Seed metering mechanism with double discs [14]

In another study, a disc with a single notch the same size as the target seed was used for the seed dispensing mechanism [9]. It was connected to a motor and placed in a funnel that was attached to the seed tank such that the disc's axis of rotation was perpendicular to the tank. When the notch in the disc faced up in the seed tank, it would fill up with a seed, move the seed with it, and after a 180° turn, the seed would drop under gravity, and this process would be repeated for all seeds. The system was tested in a field, and the authors measured the time taken by the robot to sow seeds in the given area and compared it with the time taken by manual labor. The results showed that the robot was significantly faster than manual labor, indicating its potential to improve the efficiency of seed sowing.

Another paper proposed a mechanism that uses a combination of two plates and a seed picker for its seed dispensing system as shown in Figure 7 [15]. The seeds are transported from the hole in the first plate which lets the seed settle into the jaw of the picker. The seed picker then rotates 180°, allowing the seed to come in line with the hole in the other plate and drop into the furrow. Furthermore, different seed picker jaws can be used for different seed types. Similar to the previous design, the results showed that the robot was able to sow seeds with high accuracy and consistency and the robot's efficiency was also found to be significantly higher than manual sowing accompanied by a reduction in sowing time.

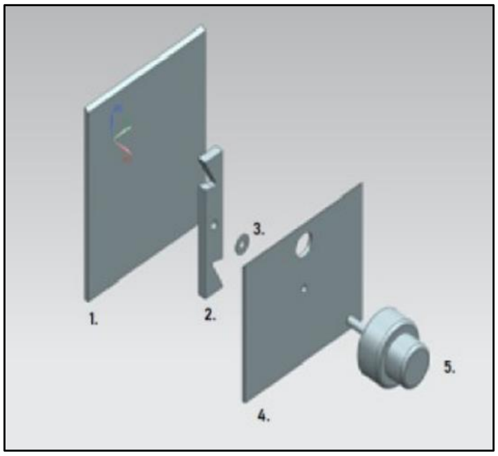


Figure 7: Seed metering mechanism with two-jawed seed picker [15]

Furthermore, another experiment was conducted to observe the use of a robotic arm to sow seeds [16]. The robot is designed to be lightweight and portable, allowing for easy transportation and operation in the field. It uses a rotary mechanism to pick up and dispense the seeds, which are held in a tank. The seed spacing is controlled by adjusting the speed of the rotary mechanism of the robotic arm and can be customized for different crop requirements. The experiments showed that the robot can efficiently sow seeds of various sizes and adjust the seed spacing as per crop requirements.

Leveler

The purpose of a leveler is to gather the soil that is displaced during furrowing, and use it to fill the furrow and cover the seed to prevent the seed from being eroded by the wind or picked by a bird. Hence, the leveler is attached at the end of the rover in a design presented in a paper [14]. Their design is rather simplistic as shown below in Figure 8. The leveler is made from a sheet of glass fiber and connected to the rover with a hinge-like mechanism so that it could move up and down without getting damaged or needing to use more force to move in case of any obstacles that may fall in its path and get stuck.

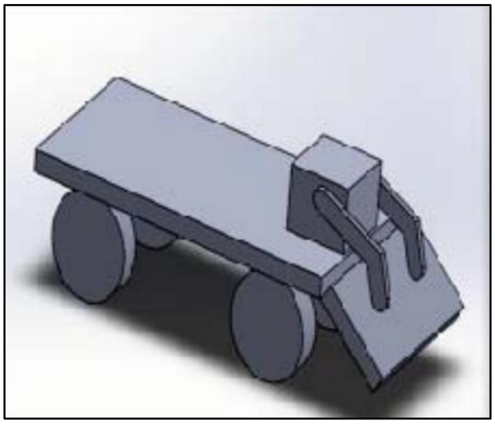


Figure 8: Leveler design [14]

CHAPTER 3: METHODOLOGY

Initial Design

The design of our Agri-Rover is derived from the research conducted, however, the majority of the reviewed literature includes furrowing mechanisms on seed drill machines driven by tractors causing soil compaction, or on slow agricultural rovers with step-wise motion. Hence, our goal: integrate furrow openers onto a high-speed rover for precise, accurate seeding without compromising speed or causing soil compaction.

Rover

The selection of a 6-wheeled rover design was based on several factors, including mobility on rough terrain, stability, and load capacity. The advantages of the chosen design are as follows:

1. **Improved mobility:** The additional set of wheels allows for better weight distribution, leading to enhanced traction and stability on rough terrain. This enables the rover to navigate difficult and steep surfaces like rocks and slopes.
2. **Better load capacity:** The extra wheels distribute the load more evenly, resulting in an increased weight capacity for the rover.
3. **Redundancy:** A 6-wheeled rover design may incorporate redundancy, meaning it can continue functioning even if one or more wheels fail. This improves the reliability and lifespan of the rover.
4. **Flexibility:** The additional wheels offer greater flexibility in terms of movement and turning capabilities. The rover can make tighter turns and maneuver around obstacles more easily.
5. **Stability:** Having more wheels in contact with the ground enhances stability, particularly on uneven or slippery surfaces. This reduces the risk of tipping over or becoming stuck. [17]

Our finalized rover design is based on the Mars Perseverance rover, which is an open-source design. This design was selected because of the aforementioned perks it offers, making it the optimum choice for our application as the Agri-Rover will be used on uneven agricultural land. Figure 9 shows our rover design.

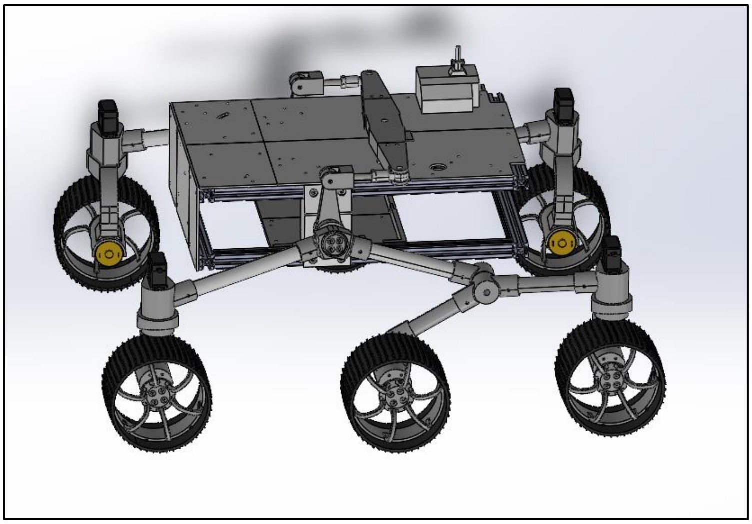


Figure 9: A 6-wheeled Rover skeleton designed on Solidworks 2021

Furrow Opener

The furrow opener is a critical component of the design, responsible for creating furrows at the desired depth for planting crop seeds. After considering two options, wedge type and disc type, the disc type furrow opener was chosen for the Agri-Rover due to the following advantages:

1. **Reduced soil displacement and compaction:** The disc type furrow opener causes less soil displacement compared to the wedge type, minimizing the loss of essential nutrients through erosion.
2. **Less soil compaction:** The disc type furrow opener causes less soil compaction, which is crucial for water absorption and nutrient uptake by seeds and plants.

3. **Lower resistance:** The disc type furrow opener experiences less resistive force compared to the wedge type, as it slices through the soil instead of pushing through it.
4. **Decreased moisture loss:** With less soil displacement, the disc type furrow opener results in reduced moisture loss from the soil compared to the wedge type.

In addition to selecting the suitable furrow opener, the design incorporates flexibility in sowing depth by including multiple slots in the attachment assembly. Adjusting the position of the attachment arm allows for different penetration depths. The size and thickness of the furrow opener were determined based on the required furrow width.

