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Designing a Low-Cost Automated Mobile Robot for South African Citrus Farmers †

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Abstract: Citrus farming in South Africa, has become extremely loop-sided in terms of economic opportunities. The statistics show that the wealthy large-scale farmers simultaneously control 100% of the international export market and 77.1% of the local market hence endangering the prospect of the low and medium-scale farmers. This research presents a novel, low-cost autonomous mobile robot (AMR) designed to support small and medium-scale citrus farmers in South Africa, enhancing their competitiveness in both local and international markets. Developed using GENESYS software for systems integration, the AMR offers real-time crop monitoring to aid phytosanitary regulations compliance, autonomous navigation with object avoidance, error alerts, GPS functionality, and auto-homing when battery levels drop to 30%. Additionally, it captures periodic snapshots of citrus crops for visual inspection and assists with proof of protocols for sustaining citrus and treating infected trees, hence increasing their credibility and accountability for export and local markets. The AMR represents a significant advancement in affordable smart technology for sustainable citrus farming.

Keywords: holistic conceptual design; autonomous mobile robot; phytosanitary regulations compliance; low-cost design; citrus farming

1. Introduction

The South African citrus sector is a global leader in citrus production and exportation, ranking 10th in production and 2nd in exports worldwide. Dating back to the 19th century, the industry now boasts over 1500 growers and employs around 140,000 full-time workers, contributing significantly to employment in the country. Despite being valued at approximately $2 billion, the South African citrus farming industry faces a chain of challenges that threatens the industry's economic relevance over time if not urgently addressed. The industry is under immense pressure for diverse reasons, ranging from domination by large scale farmers with financial wellness, adhering with stringent international requirements and regulations, inconsistent weather patterns due to climate change, inadequate infrastructure to provide basic supplies such as water and electricity, a struggling economy, and environmental issues bothering around pest infestations and ineffectiveness in the control of disease outbreaks including citrus greening disease, which poses a significant threat to the industry.

Large-scale citrus farmers, often capitalise on this as they have the financial capacity to do so, as opposed to small to medium scale farmers who lack this privilege. This makes it difficult for the upcoming farmers to compete with the large-scale farmers hence,

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increasing the economic gap between these categories of farmers, resulting in a skewed growth of the South African economy.

The South African citrus sector faces a unique challenge in adopting the use of automated machineries developed abroad due to the peculiarities of the indigenous citrus crops size and rough farm topography. For instance, large tractors have proven to be ineffective due to their need for substantial distances between trees to operate successfully. On the other hand, the use of drones for spraying of crops, has a peculiar challenge when used on citrus crops following the level of imprecision spraying especially with sufficient reachability of the root. Automated tractors are costly and suited for large-scale farmers only. Though drones are cheaper and more accurate, their limited storage, short battery duration, and inability to monitor every tree in large citrus fields increase production costs significantly. The development of more affordable and applicable technologically advanced machinery can aid as a pedestal to level the playing field. New treatment methods and improved farming techniques are being explored to enhance productivity and meet market demands.

Various attempts have been made to design agricultural robots that assist in agricultural activities [1]. The most widely used current "methodology" is developing a robot according to the requirements of the project only and not considering various design concepts to improve the overall design [2–6] Studies that utilise the systems engineering approach (most likely as an oversight technique to monitor the actual technical design process) were reviewed, as a conceptual system engineering design approach will improve the overall design of the automated robot. Systems engineering (SE) is a multidisciplinary engineering subject that focuses on the design, integration, and management of various systems throughout their lifecycle. SE is a complete system strategy with several interacting components. The SE framework is applicable to a wide range of jobs and sectors, including aerospace, software engineering, automotive, medical, and civil engineering, and as a management tool. In an era of limited flight physics knowledge, the SE framework was utilized to minimize aircraft emissions while lowering costs and increasing safety [7]. Sadraey (2012) proved the effectiveness of the SE framework by designing a fully functional airplane, amidst contemporary aerospace challenges at the time [8].

Fairley (2018) employed SE to design and implement software-enabled systems (SES), integrating traditional development methods with an integrated-iterative-incremental (I^3) model derived from linear development models [9]. The SE framework acts as an assessment tool for analysing the impact of additive manufacturing (AM) on systems processes, whilst identifying other or new use cases like project crashing tools and enhancing return on investment [10]. SE serves as an oversight management tool for projects and design cycles [11]. The SE framework proved advantageous for integrating the SE and knowledge management framework, which enhanced decision-making, innovation, and learning [12]. However, there were challenges that need to be addressed, such as cultural change, technical expertise, data quality, and management commitment.

The SE methodology is systematic and generic, enabling its application to a variety of systems. This methodology was utilized to design an effective and efficient architecture for Prognostics and Health Management (PHM) systems [13]. The previous study used the "RFLP" (requirement, functional, logical, and physical) process to define the architecture, as shown in Figure 1, which was developed by incorporating the core principles of SE. Finally, six Dutch water board projects were analysed using the SE process model, to improve the efficiency and effectiveness of the civil engineering project all across the board [14].

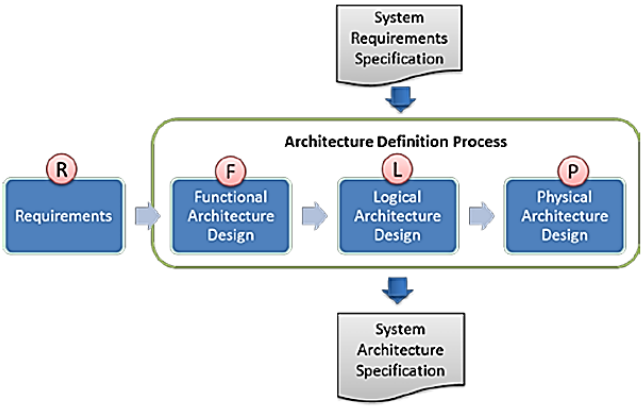


Figure 1. Architecture Definition Process.

