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**Projeto de um Rover para aplicações de
Agricultura de Precisão**

Tese de doutorado apresentada ao Programa de Engenharia Mecânica da Escola de Engenharia de São Carlos como parte dos requisitos para a obtenção do título de Doutor em Ciências.

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Orientador: Prof Assoc Marcelo Becker

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Abstract

Archila-Diaz, John Faber **Design of a Rover to Precision Agriculture applications**. 154 p. Ph.D. Thesis – São Carlos School of Engineering, University of São Paulo, 2016.

The population growth associated with natural resources shortage, food demand increasing and the lack of manpower for agricultural activities generate important challenges to agriculture and engineering. The challenges imply the improvement of productivity with fewer resources, This scenario is consisted parameters that generally are in opposite directions.

This work presents the development of a rover to agriculture (R2A) to support agriculture-scouting tasks, the tasks will be in the future important tools to improve the productivity and enable the use of less agricultural supplies.

The research presents the development of a rover for agriculture (R2A) to support scouting tasks; tasks that in the future will improve productivity and allowed the use of less agricultural supplies. The study begins with a bibliographic review of Robots for agriculture, Rovers, and agricultural Rovers developed by different research institutions. After the review is presented the work methodology based on mechanic and mechatronic design methodologies; in the development of the methodology are presented the general crop characteristics, the proposed of scouting tasks, the benchmarking developing mathematical models, CAD (Computer Aided Design) models, simulations and tests in order to know the different features of the Rovers and agricultural robots. Using the knowledge gained in the course of work is proposed the concept of a rover for agriculture R2A, the concept is compared in simulations, and developed the detailed design using CAE tools (Computer Aided Engineering) after it built a prototype and tested.

As results are presented comparative simulations of R2A, their mathematical modeling, R2A simulations in ideally conditions highlighting their skills, and finally R2A tests and comparison are presented.

Keywords: Mobile Robotics. Rover. Precision Agriculture. Pasive Suspension.

Resumo

Archila-Diaz, John Faber **Projeto de um Rover para aplicações de agricultura de precisão.** 154 p. Ph.D. Thesis – Escola de Engenharia de São Carlos, Universidade de São Paulo, 2016.

O crescimento populacional associado à escassez de recursos naturais, a crescente demanda alimentar e a falta de mão de obra para as actividades agrícolas geram importantes desafios para a agricultura e a engenharia. Os desafios implicam a melhoria da produtividade com menos recursos. O cenário é constituído por parâmetros que geralmente estão em direcções opostas.

O trabalho apresenta o desenvolvimento de um rover para agricultura (R2A) para suportar tarefas de *Scouting*, tarefas que no futuro melhorarão a produtividade e permitirão o uso de menos subministros agrícolas.

O estudo começa pela revisão bibliográfica de Robôs para agricultura, Rovers e Rovers agrícolas desenvolvidos por diferentes instituições de pesquisa. Após a revisão é apresentada a metodologia do trabalho baseada nas metodologias de projeto mecânico e mecatrónico; no desenvolvimento da metodologia são apresentadas as características das culturas de maneira geral, a proposta de tarefas de *Scouting*, o benchmarking desenvolvendo modelos matemáticos, modelos CAD (Computer Aided Design) simulações e testes com o intuito de conhecer as diferentes características dos Rovers e Robôs agrícolas. Usando o conhecimento no decorrer do trabalho é proposto o conceito do rover para agricultura R2A, o conceito é comparado em simulações, e feito o projeto detalhado usando ferramentas CAE (Computer Aided Enginnerring), após é construído o protótipo, e testado. Como resultados são apresentadas simulações comparativas do R2A, a sua modelagem matemática, simulações do R2A em condições ideais, destacando as suas capacidades, e finalmente são apresentados os testes e comparações do R2A.

Palavras-chave: Robótica móvel. Rover. Agricultura de precisão. Suspensão Passiva.

John Faber Archila-Diaz

**Design of a Rover to Precision
Agriculture applications**

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Doctor of Sciences.

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To my family and friends

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*“We cannot solve our problems
with the same thinking
we used when we
created them.”
(Albert Einstein)*

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List of Acronyms

AGV Automated Guided Vehicles

ASL Autonomous System Lab

AUV Autonomous Underwater Vehicle

AUVs Autonomous Underwater Vehicles

CAD Computation Aided Design

CAE Computational Aided Engineering

CD Coupled Differential

EESC-USP Engineering School of Sao Carlos University of Sao Paulo

FAO Food and Agriculture Organization

GDP Gross Domestic Product

ID Independent Differential

ITSS Independent Traction Steerable Systems

JPL Jet Propulsion Laboratory

LRH Legged Robots and Hybrid (Legs and wheels)

PA Precision Agriculture

PIAP Industrial Research Institute for Automation and Measurements

R2A Rover to Agriculture

SENA Embedded Assistive Navigation System

UN United Nation

UAV Unmanned Aerial Vehicle

UAVs Unmanned Aerial Vehicles

UGVs Unmanned Ground Vehicles

USAR urban search and rescue

List of symbols

α	Angular acceleration
β_1, β_2	Left and right bogie angles
$\check{I}$	Inertia tensor of robot
$\ddot{x}_r$	Robot Acceleration in x
$\dot{\phi}$	Agulat velocity around the Z-axisAgulat velocity around the Z-axis
$\dot{\rho}$	Angular velocity around the Y-axis
$\dot{\theta}_r$	Robot angular velocity
$\dot{\theta}$	Angle of rotation
$\dot{\varphi}$	Angular velocity
$\dot{\xi}_r$	State variable vector (Robot)
$\dot{\xi}$	State variable vector
$\dot{r}$	Angular velocity around the x-axis
$\dot{x}_r$	Robot velocity in x
$\dot{x}$	Linear velocity in X
$\dot{y}$	Linear velocity in Y
$\dot{z}$	Linear velocity in Z
η	Slip and steering rates sum
γ_j	Rotation about z according D-H
$(\dot{\theta}_i, \dot{\Psi}_i, \dot{\beta}_i, \dot{\rho}_i, \dot{\zeta}_i)$	Angular rates

ω_i	Rotational velocity of system i inertial system
ϕ	Rotation about the Z-axis
Ψ_1, Ψ_2	Steering angles
Ψ_i	Steering angle
ρ	Rotation about the Y axis
ρ_1, ρ_2	Joint angle between the smaller rockers and the main rockers
θ	Angle of rotation
θ_i	Rotation wheel angle
ϑ_i	Velocity in i inertial system
$\vec{\vartheta}$	Velocity vector
$\vec{w}$	Angular velocities
ζ_i	Wheel slip
${}^i\bar{X}\bar{Y}$	Vector from X to Y expressed in coordinate system i
${}^j_iR(\alpha)$	Transformation from system j to i by rotation of angle α
a	Accelerations
d	Distance between wheels
F	Forces
F_f	Friction forces
g	Gravity
I	Inertia
l	Robot length
M	Momentum
m	Mass
N	Normal force
p	Position vector
R	Rotation Matrix

r	Wheel radius
R_w	Wheel radius
T	Torque
$T\hat{R}, \hat{M}i$	Instantaneous transformation
V	Robot speed
V_l	Tangential velocity left wheels
V_r	Tangential velocity right wheels
x	Position in x
X_{Ai}, Y_{Ai}, Z_{Ai}	Wheel coordinate system
X_o, Y_o, Z_o	Inertial coordinate system
x_r	Robot position in x
X_R, Y_R, Z_R	Gravity center of the robot
y	Position in y
y_r	Robot position in y

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Introduction

According to the United Nation (UN) - the current world population is 7.4 billion. It will reach 8 billion in the next ten years. In 22 years, there will be 9 billion people. Therefore, food production will have to increase 70% until 2050, according to Food and Agriculture Organization (FAO). Increasing food production in a sustainable way is mandatory since climate has changed dramatically and supplies are less available.

The principal sources for agriculture production are land and water. Few countries around the world have resources available i.e. India, Brazil and Colombia. Due to the fact that the population of the world is growing considerably, and that food resources are limited, it is obligatory that current methods of food production become more expeditious and more efficient. For this reason, it is important to make use of new techniques and technologies to support agriculture production.

Nowadays, Brazilian economy is supported by commodities exploitation, especially agriculture production (Embrapa, 2014). Brazilian agriculture is one of the engines of its economy accounting for about one quarter of Gross Domestic Product (GDP), according to the Center for Advanced Studies in Applied Economics (Cepea, 2015). In a global view, Brazil is the largest producing and exporting country of orange juice, sugar cane, soybeans, chickens, coffee, beef, pork, maize and cotton. This statistic grows year by year and achieves new productions records (Foreign Agricultural Service/USDA, 2016). It sets Brazil as a major producer and exporter of food in the world.

Extensive agriculture aims to supply the demand of foods in the world. To attend the requirements of this kind of agriculture, the use of new techniques contemplated by Precision Agriculture (PA) and new technologies is necessary. Some of the new technologies to be applied in agriculture production are provided by mobile robotics. They are used to automate repetitive tasks, assist specific needs of each plant in the crop and reduce risk for operators. Some robots and machines are able to weed, apply pesticides, mow, spray, thin, and prune.

These new technologies present considerable challenges. The agricultural environment, for instance, has spatial and temporal variability. It consists of an unstructured

environment, which poses big challenges for outdoor mobile robotics. In this scenario, the present investigation aims to develop a rover to be applied in agricultural environment. This robot is able to overcome obstacles, and support scouter equipment.

The first chapter introduces this investigation and briefly presents the objective of this investigation. The description of the main objective is followed by the delineation of specific purposes that were accomplished along the investigation.

A bibliographical review of outdoor robotics is in the second chapter. It starts with a general description and classification of some robots according to their locomotion systems. It is followed by a description of agricultural robotics applications, rovers and agricultural rovers. A chronologic classification regarding suspension is presented. It highlights mechanical characteristics, and simplified Computation Aided Design (CAD) diagram.

The third chapter presents the materials and methods. It shows how this investigation was conducted. It starts with the methodology and its different stages, such a general report on crop characteristics, scouting tasks, benchmarking. A detailed account of Rover to Agriculture (R2A)'s concept is also given. Finally, the Computational Aided Engineering (CAE) models that made the virtual prototype possible are presented.