Initially, there were plans to motorize the wheel to spin in the opposite direction of the rover's motion, similar to a circular saw. However, this idea was abandoned to maintain a simpler and more robust design for the Agri-Rover, avoiding the complexity and potential wear and tear associated with connecting a motor to the furrow opener.

The complete furrow opener and its attachment assembly can be seen in Figure 10.

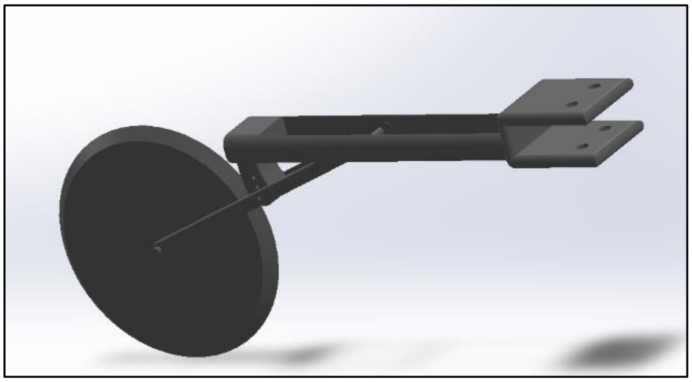


Figure 10: Furrowing wheel design on ProE

Seed Dispensing Mechanism

The Seed Dispensary Mechanism (SDM) plays a crucial role in collecting and dropping seeds with precision to achieve the desired inter-seed distance for successful germination.

After reviewing various designs from literature, a modified version was developed for the project.

Figure 11 depicts the SDM design, including the seed storage tank that narrows down to a funnel. The key component of the SDM is the wheel, which separates individual seeds and transfers them to the delivery chute for dropping into the furrow. The wheel features four bores positioned at 90° angles from each other, capable of accommodating seeds of maximum size. It is connected to a stepper motor. When a bore opening aligns with the funnel opening, a seed enters the bore, and as the wheel rotates, it carries the seed. The seed is released when the bore aligns with the delivery chute opening, allowing it to drop into the furrow.

The dispensing rate of the SDM wheel is determined by the distance covered by the rover, ensuring that seeds are dropped at the specified inter-seed distance.

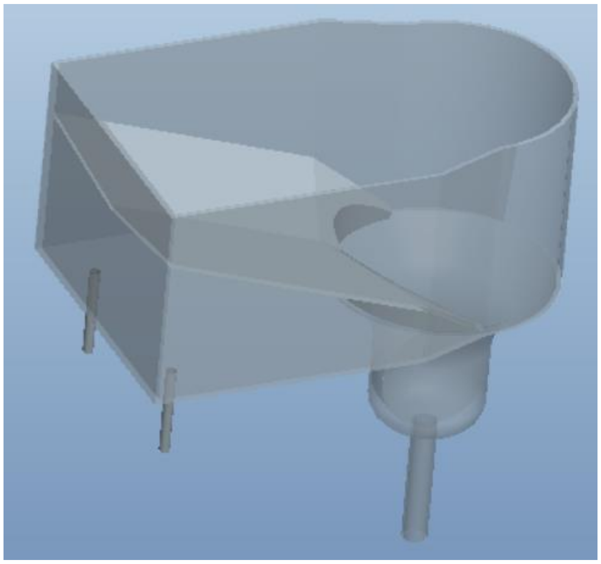


Figure 11: SDM designed on ProE

Leveler

The leveler plays a crucial role in our Agri-Rover by covering the furrow with soil to protect the dropped seeds from exposure to the atmosphere and erosion, promoting proper germination. Unlike a simple rectangular leveler design found in some literature, our design features two V-shaped plates arranged at an angle to each other, as depicted in Figure 12. This design effectively collects displaced soil and directs it towards the furrow, ensuring complete coverage. Additionally, a damper is incorporated to mitigate vibrations caused by uneven terrain, keeping the plates in contact with the ground and ensuring thorough furrow coverage.

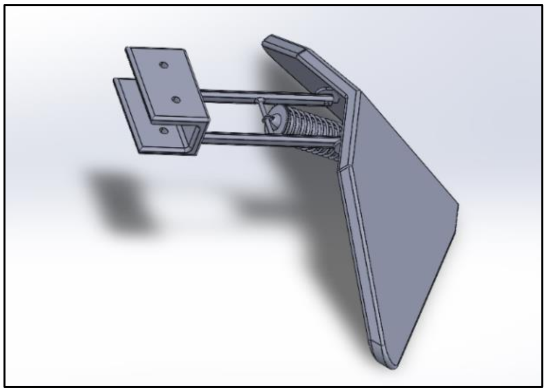


Figure 12: Leveler designed on ProE

Assembly

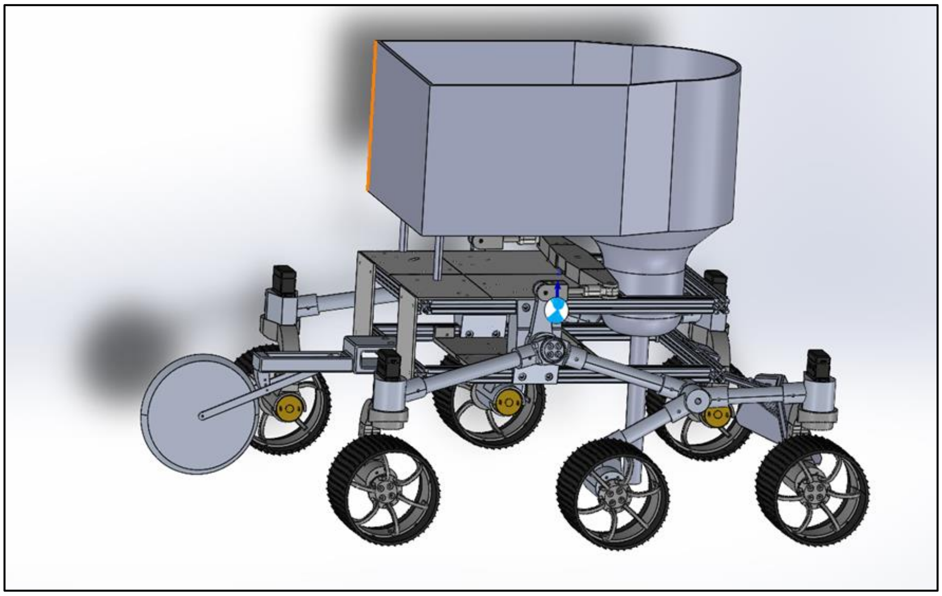


Figure 13: Rover design

The Agri-Rover design assembly, depicted in Figure 13, consists of two modules: the rover and the seed-sowing module. The rover utilizes a six-wheel rocker-bogie design, enabling it to navigate rough and uneven agricultural terrain. The seed-sowing module comprises the furrow opener positioned at the front of the rover, the SDM (Seed Dispensary Mechanism) in the middle, and the leveler at the back. These components work in tandem with the rover's movement to achieve the desired seed depth and inter-seed distance, thereby enhancing crop yield.