The SE concept was used to improve efficiency, reduce labor, enhance safety, and increase sustainability for precision autonomous farming (PAF). An development framework for designing autonomous farming systems by applying the fundamentals of the systems engineering (SE) approach [15,16]. The SE approach has also proven to be beneficial in the irrigation sector, where the framework was used interchangeably but with different interpretations, to model and manage irrigation networks [17–19]. The authors stated that the SE approach can be further researched and applied to model and control a variety of irrigation systems, including canals, pipelines, and sprinkler systems. Additionally, the SE model was used to address the complex challenges associated with renewable ammonia production, such as the intermittent availability of renewable energy, the need for efficient transportation and storage, and the need for public acceptance [20].

The fundamentals of the SE approach presented a framework to control and design more robust UASs [21]. Upon conclusion they presented an SE approach of defining system requirements, based on Collaborative Operations in a Denied Environment (CODE) and Distributed Battle Management Program (DBM), then designing the system architecture, developing control algorithms, and lastly developing and testing the system.

Automated Guided Vehicles (AGVs) have been adapted to the agricultural field, commonly used in manufacturing or warehouse facilities for material handling, to perform various functions. These adapted AGVs, called Automated Mobile Robots (AMRs), use intelligent systems, machine learning, deep learning, artificial intelligence, and data manipulation to perform more complex tasks. For this project, instead of an AGV, an AMR will be designed on the foundation of an AGV, due to their inherent flexible development. AMRs allow for flexible high-level architecture and software development methods, tools, and approaches that are more comparable to those used in other domains, such as cloud-native, as opposed to the typical vertically integrated AGV domain [22]. The conceptual architecture of AMRs is comprised of AMR hardware, components, functional AMR software, operational or non-functional AMR software, and APIs (Application programming interface).

This research has designed an affordable low-cost AMR for the upcoming South African citrus farmers in a bid to manage pests and diseases in their crops, improve production quality and output, and decrease the overall cost of production. The research focused on exploring the South African citrus farmers challenges and the limiting factors towards the adoption of intelligent systems. Finally, identification of the most suitable type of automated guided machine to design the AMR.

2. Research Design Methodology

This chapter demonstrates the procedure that will be followed to obtain the design, along with the explanation of how they will be conducted, to complete the project.

2.1. Conceptual Framework

The methodology that will be used to perform this project is the systems development process. The process consists of 4 main phases and 4 sub-phases within each to further analyse the design, further discussed in 2.2.

Data gathered from analysing citrus farmers' constraints, biggest problems or challenges, citrus farmer's needs, and the factors limiting the adoption of robotics in citrus farming will be used as 'inputs' for this project. As part of an interactive process, the 'output' of each phase shown below (Figure 2), will then serve as inputs for the next phase.

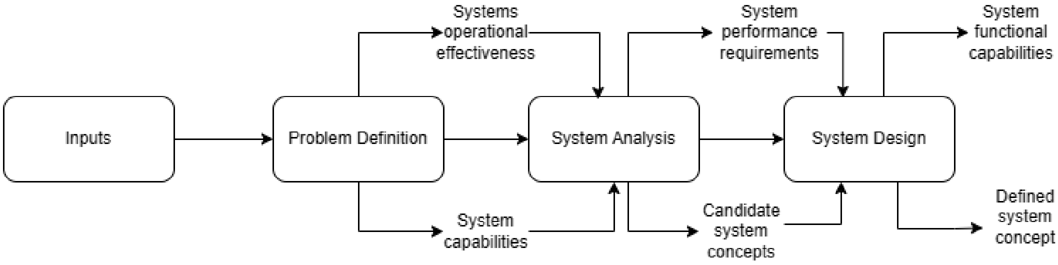


Figure 2. Overview of the concept development stage.

The concept development will be performed to provide a final concept design of an AMR for citrus farmers in South Africa. The final concept design will be displayed as a complete structure of an AMR system. An incomplete example of the template can be seen in Figure 3. It illustrates a system as a set of entities that work together to perform a single goal, consisting of various elements with different functions.

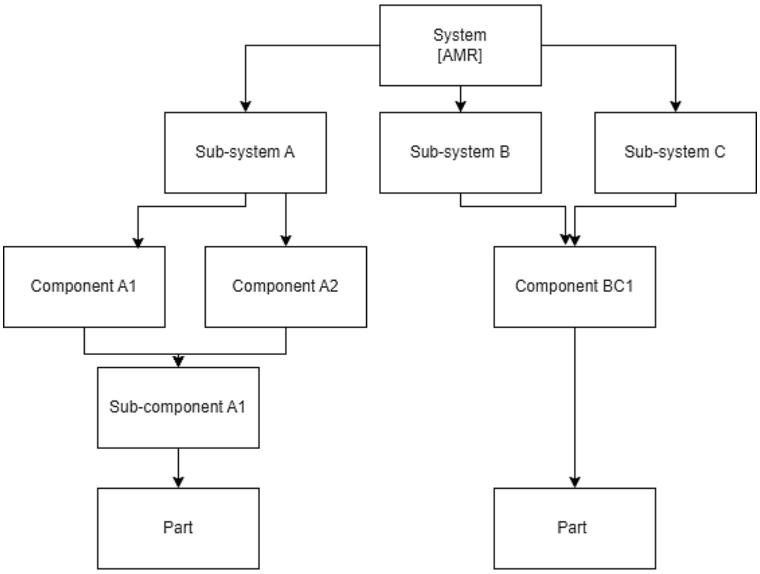


Figure 3. Structure of system for AMR.

2.2. Theoretical Framework

The overview of the methodology that was performed is explained in this chapter in more depth.

2.2.1. Concept Design & Development [Phase 1]

Operational Analysis [Sub-Phase 1.1]—The need for a new AMR system to address the stated inputs will be showcased and the different operational objectives of the new AMR system will be portrayed in an objective tree.