Results supported by CAD and CAE tools are depicted in chapter four. One will be able to compare the behavior of passive suspensions in different situations. Maximum height of the obstacle to overcome, maximum torque, and maximum torque average are obtained from the simulations. Tests were performed to validate the rover prototype in even and uneven terrain. Finally, a comparison among R2A, Agricultural Robot AgriBot and Mirã Rover is presented.

The fifth chapter presents the conclusions of work highlighting the performance of R2A in even and uneven terrain. It also provides some comparison involving R2A and some robots.

1.1 Objectives

The present investigation aims to develop a rover to be applied in agriculture environment. This robot will be able to travel in even and uneven terrain and overcome obstacles. It will also be able to serve as a platform for agricultural scouting tasks. To achieve the principal objective the next specific objectives are necessary:

- Present a bibliographic review portraying the basic features of agricultural robots, rovers and agricultural rovers;

-
- Study the rovers and robots to understand their characteristics. The study involves the development of mathematical models, the performance of simulations and tests;
 - Adapt a methodology regarding the development of rovers for agriculture (R2A) based on mechanic and mechatronic design methodology;
 - Describe some scouting tasks that could be supported by R2A;
 - Present a conceptual design of a agricultural rover R2A based on the proposed methodology and research data;
 - Build a prototype of R2A and validate the concept in simulations, and tests.

Bibliographic Review

Mobile robotics is about eight decades old. The first register of works dates back from 1939 (SCHAUT, 2006). Its development is a result of the advances in Mechanics, Electronics, Cybernetics and Computer science. Nowadays, there are applications in different fields such as Logistics (Automated Guided Vehicles (AGV)), Industry (Partner Robot), Military (PacBot Robot), Navy (Autonomous Underwater Vehicle (AUV)), Aviation (AUV Unmanned Aerial Vehicle), Agriculture (AgriBot Robot), Sidereal Space (Curiosity), Automobilitics (Embedded Assistive Navigation System (SENA)) etc. Robots replace and assist the man in repetitive or hazardous tasks. The inclusion of this kind of robots in human activities and environments is imminent and corresponds to the present and future of our lives, (BECKER, 2012). Currently, one of the main foci of this discipline is outdoor robotics that is concerned with outdoor applications of robots.

2.1 Outdoor Robotics

One of the challenges in mobile robotics nowadays regards outdoor applications. There are several complications to develop functional systems for this kind of environment. The unstructured environment, the terrain type, the sensors response, and the traction system are some of the issues. The unstructured environment, for example, requires "real time" data acquisition and processing aiming to use the information and, therefore, plan the tasks. This information is acquired by the sensors and sent to the processors. The processors send the decisions to the traction system and they use their negotiation capabilities to travel in different outdoor terrains. This way, it is possible to define the route to be followed.

There are several applications and kinds of robots for outdoor environment. It is not possible to present all of them here. They regard different criteria i.e. the environment where the robot travels (Land: Unmanned Ground Vehicles (UGVs), Aerial: Unmanned Aerial Vehicles (UAVs), Underwater: Autonomous Underwater Vehicles (AUVs) and Polar); the kinematic models (CAMPION; BASTIN; D'ANDRÉA-NOVEL, 2011); the device that

the robot uses to move (Legged, Wheeled, Tracks) (ARCHILA; BECKER, 2013b). A review of locomotion mechanisms for outdoor robotics specific to urban search and rescue (USAR) may be found in Loughlin, Wang e Gu (2007). The classification proposed bellow is based on a significant characteristic: the locomotion system. This system may be used to classify the robotics outdoor applications.

Table 1: Outdoor robots Locomotion system classification.

TYPE	SCHEMATIC DRAWING (gray color corresponds to drive element, wheel with cross line is steerable)	EXAMPLES
1. Coupled Differential (CD) (2, 4, 6 wheels and Crawler) (EESC-USP Robot (FURLANETTI et al., 2012), Navy Talon (U.S. Department of Defense))
2. Independent Differential (ID) (Sand Flea (NOH et al., 2012), IBIS Industrial Research Institute for Automation and Measurements (PIAP))
3. Independent Traction Steerable Systems (ITSS) (Agribot (TABILE et al., 2011) and Curiosity Rover (STELTZNER; MARTIN; RIVELLINI, 2013))
4. Legged Robots and Hybrid (Legs and wheels) (LRH) (BigDog (RAIBERT et al., 2008), Workpartner (HALME et al., 2003))
5. Others (Snake (MELO; PAEZ; PARRA, 2012), Groundbot (GUO; LI; YUE, 2013))

Table 1 presents the classification following the different traction systems. It starts with CD or differential traction. In this category one has Navy Talon (U.S. Department of Defense) and EESC USP robot (FURLANETTI et al., 2012). In these examples, the

lateral wheels have one motor and the wheels can be interconnected in a way that is similar to a crawler system. The steering system uses the differential velocity among the lateral wheels to turn left, right or around its gravity center. It is a typical configuration of indoor robots. For outdoor application, the rough terrain makes this function more complex and the energy consumption may be high. This will be contemplated in chapter three.

Figure 1: Differential Robot

Figure 1 shows USP Robot at Engineering School of Sao Carlos University of Sao Paulo (EESC-USP). This robot has motors in the rear wheels and the front wheels are free. The rear wheels were development to obtain better traction in rough terrain and were made by rapid prototyping technique. Its dimensions are 500x 495x 350 mm and the total weight is 15 kg.

The second category is called ID. In this case, each wheel has independent traction. Some examples of this type are the Sand Flea (Boston Dynamics Lab) (NOH et al., 2012) and Ibis (PIAP). See Figure 2

Figure 2: Sand Flea and IBIS (Boston Dynamics and PIAP)

The ITSS is the third category. Autonomous cars in general, such as Ackerman type, SENA (RONCANCIO et al., 2012), AgriBot (DIAZ et al., 2013) and Rovers are some examples. Curiosity is also classified as ITSS and will be shown in detail in section 2.3.

Figure 3 presents SENA (PEDRAZA et al., 2014). This system uses a Fiat Stilo 1.8 Ackerman steering system and front traction. Equipped with lasers, cameras, IMU, GPS, it has five computers to process and assist the driver on the road.

Table 1 also presents the fourth type called LRH. Some examples are Atlas and Big Dog (RAIBERT et al., 2008). See Figure 4. These robots were developed by Boston

Figure 3: SENA LabRom EESC USP

Dynamics Lab. Both were designed to negotiate outdoor in rough terrain. According to the authors, Big Dog is the most advanced rough terrain robot. It walks, runs, climbs and carries heavy loads. Big Dog is powered by an engine that drives a hydraulic actuation system (SAUNDERS; RAIBERT, 2012). U.S. Patent No. 8,126,592. It has four legs that are animal-like articulated. It has compliant elements to absorb shock and recycle energy from one step to the next. Big Dog is the size of a large dog or small mule; about 3 feet long, 2.5 feet tall and weights 240 lbs. (Boston Dynamics) (WOODEN et al., 2010).

Figure 4: Atlas and Big Dog (Boston Dynamics)

Inside the third category we find robots with hybrid locomotion systems. They use legs and wheels i.e. Athlete (WILCOX, 2009), and Workpartner Robot (HALME et al., 2003). Workpartner, in Figure 5, is used mainly in outdoor environments and interacts with humans. The estimated weight of the platform is about 160 kg and the pay-load is about 60 kg. The actuation system is fully electrical and the power system is a hybrid one. It has a 3 kW combustion engine and battery. The locomotion system includes legs feet and wheels that may be used alternatively. It allows motion in three modes: with wheels only, with legs only, and hybrid locomotion with legs and wheels powered at the same time. When it uses the wheels, the machine is designed to reach 7 km/hour on hard and even ground.

Finally, Table 1 presents other types: Snake (MELO; PAEZ; PARRA, 2012), Spherical (GUO; LI; YUE, 2013) and Aerial (Sydney University). These examples do not have wheels or legs. They also have peculiar locomotion ways.

Figure 5: WorkPartner robot (Automation Technology Lab at Helsinki University)

Figure 6: Aerial robot in agriculture (Sidney University.)

Figure 6 presents an aerial robot applied to agriculture. Its locomotion system uses some propellers. Aerial Robotics is currently a low cost application and promisor field for Unmanned Aerial Vehicle (UAV). As mentioned previously, the locomotion system is a remarkable characteristic of mobile robots. For robots that are used in the agricultural field, this system is quite relevant since it allows the robot to move in the chosen path satisfactorily. Accidents in slippery terrains or sloppy areas may be avoided by using an adequate traction system in the robot.

2.2 Agricultural Robots

Today, there is considerable effort aiming to advance in robotic technologies to be used in the field in different segments: academic, research, development, as well as industrial. Figure 7 presents different approaches to robotics applications in agriculture by different universities, laboratories and industries around the world.

Figure 7 shows distinct robotic applications: a) RAM by NEPAS and Embrapa, (GODOY et al., 2010); b) Weeding Robot by Tijmen Bakker (BAKKER et al., 2010); c) Autonomous Crop Vehicle of Tillett and Hague Technology Ltda; d) The Weedy Robot

(a)

(b)

(c)

(d)

(e)

(f)

(g)

(h)

(i)

(j)

(k)

(l)

(m)

(n)

(o)

Figure 7: Robotic applications for precision agriculture

from the Faculty of Engineering and Computer Science University of Applied Sciences Osnabrueck (RUCKELSHAUSEN et al., 2006); e) Autonomous tractor developed at Copenhagen University (BLACKMORE et al., 2004); f) Autonomous Christmas Tree Weeder developed at Copenhagen University (HAVE et al., 2002); g) Hortibot by Rasmus Jorgensen. (JØRGENSEN et al., 2007); h) The Supportive Autonomous Vehicle for Agriculture by Piraeus Institute of Technology in collaboration with University of Thessaly (TRESSOS et al., 2007); i) The Modulaire tractor; j) Autonomous guidance projects at the University of Illinois at Urbana-Champaign (NOGUCHI et al., 1998); k) Weed Management by Norwegian Institute for Agricultural and Environmental Research (BERGE et al., 2012); l) AgriBot, precision agriculture robotic platform by NEPAS and Embrapa. (TABILE et al., 2011); m) Prospero, Collaborative robots for agriculture by David Dorhout; n) Exoskeleton by Tokyo University of Agriculture, (TOYAMA; YAMAMOTO, 2009); o) The AgRover robot Iowa State Lie Tang (KHOT et al., 2006). The robotic platforms previously described represent the different applications of robotics in PA engineering, e.g. application of fertilizers, data collection and weeding, among others. Different devices as electric motors, combustion engines, hydraulic systems, artificial vision, pH sensors, odometers, GPS (Global Positioning system), inertial navigation system and RF (radio frequency) are used. Most of these robots use ITSS according to Table 1. However, cases m and n in the Figure 44 use legs and an exoeskeleton system. A general scheme of hardware architecture for an autonomous mobile robot for PA is presented by Emmi e Gonzalez-De-Santos (2012).