Calculations

Rover Turning

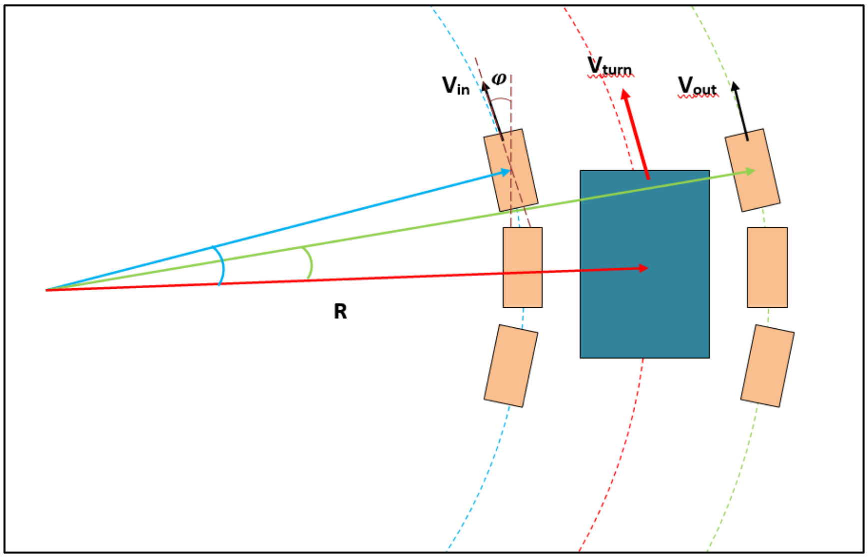


Figure 14: Rover turning radius

Taking T = 0.69 m, L = 0.79 m, R = 0.25 m, V_{turn} = 0.1 m/s, d = 0.13 m, μ = 0.58, θ = 30°

$$V_{f,in} = V_{r,in} = \frac{V_{turn}}{R}\sqrt{\left(R-\frac{T}{2}\right)^2+\left(\frac{L}{2}\right)^2} = V_{r,in} = \frac{0.1}{0.25}\sqrt{\left(0.25-\frac{0.69}{2}\right)^2+\left(\frac{0.79}{2}\right)^2} = \mathbf{0.163\ m/s}$$

$$V_{f,out} = V_{r,out} = \frac{V_{turn}}{R}\sqrt{\left(R+\frac{T}{2}\right)^2+\left(\frac{L}{2}\right)^2} = \frac{0.1}{0.25}\sqrt{\left(0.25+\frac{0.69}{2}\right)^2+\left(\frac{0.79}{2}\right)^2} = \boldsymbol{0.286\ m/s}$$

$$N = \frac{60V_{wheel}}{\pi d} = \frac{60 \times 0.286}{\pi \times 0.13} = \boldsymbol{42\ RPM}$$

$$\varphi_{f,in} = \tan^{-1}\left(\frac{L}{R-\frac{T}{2}}\right) = \tan^{-1}\left(\frac{0.79}{0.25-\frac{0.69}{2}}\right) = \boldsymbol{-83.1}°$$

$$\varphi_{r,in} = -\varphi_{f,in} = \boldsymbol{83.1}°$$

$$\varphi_{f,out} = \tan^{-1}\left(\frac{L}{R+\frac{T}{2}}\right) = \tan^{-1}\left(\frac{0.79}{0.25+\frac{0.69}{2}}\right) = \boldsymbol{53.0}°$$

$$\varphi_{r,out} = -\varphi_{f,out} = \boldsymbol{53.0}°$$

$$v_{roll,h} = \sqrt{\frac{TgR}{2H}} = \sqrt{\frac{0.69 \times 9.81 \times 0.25}{2 \times 0.25}} = \boldsymbol{1.84\ m/s}$$

$$v_{skid,h} = \sqrt{\mu g R} = \sqrt{0.58 \times 9.81 \times 0.25} = \boldsymbol{1.19\ m/s}$$

$$v_{roll,b} = \sqrt{gR\left(\frac{H\tan\theta+\frac{T}{2}}{H-\frac{T}{2}\tan\theta}\right)} = \sqrt{9.81 \times 0.25\left(\frac{0.25\tan 30+\frac{0.69}{2}}{0.25-\frac{0.69}{2}\tan 30}\right)} = \boldsymbol{4.86\ m/s}$$

$$v_{skid,b} = \sqrt{gR\left(\frac{\mu+\tan\theta}{1-\mu\tan\theta}\right)} = \sqrt{9.81 \times 0.25\left(\frac{0.58+\tan 30}{1-0.58\tan 30}\right)} = \boldsymbol{2.07\ m/s}$$

Force and Power

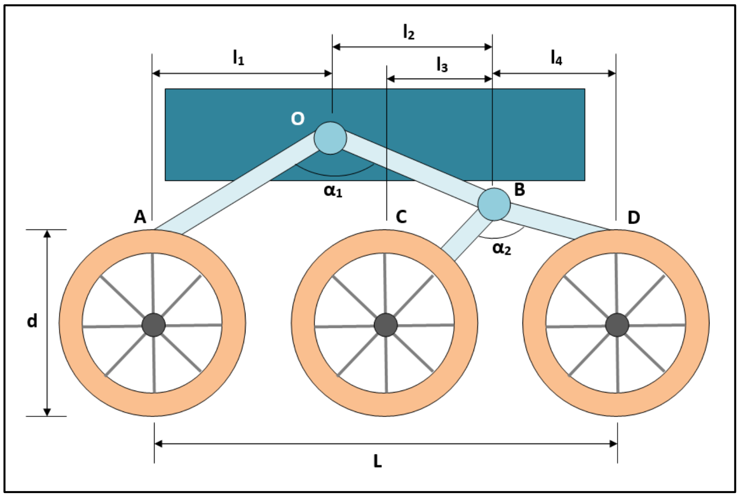


Figure 15: Rover side view

$$P_{peak} = \frac{(\mu mg + ma + F_{furrower} + F_{leveler} \pm F_{incline}) \times V_{rover}}{\eta_{motor}}$$

$$F_{AO} = F_{BO} = 0.534 \times mg$$

$$F_{DB} = 3.468 \times mg$$

$$F_{CB} = 1.485 \times mg$$

Furrow Wheel

Taking h = 4, r = 8 cm, V = 0.2 m/s, δ= 30° and λ = 1 (Figure 19)

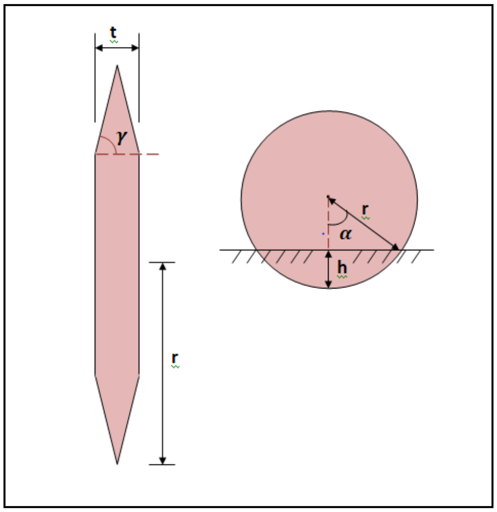


Figure 16: Furrow wheel

$$u_o = \cos^{-1}\left(1-\frac{h}{r}\right) = \cos^{-1}\left(1-\frac{4}{8}\right) = \mathbf{60}°$$

$$u_1 = \delta - \cos^{-1}(\lambda\cos\delta) = 30 - \cos^{-1}(1\times\cos 30) = \mathbf{0}°$$

$$u_2 = \delta + \cos^{-1}(\lambda\cos\delta) = 30 + \cos^{-1}(1\times\cos 30) = \mathbf{60}°$$

$$\begin{aligned} R_x = Nr(\cos u_1 - 1 + \tan\delta\sin u_1) - \frac{Nr}{\cos\delta}\int_{u_1}^{u_2}\frac{1-\lambda\cos u}{\sqrt{1+\lambda^2-2\lambda\cos u}}du \\ + Nr\big(\cos u_1 - \cos u_2 + \tan\delta\,(\sin u_o - \sin u_2)\big) \\ = Nr(\cos 0 - 1 + \tan 30\sin 0) - \frac{Nr}{\cos 30}\int_0^{60}\frac{1-1\cos u}{\sqrt{1+1^2-2\times 1\times\cos u}}du \\ + Nr\big(\cos 60 - \cos 60 + \tan 30\,(\sin 30 - \sin 30)\big) = \mathbf{-5.897\ N} \end{aligned}$$