Functional Analysis [Sub-Phase 1.2]—Initial functional requirements of the system (presented in a functional tree) will be developed from the operational objectives which will then be translated into operational functions that must be performed as every basic function can be written as a functional requirement[23].

Feasibility Definition [Sub-Phase 1.3]—A feasible concept in terms of capability and estimated cost will be defined by analysing various trade-offs to generate an initial list of physical requirements that can perform the basic functions as stated in sub-phase 1.2.

Needs Validation [Sub-Phase 1.4]—Operational requirements formulation will be performed which will highlight the systems' operational effectiveness and capabilities which will be used as input for the Concept Exploration Phase (2.2.2). Operational scenarios, real world scenarios that uncover unexpected system behaviours, will uncover the updated operational requirements.

2.2.2. Concept Exploration [Phase 2]

Operational requirement analysis [Sub-Phase 2.1]—The operational objectives identified in the Needs analysis phase will be updated after considering and analysing the operational scenarios as stated in sub-phase 1.4.

Performance Requirements Formulation [Sub-Phase 2.2]—The updated operational objectives will be transformed into functions that must be performed by the system. The functions will then be translated into subsystems as seen in Figure 3 which are the various functions or outputs that the system must perform.

Implementation of Concept Exploration [Sub-Phase 2.3]—Various techniques, technologies, software, and any other means of solutions that can perform the identified functions will be explored to obtain the most promising components.

Performance Requirements Validation [Sub-Phase 2.4]—The preliminary cost-effectiveness analyses, to define a set of performance requirements that accommodate the full range of desirable system concept, that will be performed are equipment or component accessibility versus cost, and personnel cost as a function of complexity, Figure 4.

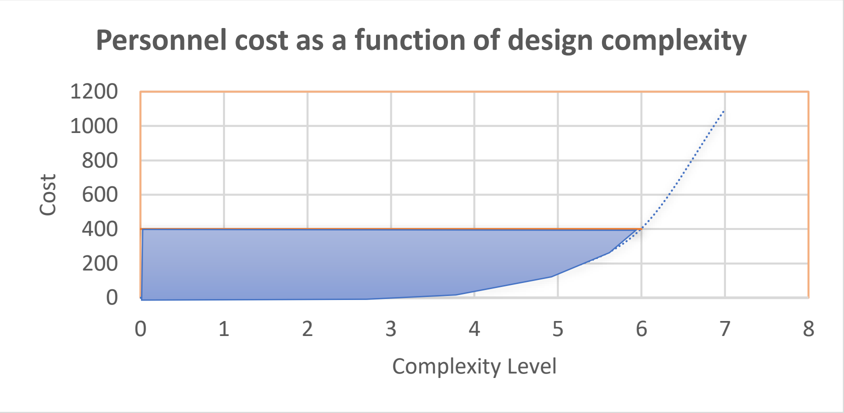


Figure 4. Cost-effectiveness analyses example.

The area of feasibility will highlight the design concepts that are still in line with the operational objectives identified. This will assist in refining the concepts to narrow them down.

2.2.3. Concept Definition [Phase 3]

Performance Requirement Analysis [Sub-Phase 3.1]—The finalised primary inputs gathered from sub-phase 2.4 will be analysed to ensure they are in line with the updated operational objectives and system performance requirements will be refined.

Functional Analysis and Formulation [Sub-Phase 3.2]—Subsystem functions will be allocated to the component level and element interactions will be defined.

Concept Selection [Sub-Phase 3.3]—The proposed candidate concepts will be analysed using trade-offs and candidate concepts. The final candidate design concept will be determined using a product tree to obtain the values for equation 1 and 2, the highest sum value thereof will reveal the final design concept.

Concept Validation [Sub-Phase 3.4]—The proposed concept will be compared against competitors to ensure its superiority.

$$x_i = \frac{WTP-z_i}{WTP}, \quad (1)$$

$$y_i = \frac{n_i}{F}, \quad (2)$$

where x_i= the cost value of design concept i, z_i is the total cost of developing the design concept.

Where y_i = the function accordance value for design concept i, n_i is the number of functions that design concept i has or can perform, and F is the determined required amount of the functions calculated in phase 1.2 to adhere to minimum requirements.

2.2.4. Functional Block Diagram

A functional block diagram will be developed to show the interrelationships of the various sub-systems and their corresponding functions of the proposed design concept [24].

3. Data Presentation, Results and Discussion

This chapter provides a sample of the data gathered throughout the entire process along with the interpretations and results of this data.

3.1. Data Presentation and Model Validation

This section presents sample data gathered from performing the conceptual systems development process along with the discussion of the results obtained. The validation of the AMR design is also described and expanded on.

3.1.1. Data Presentation

South African citrus farmers face numerous obstacles making it difficult to meet demand. Climate-change-related weather variations, pest and disease outbreaks, poor infrastructure, insufficient government assistance, low investment in research and development (R&D), labour protests, scarce water supplies, and load-shedding [25–27]. However, the largest threat to South African citrus farmers is newly instated European Union (EU) phytosanitary regulations, particularly concerning citrus black spot (CBS) and false codling moth (FCM) and Huanglongbing (HLB), or citrus greening disease [28,29]. These regulations could lead to an additional R2 billion ($106.98 million) in annual risk management expenses, impacting small to medium scale citrus farmers exponentially more [30]. These impeding factors can be reduced through new technologies. Economic experts state that the agriculture industry holds the key to South African poverty reduction through the introduction of new affordable agricultural technologies [31]. Innovative technology boosts output, save resources, improves crop quality, and improves overall fruit production efficiency, lead to an economic growth increase of 13% in 2020 from 2019 for those who can afford it [32].