Figure 8

Figure 8: General scheme of hardware architecture for an autonomous mobile robot for PA Emmi e Gonzalez-De-Santos (2012)

Figure 8 presents different sensors, controllers and communications systems to PA robotics applications. One may see the navigation system, weed detection system, scanner system, row and obstacle detection system and low-level actuation system, in a typical

architecture. The authors proposed some improvement in the architecture presented in Figure 9.

Figure 9: Architecture for agricultural robots Emmi e Gonzalez-De-Santos (2012)

The inclusion of agriculture robots or autonomous plant inspection (API) may positively influence production costs as presented by Pedersen et al. (2006). The study showed, in the case of field scouting task, the total cost of 15.6 Euros/ha/year, using API with an approximate value of the API of 35.000 euros, including the GPS system. Conversely, the use of traditional methods implies the cost of 19.4 Euros/ha/year. The cost of this technology was 27 euros/hr. It is important to highlight that the sensors applied in the robot navigation sub-system influence API cost, consuming 23.62% of economic resources in the robot design (ARCHILA; SILVEIRA; BECKER, 2013).

Most of the current agricultural robotics systems applied to agricultural environment are in the third category, which is ITSS (Table 1). They are robots that have special characteristics of torque and maneuverability. In this category, there is a sub category that corresponds to exploration rovers. They are contemplated below.

2.3 Rovers

The term Rover refers to a vehicle used especially to explore the land of a planet and/or its satellites. The first Rover was built in 1969, when the Russians tried to send the first rover called roving (remote controlled robot) to the moon. However, the mission failed during takeoff. In 1970, they sent Lunokhod 1 (Lunokhod-1) see Figure 10(a). It landed on the moon in November, 1970. Afterwards, NASA included Lunar Roving vehicles in their programs. These programs are Apollo 15, 16 and 17, in July, 1971, in April, 1972 and December, 1972, respectively. See Figure 10(b). In 1973, the Soviet Union sent Lunokhod 2. The rover in Figure 10(c) operated for about four months, traveled

Figure 10: Rovers used in the moon exploration

37 kms and sent around 80,000 pictures to be broadcasted on TV. In 1977, the Soviet Union planned to send Lunokhod 3. The mission was canceled, though. The most recent rover was sent to the moon, in 2013, by China. See Figure 10(d). The mission was called Chang'e and the rover was named Yutu ("Jade Rabbit"). This robot was designed to explore three square kilometers during its three-month mission CNSA (Chinese National Space Administration) on 28 December, 2015. The mission reported a new type of basaltic rock.

At the same time the moon was explored, Mars challenge began. The competition between the United States and Russia continued, as the Russians sent Marsokhod missions (KEMURDJIAN et al., 1992). Mission mars- 3 presented PROP- M Figure 11(a) that weighted 4.5 kg and carried a penetrometer, and a radiation densitometer for soil data density. 20 seconds after taking off to Mars communication with Mars- 3 and M - PROP was lost. (SPECTRUM, 2013), (KEMURDJIAN, 1998). NASA continued the studies, and undertook Viking 1 and 2 missions, in 1976 without rovers. See Figure 11(b). Nevertheless, it took them 20 years to send along Pathfinder Rover Sojourner (NASA) in Figure 11(c). The mission sent 559 pictures from Sojourner and 16500 from Pathfinder and 15 chemical analyzes of rocks and soil data with winds and weather factors. Data were sent between July 4th and September 27th, 1997. Later, in November 2004, a new mission was sent to Mars (acMER mision) carrying the twins Spirit MER – A and Opportunity MER - B (LINDEMANN; VOORHEES, 2005). See Figure 11(d). They landed in different places on Mars. Opportunity sent data of Mars from 2004 until 2010. The latest rover to arrive in

Figure 11: Rovers used in the Mars exploration

Mars was Curiosity. It landed on November 26th, 2011. Its real name is “Mars Science Laboratory”. The nicknamed is Curiosity (STELTZNER; MARTIN; RIVELLINI, 2013). See Figure 11(e). Curiosity is programmed with a standalone module and sensors to determine if Mars could support life and collect data. Each rover sent to Mars by NASA had different size as shown in Figure 11(f).

Other missions are being planned such as the Chandrayaan - 2 in Russia and India are also going to the Moon. ESA (European Space Agency) has a mission to Mars planned for 2018, and NASA plans a new mission to Mars in 2020.

Besides the research developed by Russian and American space agencies, other rovers have been developed by universities and research centers, such as: Solero, Figure 12(a), (THUEER; KREBS; SIEGWART, 2006); Carb Figure 12(b) (KREBS; PRADALIER; SIEGWART, 2010), Shrimp Figure 12(c) (SIEGWART et al., 2002), and Octopus Figure 12(d) (LAURIA; PIGUET; SIEGWART, 2002) all of them developed by D - MAVT in ASL, ETH Zurich

(a)

(b)

(c)

(d)

(e)

(f)

(g)

(h)

Figure 12: Concepts of Rovers

(ETHZ). The Athlete's Figure 12(e) developed by Jet Propulsion Laboratory (JPL) NASA, Micro 5 and 6 Figure 12(f) and (g) respectively, developed by AMSL (Autonomous Mobile System Laboratory) Meiji University Japan. Sherpa (Expandable Rover for Planetary Applications) Figure 12(h), is a rover developed by DFKI GmbH German Research Center for Artificial Intelligence.

Next, more details on outdoors robots will be presented.

2.3.1 Shrimp

Shrimp was presented in 2000, by Ecole Polytechnique Federale de Lausanne in the European patent EP 1118 531 A1 (CRAUSAZ et al., 2001). This rover is based on rhombus mechanism at the front and in the bogie. Shrimp has one wheel mounted in a fork in the front, one wheel in the rear and two bogies on each side. The passive suspension is able to adapt to the terrain and allows it to climb different obstacles. Its dimensions are as follows: about 0.6 m long and 0.2 m high. It is able to passively overcome obstacles of up to two times its wheel diameter and can climb stairs with steps of over 0.2 m according to Siegwart et al. (2002). The robot has six motorized wheels with a power of 1.75 W each. The total weight is 3.1 kg including 600 gr for the battery (12V, 2 A h). Figure 13 presents Shrimp climbing a step. The front wheel climbs first using its fork mechanism, as shown in Figure 13(a) and (b). After that, the parallel mechanism of bogies allows the negotiation of the step, according to Figure 13(c). Finally, the rear wheel climbs the step. See Figure 13(d).

Figure 13: Shrimp rover Siegwart et al. (2002)

2.3.2 Crab

There are five prototypes known as CRAB called CRAB 0, CRAB I, CRAB 2, CRAB 2.2 and CRAB 2.3 (ETHZ Autonomous System Lab). All of them have two parallel bogies connected to the bottom through the middle wheel and at the top with a rotational joint to prevent hyper-statism. The vertical middle levers of the bogies are placed at a $2/3 - 1/3$ ratio from the middle wheel in order to distribute the weight of chassis and payload evenly on all wheels (THUEER; KREBS; SIEGWART, 2006). Figure 14 shows this robot.

Figure 14: Crab rover Thueer, Krebs e Siegwart (2006)

CRAB is equipped with several sensors and other components allowing it to be an autonomous platform. The brain, senses, and neural system of the CRAB are presented in Figure 15. It shows CRAB's electronic components and their interaction.

Figure 15 shows an IMU (Inertial Measurement Unit), MT-9B. It is mounted on the body of CRAB. It provides absolute orientation (Euler angles) of the chassis. Figure 15 shows the Angular sensors based on a magneto-resistive technology (Autonomous System Lab (ASL)). The sensors measure the relative angle between the permanent magnet on the moving part and the sensor on the pivot joint axis. This system allows the robot to learn the complete state of the suspension mechanism. There are four angular sensors (two on each side).

The drive and the steering motor types are equipped with encoders. The drive motor encoders generate 380000 impulses per wheel turn, whereas the steering motor encoders generate 2144 impulse per degree.

The architecture presents a GPS, an EVK-5H integrated to the rover. This allows us to detect the positioning error of the rover with a 5m radius, as its data offer an absolute reference. The last prototype of CRAB has a monocular camera. It is a HD webcam from Logitech (Quickcam Pro 9000). It provides images of what lies ahead of the robot. This is the information used to determine the terrainability and trafficability based on past

Figure 15: Electronic Architecture of Crab Krebs et al. (2010)

experience. A stereo camera from Viderer (STH-MDCS2-C) provides three dimensional data about the environment. Its 9 cm baseline allows obstacle in the range of 1.2 to 10m to be detected. This data may be used to identify the obstacles. And finally, tactile wheel sensors provide the information about the wheel ground contact angles. This input to the model is necessary to compute the optimal torques in uneven terrains. See Carrasco, Krebs e Thueer (2007), Krebs et al. (2008), Risch, Krebs e Thueer (2009).