Leveler

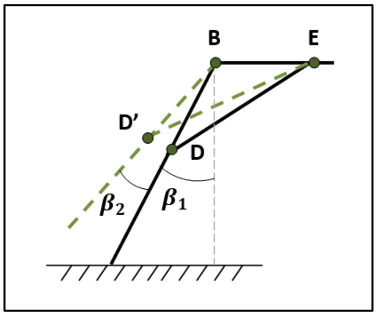


Figure17: Leveler

$$e = \left[{l_{BE}}^2 + {l_{BD}}^2 - 2(l_{BE} \times l_{BD})\cos(90 + \beta_1 + \beta_2)\right]^{1/2} - \left[{l_{BE}}^2 + {l_{BD}}^2 - 2(l_{BE} \times l_{BD})\cos(90 + \beta_1)\right]^{1/2} = [(5cm)^2 + (4.5cm)^2 - 2(5cm \times 4.5cm)\cos(90 + 45° + 12.529°)]^{1/2} - [(5cm)^2 + (4.5cm)^2 - 2(5cm \times 4.5cm)\cos(90 + 45°)]^{1/2} = \mathbf{3.43\ mm}$$

$$c_c = 2M_{leveler} \times \sqrt{\frac{F}{e \times M_{leveler}}} = 2(0.8\ kg) \times \sqrt{\frac{8}{3.43mm\ \times 0.8kg}} = \mathbf{86.4}$$

Material Research and Selection

The material research for Agri-Rover components focused on two main considerations. Firstly, certain components needed to be 3D printed with varying stress concentrations. Secondly, metallic components required low densities, high stress resistance, durability, cost-effectiveness, and the ability to be cast and machined.

For 3D printing materials, **Appendix I** provides a comparison of different materials to select the most suitable option for our requirements. **PLA** was chosen as the best material for 3D printing patterns for sand casting due to its low cost, availability, ease of use, and reasonable accuracy.

Regarding metallic components, **Appendix II** presents a comparison of different metals for casting. The selected metal needed to balance material density and toughness requirements to prevent the rover from becoming too heavy. Additionally, the material for the joints connecting the rover body to its legs and wheels required careful selection to withstand the stresses imposed by the rover's weight. Based on these considerations, **Aluminum 6061** was chosen as the best material for fabrication, machining, and casting of small components. It offered low material density, affordability, availability, and ease of use.

To ensure cost-effectiveness, a market survey was conducted (**Appendix III**) to gather quotations from various sources, both physical shops and online businesses. This allowed for the procurement of required materials and components at the best possible prices, reducing the overall financial burden.

Control System Coding and Circuitry

This project has two main control systems which work separately but in conjunction to each other to produce rover movement and seed dispensing. Therefore, data sharing between both control systems must be ensured as the parameters of the seed-sowing system are dependent on the state of the rover’s movement, inter-seed distance, land coverage rate, and overall rover speed.

Rover Motion, Turning, and RC Control

The rover's control system consists of three levels of connections as shown in Figure 18. Firstly, the RC transmitter in the remote control sends signals to the RC receiver, which is connected to the Arduino Mega microcontroller. The microcontroller is then linked to six DC motors, each with its own DC motor driver, responsible for rotating the wheels and enabling the rover's movement. Additionally, there are four servo motors: two attached to the front wheels and two to the rear wheels. These servos adjust the position of the wheels during turns, while the middle wheels remain stationary. The rover utilizes Ackerman steering, meaning that the speeds of the inner and outer wheels differ during turns, all controlled by the microcontroller's code.

Based on the signals received from the remote control, the microcontroller sends signals to either the DRV8871 DC Motor Driver to control the speed of the DC motors in the wheels or the DS3225 Servos to control the Ackerman Steering system. Therefore, the remote control serves as the input device, while the DS3225 servos and the DC motors in the wheels act as the output devices. This configuration establishes a basic control system responsible for governing the rover's motion.

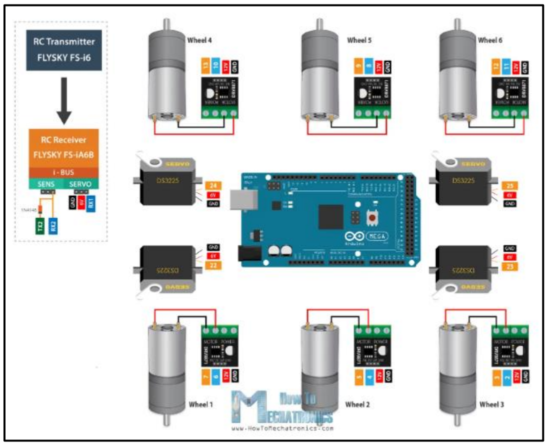


Figure 18: Circuit diagram of rover control system and electronics [20].

Seed Dispensing Mechanism

The Seed Dispensary Mechanism (SDM) is a component of the seed-sowing module and operates with its own control system. However, it relies on the rover's motion, specifically the distance traveled, to ensure accurate seed placement at the desired inter-seed distance. To achieve this, a rotary encoder is employed in the front right wheel to measure the rover's movement based on wheel rotation.

During the development of the seed-sowing module's control system, a concern arose regarding backward motion. If the rover moves backward due to obstacles or operator error, the encoder would continue adding to the distance traveled, potentially leading to inaccuracies. To address this, the code was designed to measure the displacement between two consecutive seed drop points instead. This approach ensures the reliability of the Agri-Rover by compensating for any backward motion.

The control system utilizes an Arduino Uno microcontroller, responsible for regulating the stepwise motion of the stepper motor. By adjusting the lag between successive steps, the microcontroller maintains the desired inter-seed distance relative to the rover's motion, based on data received from the rotary encoder. Consequently, the output of this system is the rate of rotation of the seed dispensing wheel (Figure 19), which is connected to the motor controlled by the Arduino system.

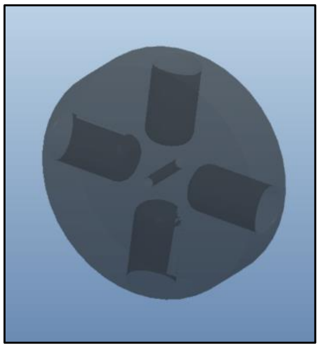


Figure 19: Seed dispensing wheel which is connected to a stepper motor

Fabrication

The fabrication of the Agri-Rover was conducted in two phases. All the parts were initially designed in SolidWorks and their stress analyses were conducted in Ansys (see **Results and Discussion**) before being finalized for fabrication. Furthermore, for the parts that were 3D printed, the CAD files were converted to G-codes for the 3D printer using the software PrusaSlicer.

Phase 1: Fabrication of Rover

The fabrication process for the rover began with the construction of the chassis, which served as the foundation. The chassis consisted of a rectangular metal frame covered with white plastic sheets, housing the control unit containing the microcontroller, motor drivers, and battery.

Next, the motor housings and wheels were 3D printed using PLA material. The DC motors were mounted in the housings and directly connected to the wheels, with each wheel having its own dedicated motor. Servo motors were secured on top of the front and rear wheels in their respective housings using bolts and nuts. These servo motor housings also acted as joints for attaching aluminum rods. The front right wheel's motor housing was modified to accommodate a rotary encoder and a pulley system was used to connect the encoder shaft to the motor shaft, allowing the encoder to measure the rover's distance traveled. Furthermore, four additional joints were manufactured, with two serving as main joints connecting the rover legs to the body, and the other two joining the middle and rear wheels to a connecting rod attached to the main joint.