Small to medium scale farmers are faced with poverty due to limited access to markets, as currently only 22.9% of South African market are willing to engaging with them [33]. Lack of collateral, track records, and economies of scale, concerns over reliability, accountability, and ability to meet food safety standards hinder the market in engaging them. Consequently, large-scale farmers are dominating the supply chain, as they have collateral, track records, economies of scale etc., through GLOBAL G.A.P. certification showcasing compliance. Affordable agricultural technologies that ensure consistent production, compliant produce quality, and assisting in meeting food regulations can reduce risk, which will assist smaller farmers to access 66.7% of the future market [33].

However, intelligent system adoption into agriculture is hindered by various factors. The main constraint is the high initial investment cost, which is magnified for small scale farmers that cannot access loans easily as stated earlier. Small to medium scale farmers lack the knowledge to implement intelligent systems appropriately, lack access to consistent signal, connectivity and electricity supply, high cost of maintenance or repairs and inaccessibility thereof reduces the adoption of such new technologies. Additionally, the farmers struggle to understand and interpret returned data correctly to make an educated decision [34].

Fluctuations in market demand and prices cause uncertainty regarding return on investment of AMRs, making farmers reluctant towards adopting them. South African farmers are very traditional, they believe "the old way is the best way". They are agnostic of the long-term feasibility of new technologies, due to its lack of proven field success. Finally, low labour costs and the possibility of job loss, potentially cause employees to threaten farmers in some cases, further deters farmers from adopting new technologies. These before-mentioned factors all contribute to the slow adoption of new technological agricultural practices in South Africa's citrus industry.

The GLOBAL G.A.P. requires an external audit, performed by an independent certification body (CB), to be performed on all exporting citrus farmers. CBs uses a principles and criteria (P&Cs) checklist to ensure that farmers adhere to the various exporting requirements and regulations. CBs are responsible for uploading the results to the GLOBAL G.A.P.'s IT systems for approval. Through developing an affordable agricultural technology that simplifies complying with the GLOBAL G.A.P.s' and Local GAP standards, small farmers can gain access to markets more easily. This is the niche market that was identified that can increase small farmers reliability, credibility, accountability and economies of scale, increasing their exposure or access to markets. An intelligent system that can perform various functions to assist small farmers without causing job loss was the primary objective.

The data that was collected through performing the system development process as stated in 2.2 will now be portrayed.

The objective tree and functional tree as described in Phase 1.1 and 1.2 can be seen in Figure 5.

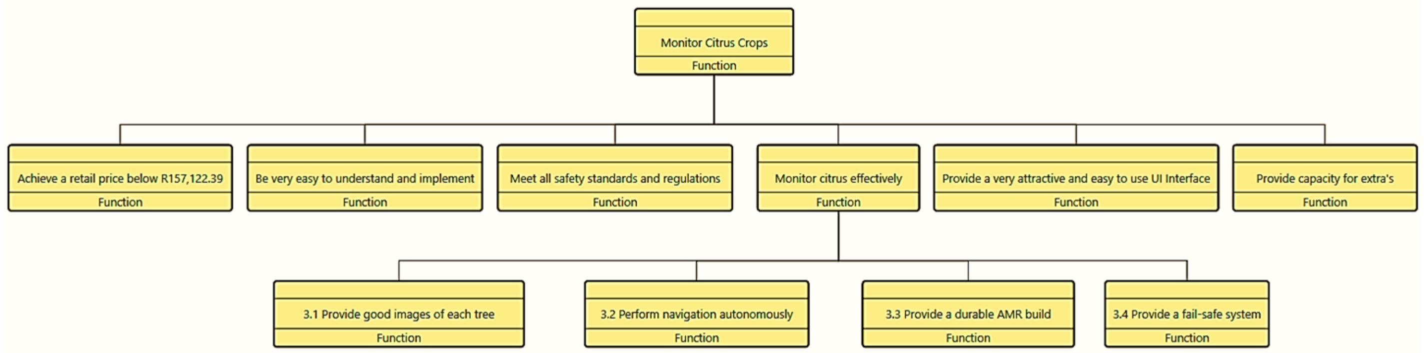


Figure 5. [Phase 1.1 and 1.2] Objective tree trickling into the sample functional tree of the robot.

The range of feasible technological options that were considered are shown in Table 1 below**.**

Table 1. [Phase 2.3] Feasibility definition: Range of feasible technologies or techniques.

Components	Options
SSD	SSD, SD Cards, MicroSD, Embedded Storage
Camera sensor	CMOS sensor, CCD Sensor
Camera interface	USB 3.0, Gige Gigabit Ethernet Interface, HDMI interface