2.3.3 MER rovers (Spirit and Opportunity)

The twins Spirit and Opportunity were patented in 2004, US D488,093S (LINDEMANN et al., 2004). Each vehicle is approximately 1.4 m long and 1.2 m wide. Their solar panels are 2.25 m wide by 1.5 m long. In their fully deployed configuration, each rover is just over 1.5 m tall and has a ground clearance of about 0.3 m. (LINDEMANN; VOORHEES, 2005). The rovers are 6-wheel drive, 4-wheel steered vehicles with a rocker bogie suspension system similar in design to their predecessor Sojourner. The rovers have the ability to traverse over obstacles of at least 0.25 m, sloped terrains of at least 20 degrees tilt, and to travel distances in excess of 1 km over hard high-traction terrains and soft deformable soils. The vehicles center of mass is near the pivot point of the Rocker-Bogie suspension. The rovers have a maximum speed on flat hard ground of 4.6 cm/s. Nevertheless, under autonomous control with hazard avoidance, the average velocity is less than 1 cm/s. The rovers were designed to drive to many different science targets for investigations by the instrument payload. See Figure 16.

Figure 16: MER rover sensors and instrumentation (NASA)

Figure 17 presents the Rocker-Bogie suspension. Its mechanism keeps the six wheels in contact with the soil when it is traveling in uneven terrain. There are two key advantages to this feature. The first advantage is that the wheels' pressure on the ground will be equilibrated. This is extremely important in soft terrain where excessive ground pressure may result in the vehicle sinking into the driving surface. The second advantage is that while it is climbing over hard, uneven terrain, all six wheels will nominally remain in contact with the surface and under load, helping to propel the vehicle over the terrain.

The suspension had to be designed to absorb most of the impact loads the rover experiences during lander egress and surface traverse. The material used was titanium alloy Ti-6AL-4V. The rover body was attached to the suspension through a differential mechanism 4:1. This mechanism helps to equilibrate the loads and balance the contact wheels pressure in the soil.

2.3.4 Curiosity

The Mars Science Laboratory MSL nicknamed of Curiosity was patented in 2010 US D673,482 S (RIVELLINI et al., 2013). It is a rover with six drive wheels and four steering wheels and Rocker-Bogie suspension mechanism, just as MER Rovers predecessors. It is approximately 900 kg heavy. The rover is powered by a radioisotope thermoelectric generator (RTG) that produces approximately 110W of continuous electrical power. Rechargeable li-ion batteries provide approximately 1600Wh of usable energy storage each

Figure 17: Rocker bogie suspension MER rovers Lindemann e Voorhees (2005)

day. The energy budget allows the rover to be awake about six hours of each Martian day and it sleeps the rest of the time to recharge batteries. (Martian solar day, or sol, is 39 minutes longer than an Earth day). An active thermal control system includes a continuously-operating pumped fluid loop to control temperature of the hardware inside the rover while Martian ambient temperature fluctuates between approximately -80C and 0C every sol. Warm-up heaters are required on exterior actuators and cameras to ensure they are above a minimum operational temperature of approximately -50C before use. The rover communication system includes a low data-rate direct-to/from-Earth XBand transceiver. It also has a high data-rate UHF-band transceiver for communication with Mars orbiters for data relay with Earth. MSL is presented in Figure 18

Curiosity includes sensors to environmental monitoring, remote sensing, in-situ contact science and analytical instruments. Some of them are: The Remote Sensing Mast (RSM), the stereo monochromatic navigation cameras called NAVCAMs and the stereo color science cameras - MASTCAMs. The laser induced breakdown spectrometer and telescopic imager (CHEMCAM) for in-situ investigation is also mounted on the mast. A 5-degree of freedom robotic arm enables precision placement of three tools and two instruments on rock and soil targets. This includes a rotary percussive drill that can gather material from up to 6.5cm inside rocks. The dust removal tool (DRT) is a small rotary brush to remove dust from rock surfaces. These two instruments include the microscopic hand lens imager (MAHLI) and LEDs for illumination. Alpha-particle X-ray Spectrometer (APXS) is a spectrometer to determine elemental composition of surface material. The two analytic science instruments include chemistry and mineralogy (CheMin), an x-ray diffraction instrument for determination of sample mineralogy. The sample analysis at Mars (SAM) is an instrument suite including a gas chromatograph, mass spectrometer and

Figure 18: Self-Portrait by Curiosity Rover Arm Camera (NASA)

tunable laser spectrometer for chemical analysis of surface material as well as atmospheric samples. The rover operation required the science and engineering teams to work closely together each day to plan the next sol (day) operations based on the outcome of the activities during the previous sols. The daily surface mission activities fall into four basic types: remote sensing, driving, contact science, and sample science. (WELCH; LIMONADI; MANNING, 2013).

2.3.5 Exo-Mars

The rover ExoMars will be sent to Mars in 2018 for the ESA (European Space Agency). See Figure 19. It was designed as a result of analyses and evolution of seven concepts of previous rovers. They are: RLC Concept C, D and E (originally by RCL - Transmash Russia), CRAB (ETHZ - EPFL), 3-Bogie and V Bogie proposed by Astrium, and Rocker Bogie (NASA – JPL). 3-bogie concept was considered the preferred arrangement. The rover has six drive wheels and six steering and tactile wheels. This design does not use the differential system used by Rocker-Bogie that decreases the weight, which means that stability is better. The rover has tactile wheels that improve the contact with the soil and the traction. (PATEL; SLADE; CLEMMET, 2010).

Since spatial rovers were presented here, it is important to highlight that all of them present low-energy consumption thanks to the suspension system that allows them to

Figure 19: Exo-Mars (ESA)

travel in uneven terrain and overcome obstacles without more actuators. They were developed to explore the Moon and Mars, which have uneven terrains that are somewhat similar to the ones we find in plantation fields. In order to explore these fields, considerable research has been carried out. Some findings are presented below.

2.4 Agricultural Rovers

In the bibliographic review two applications considered as agricultural rovers were found, i. e. Autonomous Prime Movers (APM) and AgriRover. They will be presented in this section.

2.4.1 Autonomous Prime Movers (APM)

Autonomous Prime Movers are “agricultural rovers” developed by Bergerman, Singh e Hamner (2012). These vehicles were developed to special crops (like fruits, vegetables, horticulture an floriculture), which need intensive cultivation. This means that the cost is significantly high, since it involves considerable work force. Regarding farm economy, the past decade presented the increase of 20% in the net value (from 38% to 58%). As Bergerman, Singh e Hamner (2012) observes, “In addition to labor costs, an increasing consumer demand for a safe, affordable, traceable, and high quality food supply, and the need to minimize the environmental footprint, represent key challenges for specialty crop sustainability in the United States. Given the past history of abundant supply of low-cost labor, few technological solutions to increase production efficiency have been viable. The current climate gives us an opportunity to use recent technological advances to not only increase efficiency in production of specialty crops but also to support a domestic industry in engineering solutions for specialty crops”

Among the technological solutions, one may find The APM (Autonomous Prime Mover). APM are vehicles with “Reconfigurable mobility” and low-cost, equipped with

lasers and computers. They may harvest and ease tough tasks. They consist of electrical platforms with automated routines as row following, row turn, and row entry. They are autonomous orchard vehicles that can be reconfigured and program tasks year-round for several operations. Figure 20 presents workers using the platform in a crop of green apples.

Figure 20: Autonomous vehicle Kohanbash et al. (2012)

2.4.2 AgriRover

The AgriRover is a commercial platform developed in New Zealand to be applied in PA, (MANDERSON; HUNT, 2014). The authors classified the robot as an Agricultural Ground Vehicle (AGV). The robot weights 150 kg with four 180 watt motors capable of handling uneven ground at 5 km/h and small slopes of less than 20 degrees. See Figure 21.

Figure 21: AgriRover (MANDERSON; HUNT, 2014)

The AgriRover was developed to map and monitor within-paddock variability of grazed pastures. Several applications have been considered: mapping of soil properties of grazed pastures, spatial and temporal monitoring of soils and pasture, generation of prescription

maps, soil real-time treatment and dye-marking of patches. This AGV has also general purposes such as a remote control and video feedback for other farms tasks. A GPS guided robot for the purpose of gathering dairy cows to the milking shed is being developed and will present all the features mentioned above. The robot has four wheels drive and differential skid steering. It is classified in the second category, according to Table 1 (ID).

2.5 Robot classification according to passive or active suspension

Several Rover and robot types were presented in the previous section. It is possible to classify them by their suspension mechanism - passive and active suspension (SIEWART et al., 2002). A summary is presented in Table 2.2, Table 2.3 and Table 2.4. All tables highlight the mechanical characteristics, the simplified CAD diagram and chronological development. Table 2 presents passive suspension rovers; Table 3 presents active suspension rovers; and Table 4 presents passive suspension outdoors robots.

Table 2: Passive suspension rovers.

ROVER	IMAGE	CAD
<p>Lunokhod 1, 2 and 3: 1969</p> <p>Eight independently powered wheels. Independent suspension in four bogies, electric motors. 2.3 m long. Two speeds, 0.27 m/s and 0.55 m/s. 756 kg (1) 856 kg (2). Wheels diameter 0.51 m. (Lunokhod-1)</p>
<p>Lunar Roving vehicles: 1971.</p> <p>Four independent wheels, suspension: double horizontal wishbone with upper and lower torsion bars and a damper unit between the chassis and upper wishbone. Motors powered (190 w), wheel diameter 0.81 m, four steering motors 75 w. Mass 210 kg. (NASA)</p>
<p>Prop-M: 1971 Two independent rotating skis or skids for the rover movement. Mass 4.5 kg. Smaller than a breadbox at 0.215 x 0.16 x 0.06 m (KE-MURDJIAN, 1998) and IEEE Spectrum.</p>

ROVER	IMAGE	CAD
<p>Marsokhod: 1992</p> <p>Three pairs of independent driven wheels, joined by a three DoF passively articulated frame. The steering capabilities are limited to skid steering. Mass 75 kg, 0.95x0.7-1.2 m, max speed 0.138 m/s, 25 – 30 Wh/km, separate stones 0.75 m Wheel 0.35 m, serviceability 100 km. VNIITRANSMASH and (KEMURDJIAN et al., 1992)</p>
<p>Sojourner, 1997.</p> <p>Six independent driven wheels. Two wheels steering and Rocker-Bogie suspension. Height 0.28 m, length 0.63 m, width 0.48m. Top speed of 0.007 m/s. Mass of 11.5 kg. (NASA JPL)</p>
<p>Micro 5 (PEGASUS): 1999</p> <p>Four-wheel vehicle with a pivot at the front between left and right side to allow adaptation to uneven terrain. Fifth wheel in the center connected to the pivot by means of a rigid bar, to increase terrainability. Mass 5 kg. Also called “Pentad Grade Assist Suspension (PEGASUS)”. (KURODA et al., 1999).</p>
<p>Shrimp: 2002</p> <p>Six motorized wheels. Rhombus configuration. Steering wheel in the front and the rear, and two wheels arranged on a bogie on each side. The front wheel has a spring suspension. The robot is 0.6 m long and 0.2 m high. It overcomes obstacles up to two times its wheel diameter and climbs stairs with steps over 0.2 m. (SIEGWART et al., 2002).</p>