To address the significant stresses on the main joints due to the rover's weight, sand casting was employed using Aluminum 6061 instead of 3D printing with PLA. However, the main joints were initially 3D printed as patterns for the casting process. To account for shrinkage during casting, the 3D printed patterns were cleaned, taped with electrical tape, and used as molds. The cast joints were then machined and drilled to create the metal joints.

After assembling the rover, the electronics were placed inside the body, and all necessary electrical connections were made to ensure proper functioning. Figure 20 depicts the final assembled rover.

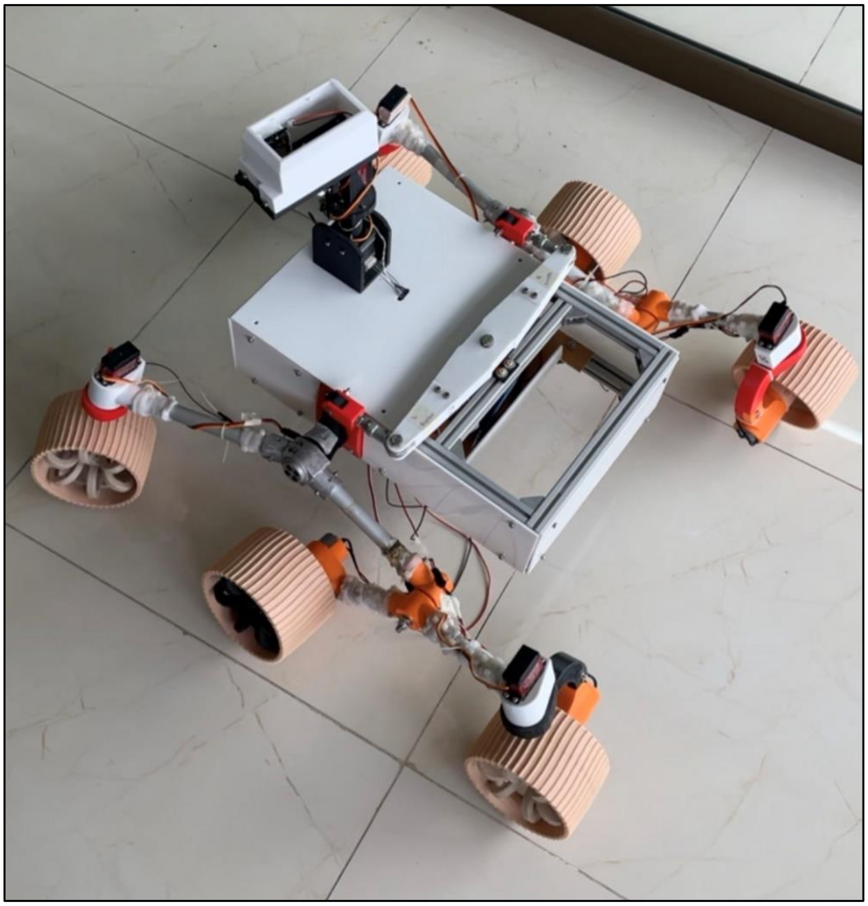


Figure 20: Final Model Assembly

Phase 2: Fabrication of furrow wheel, leveler, and seed dispenser

Initially, the plan was to 3D print most of the components but considering the high stresses on the attachment arms of the furrow opener and leveling plate, it was decided to use Aluminum for their fabrication. To visualize the auxiliaries before fabrication, a clay model approach used by car manufacturers was adopted. Instead of clay, cardboard was used as a cheap and easy-to-craft material to create 3D models based on the design. This allowed for better visualization, cost-effective modifications, and accurate dimensions in relation to the rover.

Once the design was finalized, the parts were fabricated using the required materials listed in Table 1.

Table 1: Material requirements and fabrication of specific components

Part	Material requirement
Furrow wheel, FW	Large aluminum/steel disc
FW arms	Aluminum rods
FW bearing	Bearing according to attachment point rod dia.
FW, damper attachment clamp	3d printed or CNC-ed, basic clamp with holes for screws
Levelling plate	Machined from aluminum/ steel plate
Damper	Purchased from market according to exact size requirement
Damper arms	Aluminum rods
Seed tank body	Acrylic sheets (sized according to cardboard model)
Seed tank attachment	Specialized clamp/attachment designed using cardboard for accuracy, replicated with acrylic or 3d printed attachment to seed tank
Seed tank lower portion (seed dispensing wheel and motor)	3D printed in PLA according to motor size, and SDW size
Seed dispensing wheel	3D printed using PLA

The furrow opener disc and attachment mechanism were cut from aluminum plates using a CNC milling machine and assembled onto the rover. The seed tank was constructed by gluing acrylic panels together, forming a rectangular tank that sits on top of the rover body. The tank was divided into two parts with a diagonal ramp to guide seeds into the funnel over the SDM wheel and provide space for electronics and the seed-sowing module's control system. The leveling plate was also fabricated using CNC-cut metal plates that were welded together at an angle and assembled at the rear of the rover along with the damper.

After fabricating all the auxiliaries for the seed-sowing module, the electronics were connected to the dedicated Arduino board and mounted onto the rover, completing the Agri-Rover (Figure 21).