Camera resolution	HD (720p), Full HD (1080p), 2K (1440p), 4K (2160p)
Camera	E-Con Systems See3CAM_CU130, Logitech C920s Pro HD Webcam, Arducam 12MP USB Camera Module, HuddleCamHD 12X USB 3.0 PTZ Camera, Intel® RealSense™ Depth Camera D435, Alvium 1800 U-1242, Logitech BRIO Ultra HD Pro Webcam
Wireless communication module (3G/4G module)	SIMCom SIM7600 Series, Quectel EC25, u-blox SARA-R4 Series
Navigation sensor (GNSS)	u-blox NEO-M8N, Beitian BN-880, Garmin GPS 18x LVC, Drotek XL GPS Module, SparkFun GPS-RTK2 Board, Adafruit Ultimate GPS, SkyTraq Venus838FLPx, Quectel L86 Compact GNSS, Trimble BX940
IMU Sensor	MPU-9250, Bosch BNO055, ICM-20948, BN0085, BN0086, LSM9DS1 (Adafruit)
LiDAR Sensor	RPLIDAR A1M8, Okdo Lidar Module with Bracket Development Kit for LiDAR_LD06 Raspberry Pi SBC, SFB000/B, DFR0315, SF30/c, 114992561, 101090022
Ultrasonic sensor	HC-SR04, CUSA-TR80-15-2000-TH, CUSP-TR80-18-2400-TH, CUSP-TR80-15-2500-TH, CUSP-TR80-15-2500-TH, CUSA-TR60-06-2000-W68, CUSA-TR80-065-2000-TH68, UTR-1440K-TT-R, CUSA-TR60-06-2000-WC68, CUSA-TR65-065-2200-WC68
RTK GPS Module	u-blox ZED-F9P, Here3 RTK GPS Module, Emlid Reach M2, SparkFun GPS-RTK2, Navspark NV08C-CSM, Drotek Sirius RTK GNSS, Ardusimple SimpleRTK2B, Swift Navigation Piksi Multi, Trimble BX940, Holybro Pixhawk 4 GPS Module
Frame and chassis	Online bought chassis options Bogie Runt Rover (with all-terrain wheels) Dagu Wild Thumper 6WD All-Terrain Chassis 4WD Research Robot Chassis—Rough Terrain 4WD Research Robot Chassis—Rough Terrain 5 kg Load 4WD Robot Car 12 V DC Motor Off-Road Wheel Chassis for Arduino Robot DIY Whipper Snapper Runt Rover BeeLine Chassis Kit V2 HammerHead Chassis Kit Recon Chassis Kit
Motor	Brushed DC motor, Brushless DC Motor, Stepper Motor
Motor controller	Brushed DC motor controller, Brushless DC Motor controller, Stepper motor controller
Suspension	Independent suspension, Torsion bar suspension, Spring suspension, Rubberized suspension
Battery Management system (BMS)	The battery system of choice will have a battery management system built in
Battery	Lithium Iron Phosphate (LiFePO4) Batteries, Lithium-ion (Li-ion) Batteries, Deep cycle acid batteries The battery system must be able to supply a constant output of at least to ensure that malfunctions does not occur.

Micro Controller	Arduino Uno, Arduin Mega 2560, ESP32, Teensy, Raspberry Pi Pico, Raspberry Pi 4, STM32F103C8T6 (Blue Pill), NVIDIA Jetson Nano, Raspberry Pi 4
Flight controller	Pixhawk PX4, ArduPilot APM 2.6, Navio2
Software	
Database	PostgreSQL, MySQL, SQLite, MongoDB, MariaDB
Fault detection and recovery software	Mission Planner, QGroundcontrol
Power management software	ArduPilot, PX4 Autopilot
Flight planning software	Qgroundcontrol, MissionPlanner, Universal Ground control software (UGCS), APM Planner 2.0
UI Interface	Qgroundcontrol, MissionPlanner, Universal Ground control software (UGCS), APM Planner 2.0
API	MAVLink, DroneKit, ROS API, Mapbox API, QGroundcontrol API, DJI SDK, AUterion SDK
Object detection and avoidance software	YOLO, Tensorflow, OpenCV, AirSim (Microsoft), NVIDIA DeepStream, DJI SDK
Geotagging software	QGIS with GPS tool plugin, Geosetter, GPS Phototagger, ArcGIS, Mappt
GIS Software	QGIS, ArcGIS Online, Google Eath Engine, Mapbox, GRASS GIS
Navigation Software	PX4 Autopilot, ArduPilot, DJI A3/N3, Auterion Enterprise PX4

3.1.2. Data Analysis

The model identified that the WTP for a 40-hectare orange farm (the middle between small to medium scale farmers) is R767,016.63 (This was sourced from my final year dissertation which used a mixed-integer linear model to determine the feasibility of autonomous machinery for citrus farmers). This however is assuming that the farmer only exports their produce. The price per kilogram to export oranges according to the Joburg market daily prices is R27.98/kg and R6.45/kg local. Thus, the WTP for an orange farmer supplying produce locally is R176,840.55. The second source identified that the WTP is R190,000 and the last source identified that the WTP is 349.98$/acre, this converts to roughly R104,526.605 WTP for a 40-hectare farm [35,36]. When these 3 are combined the average WTP is R157,122.385 for autonomous machinery.

Feasible design concepts were analysed, with the choice between a drone or an AMR. The objective and functional tree, Figure 5, portrays all the functions the robot must be capable of performing to adhere to the operational requirements or objectives of the robot. As numerous diseases originate on the stem of the tree, early detection on the bottom of leaves is critical which means the robots functionality to navigate underneath the trees is vital. The AMR was selected for its ability to perform more functions than its competitor. The drones increased software costs for navigating underneath trees, lack of independent tree field monitoring capabilities, and its' durability concerns made the AMR the most optimal choice. A feasible AMR concept in terms of capability and estimated cost was defined by analysing various trade-offs to generate an initial list of physical requirements that can perform the basic functions.

Two AMR design concepts were identified: Design option 1, capable of object avoidance, and Design option 2, capable of both object avoidance and object detection. The updated operational requirements were developed based on operational scenarios.

Four sub-systems were identified for the AMR: camera, operational software, functional software, and exoskeleton. These sub-systems were expanded into components and part level as seen in Figure 6. The various potential technological components and software options, Table 1, were identified and then validated trough an accessibility versus cost analysis. The most optimal options were highlighted and chosen, in some cases one was directly chosen, or two, three or four. This identified the final candidate options.