ROVER	IMAGE	CAD
<p>Spirit and Opportunity (MER): 2004. Six-wheeled, solar-powered, four steering wheels Dimensions: 1.5 m high, 2.3 m wide and 1.6 m long and 180 Kg. Rocker-Bogie and differential mechanisms suspension systems. Maximum speed is 0.05 m/s. (LINDEMANN; VOORHEES, 2005).</p>
<p>Crab: 2006. Six motor drive and 4 steering wheels. 4 parallel bogies, two for each lateral side of robot with linkage at top. 17.5 kg. Dimensions: 0.456x0.38x0.228 m. Wheel diameter 0.11 m; max speed 0.15 m/s; max torque 5.49 N-m, max step obstacle 0.11 m (THUEER; KREBS; SIEGWART, 2006).</p>
<p>Cj-1 2007 Six wheel robot. The suspension consists of a coupled positive - negative (inverted) quadrilateral lever mechanism. Left and right suspensions are identical and linked by a differential (CHEN; WANG, 2007).</p>
<p>Curiosity (MSL): 2010. Six powered wheels and four steering wheels. 2.9 m long by 2.7 m wide by 2.2 m high, 0.5 m diameter wheels, in a rocker-bogie suspension. It can roll over obstacles approaching 0.65 m in height, and it has a ground clearance of 0.6 m. The maximum terrain-traverse speed is 0.0023 m/s by automatic navigation 0.04 m/s. Mass of 899 kg including 80 kg of scientific instruments. (WELCH; LIMONADI; MANNING, 2013).</p>

ROVER	IMAGE	CAD
<p>Exomars RCL-E: 2010.</p> <p>Six motor drive and six steering and tactile wheels. Three parallel bogies, rear wheels independent of front. Mass 300k, dimensions are not available. (PATEL; SLADE; CLEMMET, 2010).</p>

Table 3: Active suspension rovers.

ROVER	IMAGE	CAD
<p>Octopus 2002.</p> <p>Autonomous 8 Wheeled Climbing Robot with Tactile wheels. It has eight wheels and dimensions of 0.42x0.43x0.23m. (LAURIA; PIGUET; SIEGWART, 2002).</p>
<p>Sherpa: 2004.</p> <p>Four wheeled robot, it is an expandable rover for planetary applications. Actuated suspension system, 30 DoF, footprint of 0.24mx0.24m and a ground clearance of approximately 0.5 m, weigh 200 kg. (CORDES; DETTMANN; KIRCHNER, 2011).</p>
<p>Athlete 2008.</p> <p>All-Terrain Hex-Limbed Extra-Terrestrial Explorer. Six wheels at the ends of six multi-degree-of freedom limbs. The wheels can be locked and used as feet to walk out of excessively soft or other extreme terrain. Wheel diameter 0.48 m. weight 850 kg. height 6 m, hexagon of 4 m.(WILCOX, 2011)</p>

Table 4: Outdoor robots passive suspension examples

ROVER	IMAGE	CAD
<p>Sena: 2010.</p> <p>Four wheel vehicle, Ackerman Steering system, traction in the front wheels with mechanic differential system. Length about 4 m. 90 Hp (PEDRAZA et al., 2014), (RONCANCIO et al., 2012).</p>
<p>EESC-USP robot: 2012</p> <p>Four wheeled robot. Differential traction system, front wheels are free and rear wheels have an independent electric motor, 0.5x0.5x0.35 m. (FURLANETTI et al., 2012).</p>
<p>Agrirobot 2012.</p> <p>Four independent wheels, each one with a hydraulic motor, and steering independent system 4WS/4WD. 2800 kg, and 3x2.25 – 2.40x1.8 m. Wheels diameter 1 m. and power of 76 hp. (DIAZ et al., 2013), (TABILE et al., 2011)</p>
<p>Autonomous Prime Movers APM: 2012</p> <p>Is an Ackerman type robot equipped with one motor DC of 1.2 kw, 3 batteries of 12V 80 Ah and differential system. Dimensions: 2.0x0.86x1.710 m (BERGERMAN; SINGH; HAMNER, 2012)</p>
<p>AgriRover 2014.</p> <p>Four wheeled robot, differential traction. Dimensions 1.0x1.34x0.5 m. Weight 150 kg. (MANDERSON; HUNT, 2014)</p>

Materials and Methods

In this chapter, the methodology used in different stages of this thesis is presented. First, the problem statement, the informational/conceptual design and detailed design are introduced. Benchmarking was made including rovers, mathematical models, simulations and robots tests. Then, the proposal is described and compared. Mechanic and electronic configurations, as well as the computation systems of Rover are given. It is followed by the description of the simulations in the section Mechatronic CAE Model.

3.1 Methodology

The methodology used in the present investigation was based on mechanical and mechatronics design methodologies (PAHL; BEITZ, 2013). The diagram in Figure 22 show the methodology in general way. It consists of three phases: problem statement, informational/conceptual design, and detailed design.

In the stage of problem statement the requirements of the project were defined. Not only classical questions were raised (Where am I? Where am I going? How do I get there? - Leonard and Durrant-Whyte, 1991) but also issues regarding environment, and tasks were contemplated. A bibliographic review on different kinds of rovers was carried out. Additionally, the sub-stages of General crop characteristics and Scouting tasks will be presented in this chapter.

The information gathered during the problem statement stage provided some guidance for the informational/conceptual design of the rover. One may see a more detail diagram in Figure 23. The informational and conceptual design presents the Benchmarking and Proposal. As part of benchmarking stage rovers characteristics were studied, mathematical models were developed, multibody dynamics simulations were carried out, and tests in robots were performed. As a result, a final proposal for the development of R2A was outlined.

After the Proposal, Detailed design stage is developed. It presents the Mechatronic CAD and CAE models. They were used to perform virtual prototype. It was simulated

Figure 22: Bloc diagram of basic methodology

and improved. After real prototype was build. Finally the prototype performance was tested and validated.

The methodology was used to develop three prototypes. They were presented in the Mechanical Engineering Congress CREEM (FURLANETTI et al., 2012), IEEE conference on Industrial Electronics and Applications ICIEA (ARCHILA; BECKER, 2013a), National Symposium on Agricultural instrumentation SIAGRO (ARCHILA et al., 2014), and Latin-American Robotics Symposium LARS (DIAZ et al., 2015).

3.2 General Crop Characteristics

In general, when it comes to time, crops may be classified as perennial semi-perennial and non-perennial. Regarding non-perennial crops, replanting is necessary after every harvest-time. Some examples of this kind of crops are soybeans and cotton. Examples of semi-perennial are sugar cane, banana, and pineapple. These crops are harvested and produce again without the need of new seeding. However, in extensive agriculture, replanting happens every year. For perennial crops such as Orange, coffee, cocoa replanting each year is not necessary. There are advantages and disadvantages for each kind of crop. Non-perennial and semi-perennial, for instance, allow crop rotation in a short time. Perennial needs years to rotate according to each type of plant. Additionally, perennial crops use soil nutrients more efficiently. Non-perennial and semi-perennials require more nutrients in each planting phase. Non-perennial and semi-perennial crops present ero-

Figure 23: Mechatronic Design Methodology for R2A.

Figure 24: Sugar cane crop (a), Orange crop (b)

sion as an important challenge (VALLEBONA et al., 2015). Figure 24 shows examples of semi-perennial and perennial crops.

Crops in general way have the following steps along time, according to Thompson 2008: Soil preparation: It has the objective of preparing the soil for planting. The principal activities are: plow, raked, leveling, subsoiling and furrowed. After this preparation, the furrows correspond to slopes between 0.3 to 1%, for sugar cane, for example. Grooves distance are 1.5 m in simple rows or 1.05 x 0.6 m in double rows. (FONAIAP) See Figure 25

Figure 25: Soil preparation (Furrows) FONAIAP.

Seeding follows soil preparation. Fertilizers are applied in this step (TORMENA et al., 2007). It is an important phase because the seeding affects directly crop production. In mechanized crops, the furrows, fertilizers (phosphor and part of nitrogenous), seed and cover the seed are made at the same time by seeder machines. Figure 26 illustrates a

seeder machine.

Figure 26: Seeder (John Deere).

Once seeding is done, growing is the next step. There are different activities in this phase. They are irrigation, fertilization (Nitrogenous and potassium), disease control and hilling (to sugar cane) or pruning (to orange). Figure 27 shows an example of spray machine used during growing phase.

Figure 27: Sprayer MONTANA (Agrishow).

When the growing phase finishes, the phase of harvest starts. In extensive agriculture harvest is made with specialized machines. Some examples are presented in Figure 28. The examples correspond to cotton harvester, grain harvester, and sugar cane harvester, respectively. They are used to semi-perennial and perennial crops. These machines can work in slopes of maximum 5 degrees. (Manufactures catalog)

Figure 28: Harvester examples (a) Cotton CASE IH FPT 400 cv (Agrishow), (b) Grains (John Deere) (c) Sugar harvester John Deere 3520 337 cv (Agrishow) (d) Coffee harvester KTR 3500 Jacto (Siagro)

In perennial crops the activities are similar until the seeding phase. The principal difference is that it is not necessary to cut the plant during harvest-time. It means that seeding takes place only once, not every year. Regarding orange crops, for example, one tree produces during ten years (Citrosuco, 2015). After that, it continues producing, but less quantity of oranges. These kinds of crops require a fertilizer plan year by year according to the nutrient deficit in each stage. Some crop types require pruning, and, depending on the climate conditions, it requires irrigation. Other important task is disease control.