Final Prototype

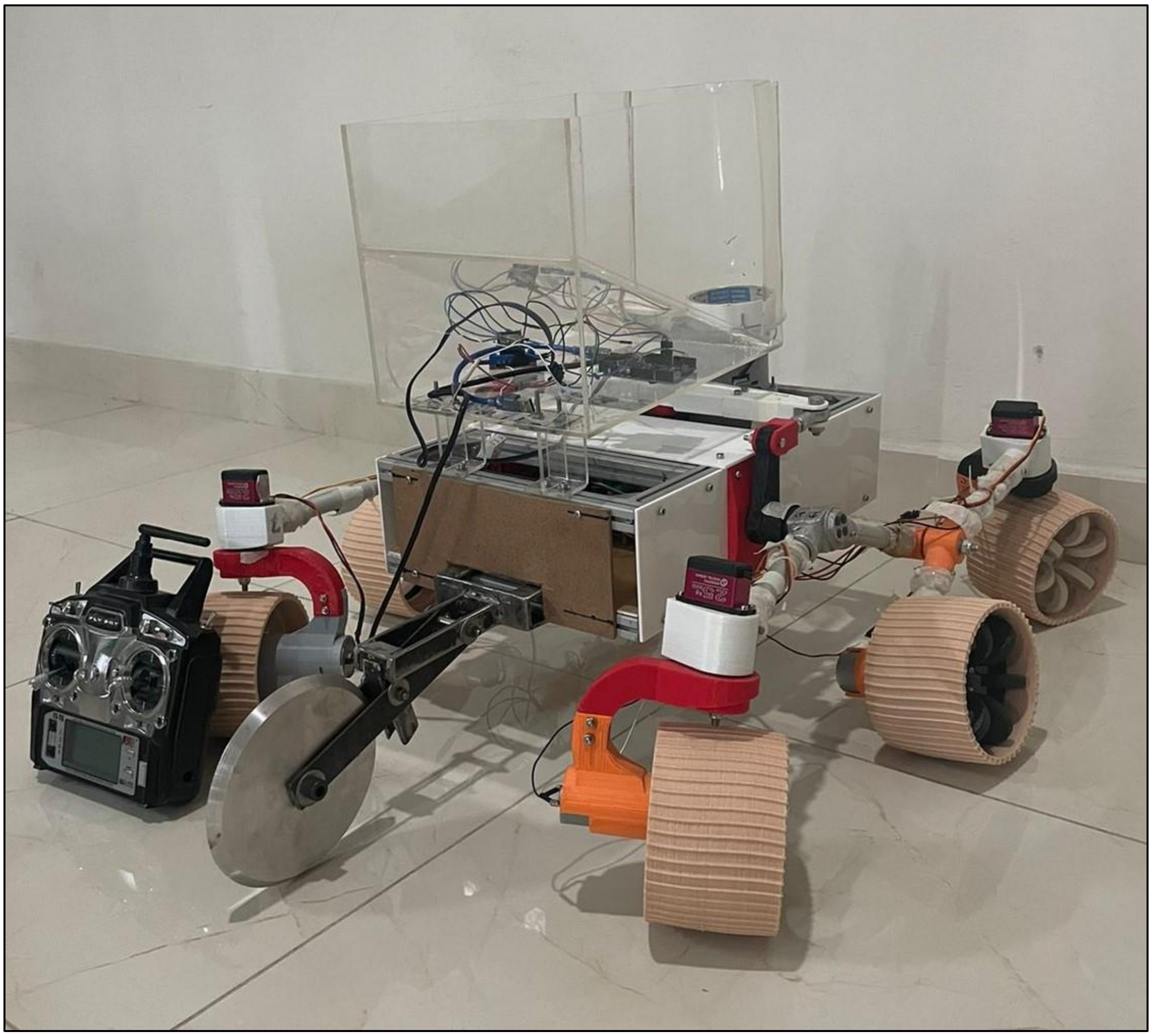
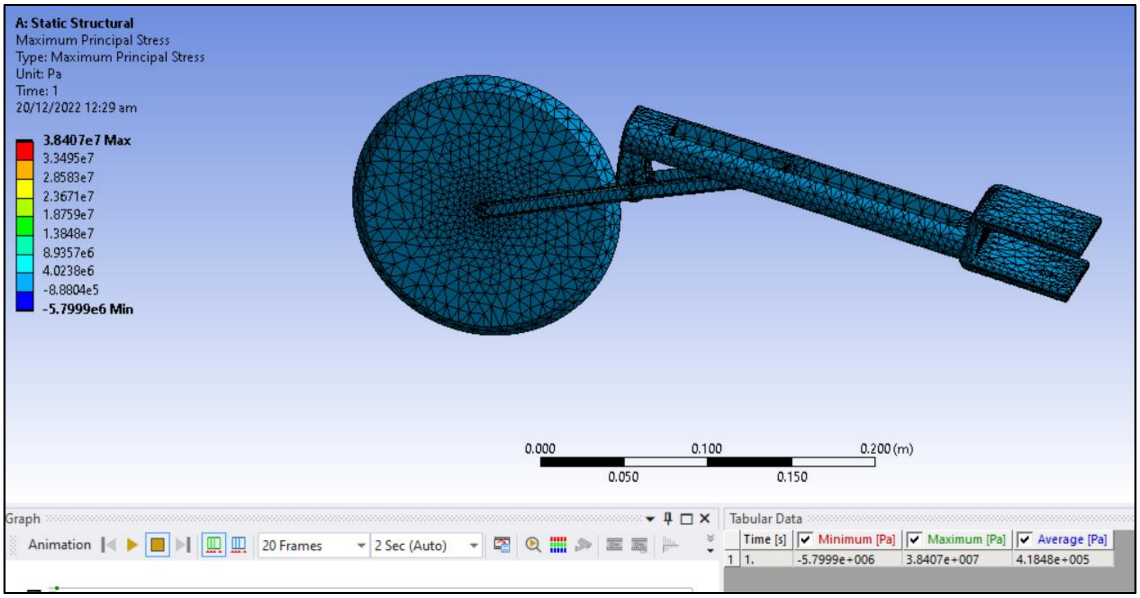


Figure 21: Final Prototype with seed sowing components assembled on the rover

CHAPTER 4: RESULTS AND DISCUSSIONS

Stress Analysis

The Agri-Rover has to carry heavy loads of the seeds, the seed-sowing module, and the electronics along with its frame while pushing through the soil to create a furrow, hence, it is subjected to a lot of resistive forces and stresses. To understand the structural integrity of the rover and all its mechanisms, stress analyses on different components were conducted on ANSYS 2021 R1.



A: Static Structural
Maximum Principal Stress
Type: Maximum Principal Stress
Unit: Pa
Time: 1
20/12/2022 12:29 am

Tabular Data

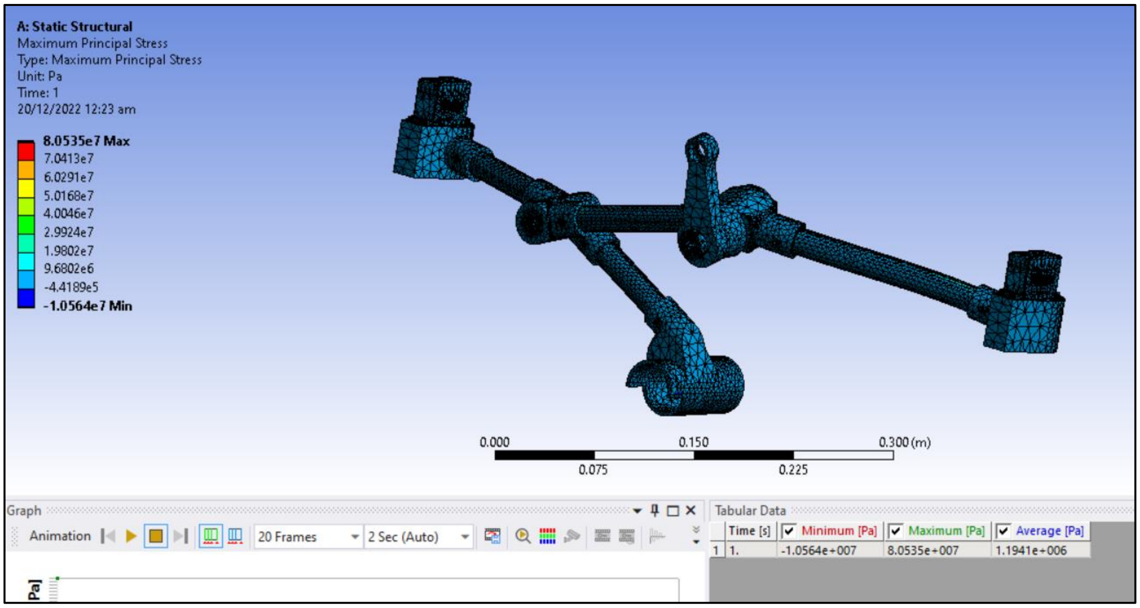
	Time [s]	☑ Minimum [Pa]	☑ Maximum [Pa]	☑ Average [Pa]
1	1.	-5.7999e+006	3.8407e+007	4.1848e+005

Figure 22: Furrow wheel stress analysis

Figure 22 shows the stress distribution acting on the furrow opener. According to the analysis, the maximum stress i.e. 38.4 MPa, was found to be at the pin joining the furrower wheel to the connecting mechanism which is also the pin on which the furrow opener wheel rotates. Thus, to avoid any failure, this pin and all stress-concentrated parts needed to be made from materials with adequate strength.

Furthermore, as the rover moves forward, the furrow opener wheel experiences an opposing force from the ground which is then transmitted through the connecting mechanism and to the rover as well. This posed a possible issue of large bending stresses accumulating in the furrower arm of our initial design (Figure 10) due to its long length which could have resulted in permanent failure.

To overcome this issue of stress accumulation in the furrower arm, we decreased the length of the arm to reduce bending. So, the new furrow opener has the same dimensions throughout except the length of the furrower arm which was shortened.