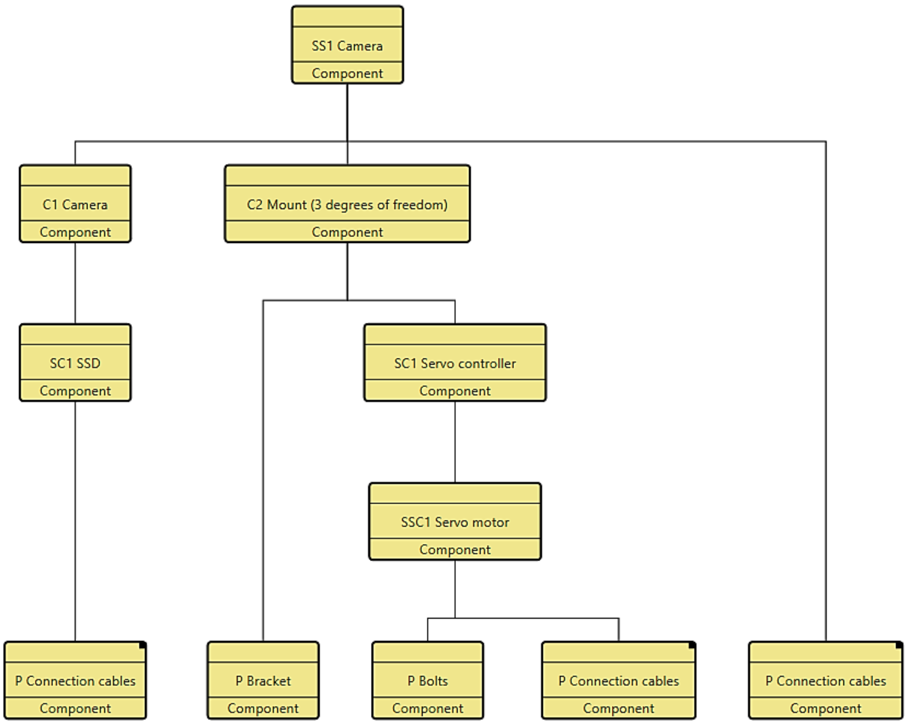


Figure 6. [Sub-phase 3.2] Sub-system hierarchy to part level of the camera software sub-system.

Final candidate options, as seen in Table 2, were evaluated based on various factors, with the highest-scoring components being selected. Some components with equal scores underwent further analysis to ensure suitability. For the decision between the that were a tie at the end of Section 2.3 Concept selection this is the explanation to the options that were chosen. For the databases PostgreSQL would be a strong choice for scalability and robustness. PostgreSQL—as the AMR must have the ability for extra customization and much room for improvements SQLite will cause problems due to the data size limitation, and as the whole world is moving to online databases, thus SQLite will not work, and backup and recovery is vital for the rover to function properly and accurately.

Table 2. [Phase 3.3] A sample of the components and software options validation analysis on based various factors for (**a**) Battery Systems; (**b**) LiDAR Sensors.

Options	Affordability	Consistent power output	Prone to malfunctions	Efficiency and effectiveness	Longest battery life	Most feasible and optimal	Strongest current	Most reliable	Best for outdoor use	TOTAL SCORE
LifeP04	0	1	1	1	1	1	1	1	1	8
Deep Cycle	1	0	0	0	0	0	0	0	0	1
Li-Ion Batteries	0	0	0	0	0	0	0	0	0	0

(a)

Options	Affordability	Accuracy and precision	Most effective and efficient	Durability and robustness	Best for outdoor use	Most versatile and adaptable	Best for citrus fields	Fastest response time	Best for object avoidance	Compatibility and integrability	Best battery power management	TOTAL SCORE
RPLIDAR	0	0	0	0	0	0	0	0	0	0	0	0
DFR0315	0	1	1	1	1	1	1	1	1	1	1	10
101090022	1	0	0	0	0	0	0	0	0	0	0	1

(b)

The internal storage system, SSD, was found to be the most optimal with these three options to acquire the needed 5 TB of storage. The options are (1) One 1 TB and two 2 TB SSDs priced at R10,545.85, (2) Three 1 TBs and one 2 TB SSD priced at R9,828.265, (3) One 1 TB and one 4 TB SSD priced at R10,018.91. Through using three main online database namely; Takealot SA (https://www.takealot.com/), Pricecheck [37] and RS Components [38] the accessibility and cost were determined for each design options. These were the results for the average cost of each combination. Option 2 for SSDs is the cheapest but the most complex due to managing four drives, increasing potential points of failure. Option 1, though the most expensive, also adds complexity. Option 3 is the most feasible, being affordable, easy to manage, and less prone to errors, making it the best long-term choice.

The cost of the motors, suspension, different sensors, microcontroller, battery system and modules were also done in the same method as stated above through using Digikey [39], RS Components, and GeeWiz [40]. The motors must be able to power the wheels up an incline of 60 degrees. To determine the torque (T) output that the motor must be capable of:

$$T = M\,(a + g * \sin\theta)r \tag{3}$$

where, Assumed weight of the robot: $M = 5$ kg

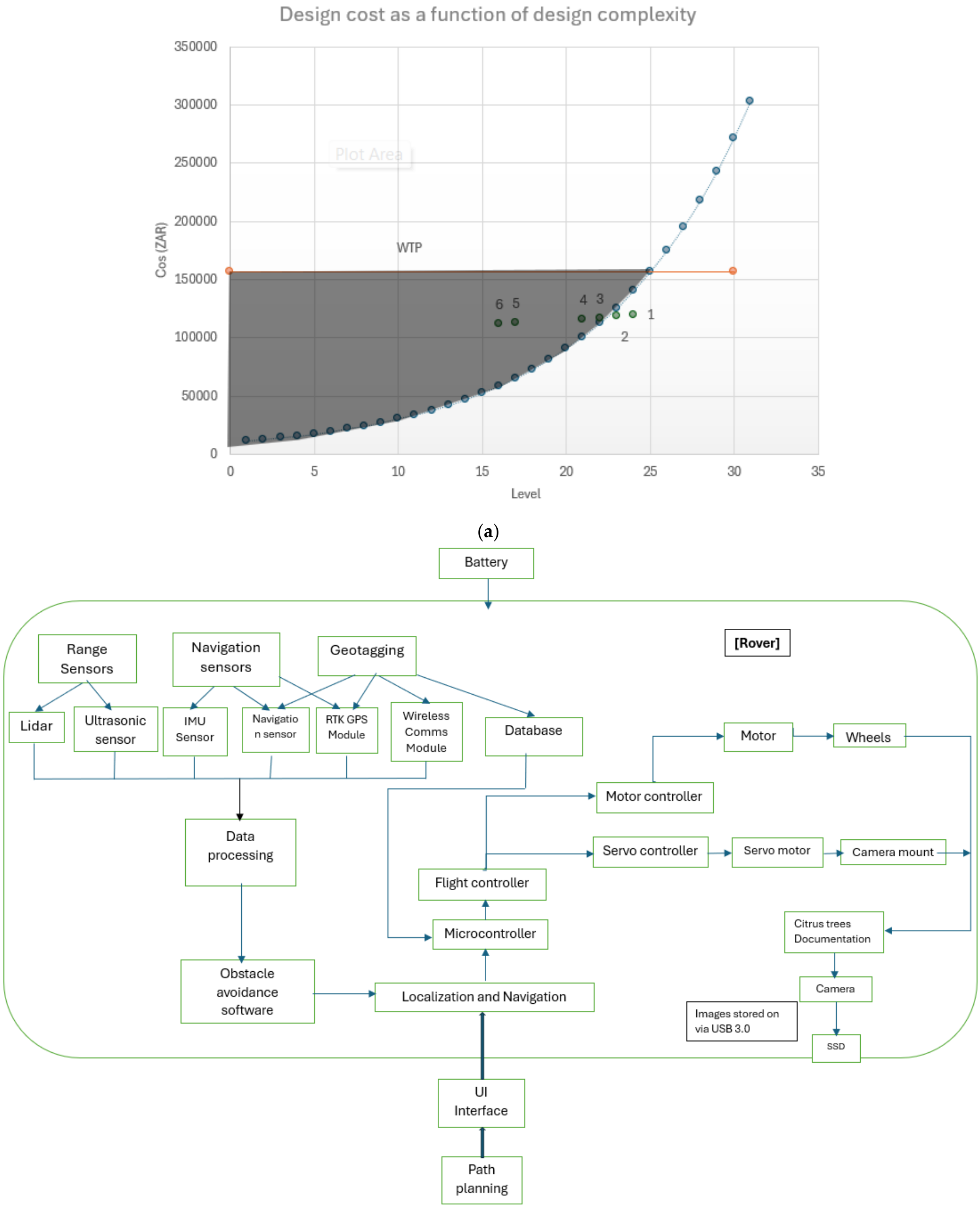
Minimum Speed: $v = 0.79$ m/s
Maximum incline to climb: $\theta = 60$ degrees
Reach maximum speed in one second: $a = 0.79$ m/s^2
Drive wheels will be at least 250 mm in diameter: $r = 0.125$ m
Minimum T = 5.804 Nm, thus 1.451 Nm per motor

A cost versus complexity graph validated the exoskeleton material design, showcasing that design options 3–6 were feasible (Figure 7a). The options were (1) 3D printed chassis and cover, (2) 3D Printed chassis and plastic cover, (3) Steel chassis and 3D printed cover, (4) Steel chassis and plastic cover, (5) Online chassis and 3D printed cover, (6) Online bought chassis and plastic cover. A custom steel frame is ideal for the rover as it offers lower costs, flexibility, and the ability to navigate rough terrain. Articulating suspension ensures all wheels stay grounded on uneven surfaces, reducing tipping risks. The robot will have four independent motors and skid-steering for improved maneuverability. For the cover plate, 3D printing is preferred due to its customizability, lower complexity compared to injection molding, and environmental benefits through reduced waste and use of biodegradable materials like Polylactic Acid (PLA).

The final overall design component, software and material options for the AMR and the functional block diagram, in Figure 7b, was developed. The final candidate solution was be determined through the design concept with the maximum Xi + Yi (Equations (1) and (2)):

The markups were also included to retrieve the final total value.

Design option 1, costing R116,499, is the most feasible solution, as seen in Table 3, being roughly R40,000 cheaper than design option 2, costing R153,499, and far below the WTP. Design option 1 leaves room for customisation of additional functionality before reaching the WTP as opposed to design option 2. Design option 1 does not facilitate any live pest detection or disease detection capabilities, it is seen as a "development kit". The design has an internal storage system (5 TB SSDs) to store images and analysed through the user's desktop, reducing the overall cost of the design significantly. Farm employees appointed to detect pests and diseases, called "scouters", can perform other tasks and use these geotagged images to identify pests and diseases, thus not relieving them of their employment. This reduces human error, increasing detection accuracy as the analysis is performed in a controlled environment.



(**a**)

(**b**)

Figure 7. (**a**) Design option 1 design cost as a function of design complexity graph feasible design concept for the various material combinations; (**b**) Functional block diagram of the AMR.

Table 3. Final design option calculation table.

Price	Design Option 1 s Value (Xi + Yi)	Design Option 2 s Value (Xi + Yi)
Normal Price	1.259	1.094
Normal Price + 5% markup	1.221	1.046

Normal Price + 10% markup	1.184	0.997
Normal Price + 15% markup	1.147	0.948
Normal Price + 20% markup	1.110	0.899
Total	**5.922**	**4.984**

Small to medium scale farmers will have easier access to local markets as the documented images can improve their credibility and accountability towards adhering to the "Local-GAP" requirements. As stated in the previous paragraph the design does not remove employees from the farm but instead aids them in performing their duties more effectively.