Generally speaking, agricultural machines are designed to plain terrain and small slopes. The recommended topography to extensive agriculture should be flat. Agricultural topography presents uneven terrain for perennial and non-perennial crops. For example after soil preparation for sugar cane, heights of furrows correspond to 0.15 m. The recommendable spacing between rows is 0.6 to 1.05 m. For orange crops, the row space is around 6 m. See Figure 29.

Topography is an important parameter in agriculture terrain. There are topographic

Figure 29: Orange and sugar cane crop row spacing (Google Maps) Maringa Farm.

studies in agriculture terrains however the studies are to flooding, irrigation and land leveling and the scale don't describes the possible obstacles to a vehicle. Studies in terrain traversability are in development (PAPADAKIS, 2013) they use cameras and LIDAR Figure 30.

Figure 30: 3D Scene of terrain. (PAPADAKIS, 2013).

One example of terrain topography in perennial crop was obtained experimentally and presented in section 4.3.

3.3 Scouting tasks

As presented in section 3.2, a lot of agricultural activities are performed on the farm. In this work, we selected scouting tasks as possible application to the robot platform. Some of them are soil composition analyses, fruit detection, and disease detection by

patterns recognition. In orange crops, for example, to study soil composition 1 sample per hectare is used. All samples are taken to the laboratory and analyzed to obtain the soil composition (Citrosuco) Figure 31. This composition is used to know the nutrients that the crop needs. This way, the application of fertilizers may be improved.

Figure 31: Example of soil sample.

Fruit detection is an important task used to estimate crop. It consists of counting the fruits in one tree in a specific area and, then, mathematically estimate the amount of fruits in a specific area and /or in a crop. Disease detection may be carried out by visual inspection. Each tree is inspected with the objective of detecting diseases or damages in a tree or fruits. See Figure 32.

Figure 32: Orange inspection (Font: FreshPlaza)

Regarding soil composition, one recent technique that is used is LIBS (Laser Induced Break Spectrum). This technique is used especially by spatial robots such as Curiosity and Exo-Mars (PÉREZ; MARTINEZ-FRIAS, 2006) Figure 33. LIBS technology was used too in nuclear reactor inspection and maintenance (GARGIULO et al., 2008). In military rescue, LIBS technology was used in the BEAR robot to found chemical, biological, and

explosive agents (GILBERT; BEEBE, 2010). When it comes to soil composition analyses, there are works of ??) that presents LIBS Applications in calcium detection. Likewise, Ferreira et al. (2015) explores the use of LIBS to measure soil pH.

Figure 33: LIBS example application (PÉREZ; MARTINEZ-FRIAS, 2006).

Recently, thermal cameras have been used to fruit recognition (PEDRAZA, 2015). See Figure 34. Cameras are also used to detect to curve path (JIANG et al., 2013), (PAPADAKIS, 2013). LIF Laser Induced Fluorence spectroscopy has been applied to identify varieties of citrus (MILORI et al., 2013). Huanglongbing has been detected with the use of infrared spectroscopy (CARDINALI et al., 2012). Pourreza et al. (2015) aiming to detect this disease, explored another technique using vision sensor. Laser induced fluorescence imaging method was studied by Pereira et al. (2011), to monitored citrus greening diseases.

Figure 34: Examples of cameras used for detection (PEDRAZA, 2015).

3.4 Benchmarking

Benchmarking phase study some robots and roves. This phase presents: mathematical models developed, rovers characteristics, simulations of Crab, Shrimp, Spirit, Curiosity and Exo-Mars rovers, and tests in EESC USP Robot, Mirã, and AgriBot.

3.4.1 Mathematical models

In this section mathematical models of different robot configurations are presented. The mathematical models start with the classic differential model in 2D. Afterwards, 3D models are presented. They were applied to nWS/mWD (n Wheels Steering / m Wheels Drive where n and m are natural numbers) configurations considering wheel slip conditions. Finally, 3D kinematics models to CRAB and Rocker Bogie rover configurations are described.

3.4.1.1 Differential model

The Kinematic modeling was done in a generic way for a differential robot configuration with two driving wheels and two free wheels. The rotation center of the robot was assumed at the center of gravity giving symmetry to the robot with the Z axis. See Figure 35, where φ_1 and φ_2 are the angular velocities of the driving wheels of the robot. V is the robot speed, V_r and V_l the tangential velocities of the right and left wheels. The velocities are toward the X_r axis of the coordinate system of the robot and in the inertial coordinate system there are components in X and Y . θ and $\dot{\theta}$ are the angle of rotation and the angular velocity of the robot respectively. Figure 35.

Figure 35: General geometric robot parameters.

The kinematic modeling considers the physical parameters of the robot and its overall dimensions. Thus, we obtain the equations 1 to 6 for the inverse kinematics. The

restrictions of the model are presented by Baturone (2005).

$$\dot{\xi}_r = R(\theta) * \dot{\xi} \quad (1)$$

$$\dot{\xi} = \begin{Bmatrix} \dot{x} & \dot{y} & \dot{\theta} \end{Bmatrix}^T \quad (2)$$

$$\dot{\xi}_r = \begin{Bmatrix} \dot{x}_r & \dot{y}_r & \dot{\theta}_r \end{Bmatrix}^T \quad (3)$$

$$R(\theta) = \begin{bmatrix} c\theta & -s\theta & 0 \\ s\theta & c\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (4)$$

$$\dot{\xi} = R(\theta)^{-1} * \dot{\xi}_r \quad (5)$$

$$\dot{\xi} = R(\theta)^{-1} * \dot{\xi}_r = \begin{bmatrix} c\theta & s\theta & 0 \\ -s\theta & c\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \frac{r\dot{\phi}_1}{2} + \frac{r\dot{\phi}_2}{2} \\ 0 \\ \frac{r\dot{\phi}_1}{2l} - \frac{r\dot{\phi}_2}{2l} \end{Bmatrix} \quad (6)$$

The dynamical model, in respect of the robot coordinate system, is described by equations 7 to 10. Where m is the mass, V the velocities, W Angular velocities, α angular acceleration, F forces, a accelerations, F_f friction forces, I inertia, M momentum, T Torque, r wheel radius and l robot length, d distance between wheels.

$$\frac{d}{dt}(m\vec{v}) = \sum F_{Ext} \quad (7)$$

$$\frac{d}{dt}(m\vec{v}) + \vec{w} \times (m\vec{v}) = \sum F_{Ext} \quad (8)$$

$$m \begin{Bmatrix} a_x \\ a_y \\ a_z \end{Bmatrix} + \begin{Bmatrix} w_x \\ w_y \\ w_z \end{Bmatrix} \times m \begin{Bmatrix} v_x \\ v_y \\ v_z \end{Bmatrix} = \begin{Bmatrix} \sum F_x \\ \sum F_y \\ \sum F_z \end{Bmatrix} \quad (9)$$

$$m \begin{Bmatrix} a_x + v_z w_y - v_y w_z \\ a_y + v_x w_z - v_z w_y \\ a_z + v_y w_x - v_x w_y \end{Bmatrix} = \begin{Bmatrix} \sum F_x \\ \sum F_y \\ \sum F_z \end{Bmatrix} \quad (10)$$

In this case, considering non-slip condition and movement on plane (x, y) the equation system is eq. 11.

$$m \begin{Bmatrix} \ddot{x}_r \\ \dot{x}_r \dot{\theta}_r \\ 0 \end{Bmatrix} = \begin{Bmatrix} F_{fx} \\ F_{fy} \\ N - mg \end{Bmatrix} \quad (11)$$

According to the kinematical modeling at eq. 6, the dynamical model may be presented in function of wheels variable as presented in eq. 12:

$$m \begin{Bmatrix} \frac{r\dot{\varphi}_1}{2} + \frac{r\dot{\varphi}_2}{2} \\ \frac{r^2\dot{\varphi}_1^2}{4l} + \frac{r^2\dot{\varphi}_2^2}{4l} \\ 0 \end{Bmatrix} = \begin{Bmatrix} F_{fx} \\ F_{fy} \\ N - mg \end{Bmatrix} \quad (12)$$

The robot moment equations are described in the equations 13 to 16, where $\check{I}$ is the inertia tensor of robot.

$$\frac{d}{dt}(\check{I}\vec{w}) = \sum M_{Ext} \quad (13)$$

$$\frac{d}{dt}(\check{I}\vec{w}) + \vec{w} \times (\check{I}\vec{w}) = \sum M_{Ext} \quad (14)$$

$$\check{I} \begin{Bmatrix} \alpha_x \\ \alpha_y \\ \alpha_z \end{Bmatrix} + \begin{Bmatrix} w_x \\ w_y \\ w_z \end{Bmatrix} \times \check{I} \begin{Bmatrix} v_x \\ v_y \\ v_z \end{Bmatrix} = \begin{Bmatrix} \sum M_x \\ \sum M_y \\ \sum M_z \end{Bmatrix} \quad (15)$$

$$\begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{xy} & I_{yy} & -I_{yz} \\ -I_{xz} & -I_{yz} & I_{zz} \end{bmatrix} \begin{Bmatrix} \alpha_x \\ \alpha_y \\ \alpha_z \end{Bmatrix} + \begin{Bmatrix} w_x \\ w_y \\ w_z \end{Bmatrix} \times \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{xy} & I_{yy} & -I_{yz} \\ -I_{xz} & -I_{yz} & I_{zz} \end{bmatrix} \begin{Bmatrix} v_x \\ v_y \\ v_z \end{Bmatrix} = \begin{Bmatrix} \sum M_x \\ \sum M_y \\ \sum M_z \end{Bmatrix} \quad (16)$$

The robot will be symmetric at plane (z_r, x_r) and (z_r, y_r) . Thus, the inertia tensor is a diagonal matrix.