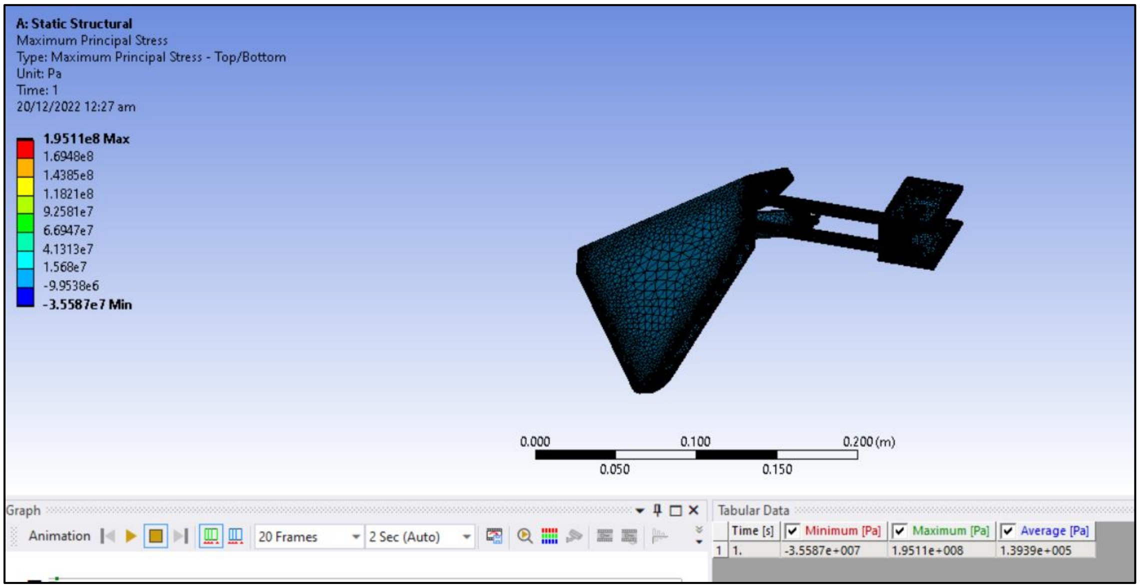


A: Static Structural
Maximum Principal Stress
Type: Maximum Principal Stress
Unit: Pa
Time: 1
20/12/2022 12:23 am

	Time [s]	☑ Minimum [Pa]	☑ Maximum [Pa]	☑ Average [Pa]
1	1.	-1.0564e+007	8.0535e+007	1.1941e+006

Figure 23: Rover link stress analysis

Another crucial part of the Agri-Rover is the set of links that connect the rover body to the wheels. The load of the rover is transmitted through these links, making the links and joints the most prone to failure. As seen in Figure 23, the maximum stress observed on these parts is 80.53 MPa in which the highly stress-concentrated region is the main joint that connects the links to the main body of the rover. Similar to the furrow opener, these joints and links, bearing high stresses, also needed to be made with metals of high strength.


A: Static Structural
Maximum Principal Stress
Type: Maximum Principal Stress - Top/Bottom
Unit: Pa
Time: 1
20/12/2022 12:27 am

	Time [s]	Minimum [Pa]	Maximum [Pa]	Average [Pa]
1	1.	-3.5587e+007	1.9511e+008	1.3939e+005

Figure 24: Leveler stress analysis

A simple yet important part of our Agri-Rover is the leveler which drags behind the rover and experiences forces due to friction and bumps on the ground while the rover is in motion. These forces produce stresses as seen in Figure 24. Upon analysis, the maximum stress on the leveler was found to be 195 MPa. This stress concentration was found to be on the damper pins as these pins are very small in size and thus accumulate stress which can be remedied by using pins with a larger surface area.

Meanwhile, the SDM does not experience any concerning forces and does not pose a stress failure issue.

Center of Gravity (GOG)

On an industrial level, vehicle manufacturers try their level best to keep the COG low and as close to the ground as possible. This increases the stability of the vehicle. Similarly, the COG for the rover is also desired to be low and in the center of its body. However, initially, the COG for our Agri-Rover was not in the center but was shifted towards the rear of the rover, causing a natural unbalance of forces on it. The furrow opener was the most affected by this as it would not get enough vertical push to dig through the soil due to the COG leaning towards the back.

In order to resolve this issue the COG of the rover was adjusted by changing the SDM tank design. The SDM tank, previously circular, was changed to a cuboidal structure to be spread across the rover body as shown in Figure 11. This spread will shift the COG forward. Moreover, the bottom face of the tank is at an angle and slants downwards like a ramp to let seeds slide toward the SDM wheel.

Final Parameters and Expected Performance Numbers

The final parameters related to the rover operation, seed dispensing operation, etc. are all provided in Table 2. They show the peak performance capabilities of both the rover and the seed-sowing control systems.

Table 2: Peak performance parameters

Parameter	Value (units)
Rover speed	0.2 (m/s)
Minimum Inter-Seed Distance	10 (cm)
Seed drop rate	0.5 (s/drop)
SDW rotation period	2 (s)
Stop time (lag between SDW steps)	0.2 (s)
Servo maximum required rotational speed	50 (rpm)
Leveler damper spring constant	2.332 (N/mm)
Leveler damper damping constant	86.4
Furrow depth (max)	5 (cm)
Number of wheels	6
Power requirement	11.39-18.19 (W)
Land coverage rate	10.5 (s/m^2)

These parameters show us that our project is capable of performing the seed-sowing task at a much faster rate than humans do, thereby and it reduces the process of manual labor greatly along with the time to sow seeds. It also provides a very high level of achievable accuracy in terms of the inter-seed distance and furrow creation for sowing seeds. This resulting increase in accuracy increases the probability of seed germination, thereby, improving harvest in the process.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

Through the use of a proven rover base equipped with custom-designed seed-sowing modules that can achieve great accuracies and be adapted to meet the sowing depth and inter-seed spacing requirements of most mainstream crops, the Agri Rover 2023 provides utility and value not seen before in the agricultural landscape of Pakistan. It presents a perfect combination of tried and tested designs coupled with novel ideas which, when powered with the right control systems, can provide a viable substitute for manual labor in the process of seed sowing.

The design was finalized after a lengthy review of existing literature to examine different viable options in terms of rover design, type of motion, and mechanisms for furrowing, seed dispensing, and leveling. Moreover, in the light of guidance from experts in the field and through efforts to keep the rover suitable for the people, crops, and environment of the country, the group is confident that the device will be able to exceed expectations in terms of performance.

The guiding principles used throughout the design process, namely accuracy, adaptability, ease of use, and reliability, served as the cornerstones for the group and ensured that the members were continuously aware of the challenges they had to meet. With these objectives in mind, the end result was a product that provided versatility and value to the customer while also being suited to the socio-economic landscape of the local population.

The final operational parameters were promising in terms of the expected performance of the rover. Some notable takeaways were (i) velocity, which led to a greater rate of land coverage when compared with manual labor, (ii) stability, which meant that the rover could traverse reasonably sized obstacles without rolling over, and (iii) minimum inter-seed spacing, which translated to a greater density of crops that could be achieved. Moreover, the stress tests which were performed on critical parts also indicated that the design would be able to bear its own weight as well as that of any seeds in the tank.

The project also served as an excellent learning experience for the group and acted as the perfect culmination of their degree. It took the members through an entire product development cycle which allowed them to get hands-on experience and use software such as Creo, SolidWorks, and ANSYS. Moreover, they adopted a problem-solving approach to tackle multiple issues at each stage of the process. Special attention was paid during the design phase and the material selection phase in order to make subsequent stages easier and lead to a better product.

In the end, the Agri Rover 2023 is perfectly positioned to tackle multiple issues faced by the agricultural sector. The most significant one is the loss of seeds faced by farmers through traditional methods. Through careful and accurate seed sowing, the rover maximizes chances of germination which can lead to reduced expenses and increased yield and productivity for both the farmer and the agricultural sector as a whole. Additionally, the benefits of reduced labor costs and time savings are also readily apparent. All in all, the rover can prove to be a worthy investment for small- to medium-scale farmers.