3.1.3. Model Validation

The inability of competitor products to navigate through citrus fields, particularly underneath the trees, combined with their extremely high costs, is their achilles heel. This research article demonstrated that small-to-medium-scale South African citrus farmers can be given a competitive advantage through the design of an affordable autonomous mobile robot (AMR) for ground-level citrus documentation, priced at approximately R120,000. In contrast, companies like DJI, Wingtra, and Aerobotics robotic options, ranging from R332,981.5 to R462,500, cater only for large scale farmers. Companies such as Aerobotics, FarmWise, AgXeed, and Deepfield Robotics specialise in aerial monitoring and disease detection, not developing ground-level citrus monitoring systems. Other AMRs, such as Bonirob by Deepfield Robotics, priced at roughly R2,817,600, are inaccessible for small scale farmers. Additionally, these AMRs are focused on techniques or areas that this proposed AMR will not be aimed at entering [41–43].

The Huanglongbing (HLB), commonly known as the citrus greening disease, poses an enormous threat to orange juice availability in supermarket shelves. HLB has caused a 90% production loss, equating to \$3 billion and half of the associated jobs [44]. As illustrated in Figure 8, HLB causes distinctive yellow mottling on the leaves of infected citrus trees, which ultimately leads to deformed and bitter fruits. Given the highly infectious nature of this disease and the risk it poses to the entire citrus industry, the European Union has introduced export regulations that require suppliers to implement appropriate surveillance and contingency plans. Surveillance is a crucial element in managing HLB, and France has deployed dedicated units for this purpose. This proposed AMR could revolutionise surveillance through enabling early detection of infected leaves. Since the disease originates at the stem of the tree before spreading, this AMR could assist in identifying infected trees from beneath the tree, enhancing efforts to contain the disease.

Moreover, the proposed AMR model can theoretically perform each of the required functions in Figure 5. The AMR will also be more than capable of navigating through the harsh environment due to its strong chassis, durable wheels and suspension and weather resistant cover. The AMR will also be more than capable of navigating through the field, even if a malfunction or large object is encountered, as it only uses roughly 22.5% of the battery power capacity when performing one cycle of citrus tree documentation on a 40-hectrae farm. With the stated motor choice and wheel size the rover is expected to travel at a speed of 0.79 m/s. To calculate whether the rover will be capable of navigating through the 40-hectare field without losing power the following equations were performed:

Assuming a reasonable pattern and path optimization, it is estimated that the total distance the rover would need to cover is roughly twice the square root of the area. The exact number would depend on the number of obstacles, tree placement, and more. The distance traveled is calculated as follows.

$$Distance = 2\ x\ \sqrt{Area} = 2\ x\ \sqrt{400{,}000} = 1264.92\ \text{m} \tag{4}$$

$$Time = \frac{Distance}{Speed} \backsimeq 1600\ \mathrm{s} \backsimeq 27\ \mathrm{min} \quad (5)$$

To determine whether the chosen battery system GeeWiz 12 V 50 Ah Lithium Ion LiFePO4 battery can power the system with a peak current draw of 25 A, the following equations were used:

$$Battery\ life = \frac{50\ \mathrm{Ah}}{25\ \mathrm{A}} = 2\ \mathrm{h} \quad (6)$$

This indicates that the battery system is more than capable of supplying enough power for the rover to navigate through the field successfully. The system will use roughly 11.25 Ah of energy on each run, leaving 38.75 Ah unused.

(**a**) (**b**)

Figure 8. (**a**) Leaf of a citrus plant infected with Huanglongbing (HLB) disease; (**b**) **C**itrus fruits infected with Huanglongbing (HLB) disease.

4. Conclusion and Recommendations

The South African agricultural industry faces numerous challenges due to economic, socio-political, and social. This has increased rules and regulations which restrain citrus farmers as it increases costs drastically. Intelligent systems are being utilised by large-scale farmers but is too costly for small to medium-scale farmers. This project affirmed that it is possible to exploit the “Local GAP” niche market through designing an affordable fully autonomous AMR capable of navigating through the South African citrus field successfully. The AMR will be revolutionary as it will aid in early detection of diseases as the stems and leaves can be inspected from a never-before-seen angle to control the outbreak of numerous diseases and pests. This will increase small to medium scale farmers’ credibility, reliability and accountability for meeting the stated food requirements and regulations through the documented imagery of each tree. Assisting them to gain access to markets and compete against large-scale citrus farmers. Additionally, the AMR model will not contribute to the high South African unemployment rate as employees will not be laid off if the system is adopted. With the assistance of governmental bodies, assisting users financially that cannot afford the AMR or a desktop, this project can help all South African citrus farmers to gain access to local markets and be competitive.

A key advantage of this recommendation / proposal is that the resulting system can be upgraded to facilitate more functions in the future, provided a reduction in the associated costs. The reduction can be achieved as follows. The project showcased that the largest “variable cost” is the software complexity cost that correlates to the functionality of the AMR. This software development cost, however, is only a once-off cost that can be exploited with economies of scale. The costs incurred per AMR are the local 5 TB database cost and the hardware or components costs. Through utilising economies of scale, the ‘once-off’ R&D software costs can be spread out over the number units sold. For example, if 10 units as sold the once-off software development cost will be R5550 per unit, thus making the final AMR price R66,549.26. This allows room for more functionality to be added to the AMR in future.

This AMR model can be utilised by the GLOBAL G.A.P. some day to potentially aid in external audits. The collected images over the course of pre-harvesting until harvesting can act as criteria to meet the stated principles of the GLOBAL G.A.P through showcasing their lack of diseases on their trees or if a disease or pest was identified that it was treated and cured after several weeks thereafter. As required per the EU to adhere to GLOBAL G.A.P. requirements to show surveillance management system as criteria to meeting the principles. These images can also be uploaded to a centralised cloud database weekly where CBs can verify whether farmers meet their stated principles with the images being used as the criteria to meet them. This will reduce their load of work when arriving at the farm and act as a potential centralised base where all principles can be verified. This AMR could act as a steppingstone for GLOAB G.A.P. and localised bodies to perform the "external audits" whilst creating new job opportunities.

Finally, a recommendation for future is enabling the AMRs' camera to lift higher off the ground to take a level photo of the citrus to identify citrus fruits and leaves on the top of the tree.

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