$$\begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} \begin{Bmatrix} \alpha_x \\ \alpha_y \\ \alpha_z \end{Bmatrix} + \begin{Bmatrix} w_x \\ w_y \\ w_z \end{Bmatrix} \times \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} \begin{Bmatrix} v_x \\ v_y \\ v_z \end{Bmatrix} = \begin{Bmatrix} \sum M_x \\ \sum M_y \\ \sum M_z \end{Bmatrix} \quad (17)$$

$$\begin{Bmatrix} I_{xx}\alpha_x \\ I_{yy}\alpha_y \\ I_{zz}\alpha_z \end{Bmatrix} + \begin{Bmatrix} w_y I_{zz} v_z - w_z I_{yy} v_y \\ w_z I_{xx} v_x - w_x I_{zz} v_z \\ w_x I_{yy} v_x - w_y I_{xx} v_x \end{Bmatrix} = \begin{Bmatrix} \sum M_x \\ \sum M_y \\ \sum M_z \end{Bmatrix} \quad (18)$$

With non-slip conditions (WONG, 2001) and movement only on plane (x, y) , the equations system is:

$$\begin{Bmatrix} 0 \\ 0 \\ I_{zz}\alpha_z \end{Bmatrix} + \begin{Bmatrix} 0 \\ w_z I_{xx} v_x \\ 0 \end{Bmatrix} = \begin{Bmatrix} N_{left}l - N_{right}l \\ N_{back}d - N_{front}d + T_{motor} \\ F_{fxright}l - F_{fxleft}l - F_{fyfront}d - F_{fyleft}d \end{Bmatrix} \quad (19)$$

The dynamical model in function of wheel variables and dimensions of robot is presented the equations system eq. 20:

$$\begin{Bmatrix} 0 \\ 0 \\ I_{zz}\ddot{\theta}_r \end{Bmatrix} + \begin{Bmatrix} 0 \\ I_{xx} \left[\frac{r^2\dot{\varphi}_1^2}{4l} + \frac{r^2\dot{\varphi}_2^2}{4l} \right] \\ 0 \end{Bmatrix} = \begin{Bmatrix} (N_{left} - N_{right})l \\ (N_{back} - N_{front})d + T_{motor} \\ (F_{fxright} - F_{fxleft})l - (F_{fyfront} + F_{fyleft})d \end{Bmatrix} \quad (20)$$

Kinematic and dynamic models presented in this section were used to the development of EESC-USP Robot (FURLANETTI et al., 2012) and Mirã Rover (ARCHILA et al., 2014).

3.4.1.2 n - Wheels Steering / m - Wheels Drive (nWS/mWD) Configuration

Some agriculture robot applications have 4WS/4WD configurations, for example the AgriBot, the Hortibor, and Zeus Robot. There are other types of nWS/mWD, where n and m are natural numbers. In the following section, we will show a general kinematics model.

Figure 36: Coordinate frames to 4WS/4WD.

The Figure 36 presents the coordinate system from the inertial coordinate system $\{X_o, Y_o, Z_o\}$ to the gravity center of the robot $\{X_R, Y_R, Z_R\}$. In this case, it represents the

translation and attitude of the robot. To each wheel coordinate system $\{X_{Ai}, Y_{Ai}, Z_{Ai}\}$ from Robot gravity center frame $\{X_R, Y_R, Z_R\}$ in general, we have the eq. 21:

$$T_{R,Ai} = T_{R,D}T_{D,Si}T_{S,Ai} \quad (21)$$

Eq. 21 represents the transformation from $\{X_R, Y_R, Z_R\}$ frame to wheel coordinate frame $\{X_{Ai}, Y_{Ai}, Z_{Ai}\}$, including the steering angle Ψ_i , and the rotation wheel angle θ_i .

To consider the wheel slip ζ_i and the translation along Z_{Ai} axis to soil in a distance of R_w (wheel radius) is necessary include more transformation matrices the Figure 37 presents the coordinate frames $\{X_{Ai}, Y_{Ai}, Z_{Ai}\}$, $\{X_{Ci}, Y_{Ci}, Z_{Ci}\}$ and $\{X_{Mi}, Y_{Mi}, Z_{Mi}\}$ necessary to include the slip conditions and wheels variables according to Denavit Hartenberg.

Figure 37: Coordinate frames to wheels to soil in 4WS/4WD configurations.

$$T_{R,Mi} = T_{R,D}T_{D,Si}T_{S,Ai}T_{Ai,Ci}T_{Ci,Mi} \quad (22)$$

Eq. 22 resumes the coordinate transformations from gravity center robot frame to each wheel subsystem. We use the Denavit-Hartenberg D-H algorithm to determinate the transformations. The parameters are presented in Table 5.

The homogeneous transformation matrix according to Denavit-Hatenberg is:

$$T_{i,j} = \begin{bmatrix} c(\gamma_j) & -s(\gamma_j)c(\alpha_j) & s(\gamma_j)s(\alpha_j) & \alpha_j c(\gamma_j) \\ s(\gamma_j) & c(\gamma_j)c(\alpha_j) & -c(\gamma_j)s(\alpha_j) & \alpha_j s(\gamma_j) \\ 0 & s(\alpha_j) & c(\alpha_j) & d_j \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (23)$$

Table 5: D-H Parameters.

FRAME	γ	$\mathbf{d}$	$\mathbf{a}$	α
$\mathbf{D}$	0	d_{zr}	0	-90
S_i	0	$d_z d_i$	$d_x d_i$	90
A_i	Ψ_i	d_{zsi}	0	-90
C_i	θ_i	0	0	-90
M_i	ζ_i	$-R_w$	$-R_w \theta_i$	0

By using the D-H parameters of Table 5 in the eq. 22 and eq. 23, we obtained the equations 24. The kinematics to each wheel subset was obtained using the matrix operations in eq. 25.

$$T_{R,Mi} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & dzr \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & dxd \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & dzd_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c(\Psi_i) & 0 & -s(\Psi_i) & 0 \\ s(\Psi_i) & 0 & c(\Psi_i) & 0 \\ 0 & -1 & 0 & dzs_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c(\theta_i) & 0 & -s(\theta_i) & 0 \\ s(\theta_i) & 0 & c(\theta_i) & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c(\zeta_i) & -s(\zeta_i) & 0 & -R_w \theta_i c(\zeta_i) \\ s(\zeta_i) & c(\zeta_i) & 0 & -R_w \theta_i s(\zeta_i) \\ 0 & 0 & 1 & -R_w \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (24)$$

$$T_{R,Mi} = \begin{bmatrix} c(\theta_i)c(\Psi_i)c(\zeta_i) + s(\Psi_i)s(\zeta_i) & -c(\theta_i)c(\Psi_i)s(\zeta_i) + s(\Psi_i)s(\zeta_i) & -c(\Psi_i)s(\theta_i) \cdots \\ c(\theta_i)s(\Psi_i)c(\zeta_i) + c(\Psi_i)s(\zeta_i) & -c(\theta_i)s(\Psi_i)s(\zeta_i) + c(\Psi_i)c(\zeta_i) & s(\Psi_i)s(\theta_i) \cdots \\ -s(\theta_i)c(\zeta_i) & -s(\theta_i)s(\zeta_i) & -c(\theta_i) \cdots \\ 0 & 0 & 0 \cdots \\ \cdots - R_w \{ \theta_i [c(\zeta_i)c(\theta_i)c(\Psi_i) + s(\Psi_i)s(\zeta_i)] - c(\Psi_i)s(\theta_i) \} + dxd_i \\ \cdots - R_w \{ \theta_i [c(\zeta_i)c(\theta_i)s(\Psi_i) - c(\Psi_i)s(\zeta_i)] - s(\Psi_i)s(\theta_i) \} + dzd_i \\ \cdots R_w [\theta_i c(\zeta_i)s(\theta_i) - c(\theta_i)s(\zeta_i)] + dzs_i + dzr_i \\ \cdots 1 \end{bmatrix} \quad (25)$$

In order to obtain the wheel Jacobian matrix, we must express the motion of the rover (derivatives of rover reference position and orientation) to the wheel motion (wheel rotation velocity, rocker and bogie angular rates, etc.). This is done by applying the instantaneous transformation $T_{\hat{R}, \hat{M}_i}$ as follows. Adapted of Tarokh e McDermott (2005).

$$\dot{T}_{M_i, R} = T_{\hat{R}, \hat{M}_i} \dot{T}_{\hat{R}, R} \quad i = 1, \dots, 4 \quad (26)$$

$$\dot{T}_{\hat{R}, R} = T_{\hat{R}, \hat{M}_i} \dot{T}_{M_i, R} \quad i = 1, \dots, 4 \quad (27)$$

Too is possible to obtain the relationships as follow:

$$\dot{T}_{R,M_i} = T_{\hat{R},\hat{M}_i} \dot{T}_{\hat{R},R} \quad i = 1, \dots, 4 \quad (28)$$

$$\dot{T}_{\hat{R},R} = T_{\hat{M}_i,\hat{R}} \dot{T}_{R,M_i} \quad i = 1, \dots, 4 \quad (29)$$

Derivative of transformation matrices and instantaneous transformations are discussed in Muir e Neuman (1987). Using Z - Y - X Euler angles yaw ϕ (rotation about the Z -axis), pitch ρ (rotation about the Y axis), and roll r (rotation about the X axis), from 26 the derivative of the rover coordinate frame is found to have the following form eq. 30

$$\dot{T}_{\hat{R},R} = \begin{bmatrix} 0 & -\dot{\phi} & \dot{\rho} & \dot{x} \\ \dot{\phi} & 0 & -\dot{r} & \dot{y} \\ -\dot{\rho} & \dot{r} & 0 & \dot{z} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (30)$$

The transformations on the right hand side of eq. 27 are obtained using eq. 26. To eq. 29 and Table 5, taking the derivatives of the resulting transformations, and noting that $T_{M_i,R} = T_{R,M_i}^{-1}$. Eq. 31.

$$T_{M_i,R} = \begin{bmatrix} c(\theta_i)c(\Psi_i)c(\zeta_i) + s(\Psi_i)s(\zeta_i) & c(\theta_i)s(\Psi_i)c(\zeta_i) + c(\Psi_i)s(\zeta_i) & -s(\theta_i)c(\zeta_i) & -(\vec{p} \cdot \vec{n}) \\ -c(\theta_i)c(\Psi_i)s(\zeta_i) + s(\Psi_i)s(\zeta_i) & -c(\theta_i)s(\Psi_i)s(\zeta_i) + c(\Psi_i)c(\zeta_i) & s(\theta_i)s(\zeta_i) & -(\vec{p} \cdot \vec{o}) \\ -c(\Psi_i)s(\theta_i) & -s(\Psi_i)s(\theta_i) & -c(\theta_i) & -(\vec{p} \cdot \vec{a}) \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (31)$$