Future Recommendations

Owing to the modular design of the rover, there is a lot of potential for future developments and upgrades to further the abilities of the rover. Some of these prospects are highlighted below.

Autonomous Motion

The motion of the rover can be made completely autonomous. This means that once the dimensions of the land to be covered are input into the rover, it should be able to automatically calculate the number of rows and seeds per row based on the desired row spacing and inter-seed spacing. Subsequently, the rover can chart its path through the rows and follow the path itself, traversing each row till the end while sowing and then turning once it knows it has traveled the entire length of one row.

This upgrade can be made with minimal additional capital since it will only require some additional coding and a method for the user to input field dimensions into the rover, such as a keypad. Once completed, this will further reduce human input, and free up the farmer to tend to other tasks while the rover performs sowing in the entire field.

Obstacle Detection

This feature can be coupled with the previous proposal to achieve greater reliability in autonomous operation. It involves giving the rover the ability to detect obstacles in its path, such as large rocks, which it can then circumvent before continuing on its charted course. This can be achieved in two ways:

1. Installing a camera in front of the rover. Using image recognition algorithms, the rover can detect if there is an obstacle in its path and take corrective action.
2. Installing proximity sensors, such as infrared or ultrasonic sensors, that can detect when there is an obstacle in front of the rover and allow it to take corrective action.

This can further reduce the need for human intervention while the rover is in operation. Moreover, it can reduce the chance of impact and subsequent damage to the rover, thereby increasing its reliability.

Solar-Powered Charging

The rover can be fitted with a solar panel that can provide a source of steady charging to the rover battery, even during operation. This can be placed on top of the seed tank cover which has a large area available. This will present two major benefits:

1. It will provide an alternate means of charging the rover in places where electricity may not be readily available or may be in short supply. This makes the rover more accessible for people belonging to different regions.
2. By charging the batteries even during operation, the rover can run for longer periods continuously. This can allow the rover to cover greater areas of land without the need to be recharged.

Modular attachments for different functions

Much like the detachable seed sowing components were designed and installed onto the rover, more components could be designed and installed to provide different functionalities to the rover. For example, the rover could perform other important agricultural processes such as plucking weeds or dispersing fertilizer. Such add-ons can either be packaged with the rover or can be sold separately to create an additional revenue stream. This will make the rover much more versatile and provide users with greater value from a single machine.

App integration

Mobile phone usage in rural areas is growing at a staggering pace, with nearly 91% of individuals in rural areas having access to mobile phones [22]. Since the rover is controlled by microcontrollers present on board, some additional hardware, such as Bluetooth modules, can be installed to make the rover connect with apps on mobile phones. App integration can be carried out in two major ways:

1. Creating a proprietary app specifically for the rover. This can provide different functionalities such as being able to control the rover manually, viewing battery levels, and observing the progress of the rover on a specific sowing task.
2. Partnering up with existing apps in the Agri-tech sector. For example, Agronomics is a startup that offers mobile apps for farmers. One specific app is their ‘Crop Simulator’ which tracks the growth of crops under certain external factors and provides solutions to problems that arise [23]. Our rover could easily be linked with this app so that the app can, for example, display its battery level and notify the farmer about the correct time and path to use the rover for optimum sowing.

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APPENDIX I: COMPARISON OF 2D PRINTING MATERIALS

3D Printing Material	**Properties**	**Material Cost**	**Ease of Use**	**Availability**	**Maximum Accuracy (Grain Size)**	**Yield Stress**	**Type of 3D Printer Required**	**Cost of 3D Printer Type**	**Sources**
PLA	Biodegradable, easy to print, low strength, low-temperature resistance	\$20-\$30/kg	Easy	Widely available	50 microns	40 MPa	FDM 3D printers	\$200-\$500	[24] – [27]
ABS	Strong, temperature resistant, prone to warping, requires heated bed	\$20-\$30/kg	Moderate	Widely available	20-50 microns	40-60 MPa	FDM 3D printers with heated bed	\$200-\$500	[24] – [26], [28]
PETG	Durable, temperature resistant, easy to print, flexible	\$20-\$30/kg	Easy	Widely available	20-50 microns	50-70 MPa	FDM 3D printers	\$200-\$500	[24] – [26], [29]
Nylon	Strong, flexible, chemical resistant, difficult to print,hygroscopic	\$50-\$100/kg	Difficult	Less common	5-20 microns	50-80 MPa	FDM 3D printers with heated chamber	\$500-\$1000	[24] – [26], [30]

TPU	Flexible, impact resistant,low temperature resistance, difficult to print	$40-$60/kg	Difficult	Less common	100-200 microns	5-10 MPa	FDM 3D printers with direct drive extruders	$500-$1000	[24]–[26], [31]
Carbon Fiber Reinforced PLA	Strong, stiff, lightweight, brittle, abrasive, prone to clogging	$50-$100/kg	Moderate	Less common	100-200 microns	80-100 MPa	FDM 3D printers with wear-resistant nozzle	$1000-$2000	[24]–[26], [32]

APPENDIX II: COMPARISON OF METALS FOR FABRICATION

Material	**Yield Stress (MPa)**	**Tensile Stress (MPa)**	**Density (kg/m3)**	**Machinability**	**Durability**	**Cost per kg ($)**	**Casting Temperature (C)**	**Casting Type**	**Sources**
Aluminum 6061	240	310	2700	Good	Good	2.5	600-750	Sand casting, die casting, permanent mold casting	[33], [34]
Low carbon steel	250	400	7850	Fair	Good	1.2	1370-1480	Sand casting, investment casting, die casting	[35], [36]
Stainless steel	205	520	8000	Poor	Excellent	4.5	1480-1570	Investment casting, die casting	[37], [38]
Copper	70	220	8900	Poor	Excellent	9.0	1080-1200	Sand casting, investment casting	[39], [40]

APPENDIX III: MARKET SURVEY, PRICE LIST, AND REQUIREMENTS

Component name	**Function**	**Cost (PKR)**	**Number required**
MG 996 Servo	Used as the stepwise motion generator used in the seed dispensing mechanism	950	1
Aluminum 6061(plates and bars)	Used for fabrication and casting of mechanism and rover components	1400/Kg	N/A
3s Lipo Battery 12V Output: 1250 mAh	Used to power the rover motion and the seed dispensing mechanism.	1600/unit	Upon field size requirement, currently we are looking at 4 batteries for the rover motion and 1 for the seed dispensing mechanism
DC Motor 12V 25 RPM	These are high torque motors which will be at the wheels of the rover.	650/unit	6
Rotary encoder	To accurately determine the distance moved and the speed of the rover for accurate position measurement and to maintain accurate inter seed distance	200/unit	3
Arduino uno	To be the microcontroller for the seed dispensing mechanism and take input from the rotary encoders and control	1450	1

	dispenser servo speed accordingly		
Arduino Mega	Used as the microcontroller for the rover movement servos and motors	4200-4500	1
Damper	To dampen the vibrations in the levelling plate to keep smooth contact with the ground.	1000-1200	1
CNC, Casting, Machining	Required to fabricate the metal components of the rover and the auxiliaries	(Only material costs incurred due to courtesy of MRC for aid in fabrication)	N/A
PVC/Acrylic sheets	Used to fabricate the seed tank, these sheets have to be laser cut and joined using specialized glue.	300-400	5-8
FLYSKY RC Transmitter	For the RC connectivity of the remote control to the rover	7000-10,000	1
DRV8871 DC Motor Driver	Used to Drive the DC motors via the Arduino mega controller	1200-1400 [41]	6