Where $\vec{n}$, $\vec{o}$, $\vec{a}$, and $\vec{p}$ are described at eq 32 to eq. 35.

$$\vec{n} = \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} = \begin{bmatrix} c(\theta_i)c(\Psi_i)c(\zeta_i) + s(\Psi_i)s(\zeta_i) \\ c(\theta_i)s(\Psi_i)c(\zeta_i) + c(\Psi_i)s(\zeta_i) \\ -s(\theta_i)c(\zeta_i) \end{bmatrix} \quad (32)$$

$$\vec{o} = \begin{bmatrix} o_x \\ o_y \\ o_z \end{bmatrix} = \begin{bmatrix} -c(\theta_i)c(\Psi_i)s(\zeta_i) + s(\Psi_i)s(\zeta_i) \\ -c(\theta_i)s(\Psi_i)s(\zeta_i) + c(\Psi_i)c(\zeta_i) \\ -s(\theta_i)s(\zeta_i) \end{bmatrix} \quad (33)$$

$$\vec{a} = \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} -c(\Psi_i)s(\theta_i) \\ -s(\Psi_i)s(\theta_i) \\ -c(\theta_i) \end{bmatrix} \quad (34)$$

$$\vec{p} = \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} = \begin{bmatrix} R_w \{ \theta_i [c(\zeta_i)c(\theta_i)c(\Psi_i) + s(\Psi_i)s(\zeta_i)] - c(\Psi_i)s(\theta_i) \} + dx d_i \\ R_w \{ \theta_i [c(\zeta_i)c(\theta_i)s(\Psi_i) - c(\Psi_i)s(\zeta_i)] - s(\Psi_i)s(\theta_i) \} + dz d_i \\ -R_w [\theta_i c(\zeta_i)s(\theta_i) - c(\theta_i)] + dz s_i + dz r_i \end{bmatrix} \quad (35)$$

With non-slip conditions the transformation is presented at eq 36 to eq 40.

$$T_{R,Mi} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & dzr \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & dxd_i \\ 0 & 0 & -1 & 0 \\ 0 & -1 & 0 & dzd_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c(\Psi_i) & 0 & -s(\Psi_i) & 0 \\ s(\Psi_i) & 0 & c(\Psi_i) & 0 \\ 0 & -1 & 0 & dzs_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c(\theta_i) & 0 & -s(\theta_i) & 0 \\ s(\theta_i) & 0 & c(\theta_i) & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & R_w \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (36)$$

$$T_{R,Mi} = \begin{bmatrix} c(\Psi_i)c(\theta_i) & s(\Psi_i) & -c(\Psi_i)s(\theta_i) & dxd_i \\ s(\Psi_i)c(\theta_i) & -c(\theta_i) & -s(\Psi_i)s(\theta_i) & dzd_i \\ -s(\theta_i) & 0 & c(\theta_i) & dzs_i + R_w \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (37)$$

$$T_{Mi,R} = \begin{bmatrix} c(\Psi_i)c(\theta_i) & s(\Psi_i)c(\theta_i) & -s(\theta_i) & dxd_i c(\Psi_i)c(\theta_i) + dzd_i s(\Psi_i)c(\theta_i) - (dzs_i + R_w)s(\theta_i) \\ s(\Psi_i) & -c(\theta_i) & 0 & dxd_i s(\Psi_i) - dzd_i c(\theta_i) \\ -c(\theta_i)s(\theta_i) & -s(\Psi_i)c(\theta_i) & c(\theta_i) & -dxd_i c(\Psi_i)c(\theta_i) - dzd_i s(\Psi_i)c(\theta_i) + (dzs_i + R_w)c(\theta_i) \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (38)$$

$$\dot{T}_{Mi,R} = \begin{bmatrix} -s(\Psi_i)c(\theta_i)\dot{\Psi}_i - c(\Psi_i)s(\theta_i)\dot{\theta}_i & c(\Psi_i)c(\theta_i)\dot{\Psi}_i - s(\Psi_i)s(\theta_i)\dot{\theta}_i & -c(\theta_i)\dot{\theta}_i & a_1 \\ c(\Psi_i)\dot{\Psi}_i & s(\theta_i)\dot{\theta}_i & 0 & a_2 \\ s(\Psi_i)s(\theta_i)\dot{\Psi}_i - c(\Psi_i)c(\theta_i)\dot{\theta}_i & -c(\Psi_i)s(\theta_i)\dot{\Psi}_i - s(\Psi_i)c(\theta_i)\dot{\theta}_i & -s(\theta_i)\dot{\theta}_i & a_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (39)$$

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} -dxd_i s(\Psi_i)c(\theta_i)\dot{\Psi}_i - dxd_i c(\Psi_i)s(\theta_i)\dot{\theta}_i + dzd_i c(\Psi_i)c(\theta_i)\dot{\Psi}_i - dzd_i s(\Psi_i)s(\theta_i)\dot{\theta}_i - (dzs_i + R_w)c(\theta_i)\dot{\theta}_i \\ dxd_i c(\Psi_i)\dot{\Psi}_i + dzd_i s(\theta_i)\dot{\theta}_i \\ dxd_i s(\Psi_i)c(\theta_i)\dot{\Psi}_i - dxd_i c(\Psi_i)s(\theta_i)\dot{\theta}_i - dzd_i c(\Psi_i)c(\theta_i)\dot{\Psi}_i + dzd_i s(\Psi_i)s(\theta_i)\dot{\theta}_i - (dzs_i + R_w)c(\theta_i)\dot{\theta}_i \end{bmatrix} \quad (40)$$

The next equation was obtained replacing the equations 31 to eq. 39 and eq. 30 where $b_1 = b_3 = 1$; $b_2 = b_4 = -1$; d_{si} and a_{si} are geometrical parameters defined by D-H.

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \dot{\phi} \\ \dot{\rho} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} R_w c(\Psi_i) & b_i d_{si} \\ R_w s(\Psi_i) & a_{si} \\ 0 & 0 \\ 0 & -1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{\theta}_i \\ \dot{\Psi}_i \end{bmatrix} \quad i = 1, \dots, 4 \quad (41)$$

It is possible to complement the kinematical model using the Ackerman restrictions. This models were validate in the AgriBot (TORRES, 2014a) and in the RAM (TORRES et al., 2013).

3.4.1.3 Rocker Bogie

For the Rocker Bogie we will work with the Rocky 7 Mars Rover, it was designed by Jet propulsion Laboratory JPL. The rover consists of six wheels Figure 38. The rover is 0.48 m wide, 0.64 m long and 0.32 m high. All six wheels have a diameter of 0.13 m. the rover has a nominal speed of 0.1 m/s.

Figure 38: Side view of Rocky 7, (TAROKH et al., 1999).

Two main rockers are hinged to the sides of the body. Each main rocker has a steerable wheel at one end and a smaller rocker at the other end. Two fixed (nonsteerable) wheels are attached to the ends of the smaller rockers. There are essentially three joints associated with the rocker-bogie system. The joint angle between the smaller rockers and the main rockers are denoted by ρ_1 and ρ_2 for the left and right sides, respectively. The two main rockers are connected to the body via a differential such that the left and right bogie angles, denoted by β_1 , β_2 , respectively, can be represented by a single joint angle $\beta = \beta_1 = \beta_2$. The two steerable wheels have steering angles Ψ_1 and Ψ_2 with a physical steering range of 270 degrees. The angular rotation of the six wheels is identified by θ_i , $i = 1, \dots, 6$. There are 8 actuators, six for driving the wheels and two for steering. The rocker-bogie joints β , ρ_1 and ρ_2 provide for compliance with the terrain and are measured by potentiometers. (TAROKH et al., 1999). The others angles are measured by encoders.

The forward kinematics model was made using the Denavit Hartenberg parameters D-H the resultant frames are presented at Figure 39.

The transformation from gravity center robot frame $\{X_R, Y_R, Z_R\}$. to $\{X_{Ai}, Y_{Ai}, Z_{Ai}\}$ is presented in genera way in eq. 42:

$$T_{R,Ai} = T_{R,D}T_{D,Si}T_{S,Ai} \quad (42)$$

Figure 39: Coordinate frames to rocky 7, (TAROKH et al., 1999).

Eq. 42 presents the transformation from $\{X_R, Y_R, Z_R\}$ frame to wheel coordinate frame $\{X_{Ai}, Y_{Ai}, Z_{Ai}\}$, including the steering angle Ψ_i .

To consider the wheel slip ζ_i , the translation along Z_{Ai} axis to soil, and the rotation wheel angle θ_i we obtain the eq. 42. Were R_w is a wheel radius the Figure 40 presents the frames $\{X_{Ai}, Y_{Ai}, Z_{Ai}\}$, $\{X_{Ci}, Y_{Ci}, Z_{Ci}\}$ and $\{X_{Mi}, Y_{Mi}, Z_{Mi}\}$ necessary to include the slip conditions and wheels variables according to Denavit Hartenberg.

Figure 40: Contact coordinate frame, (TAROKH et al., 1999).

Eq. 43 resumes the coordinate transformations from gravity center robot frame to

Table 6: D-H Parameters.

FRAME	γ	d	a	A
D	0	dz_r	0	-90
S_i	β_i	dzd_i	$dx d_i$	90
ρ_i	$\rho_i = 140.32 + \beta_i$	dzd_i	dxs_i	0
A_{1,2}	Ψ_i	dzs_i	0	-90
A_{3,4}	$\Psi_i = -122.66 + \rho_i$	0	$dx a = 2.89$	0
A_{5,6}	$\Psi_i = 22.04 + \rho_i$	0	$dx a = 2.89$	0
C_i	θ_i	0	0	-90
M_i	ζ_i	$-R_w$	$-R_w \theta_i$	0

each wheel subsystem. Tarokh e McDermott (2005)

$$T_{R,Mi} = T_{R,D} T_{D,Si} T_{S,Ai} T_{Ai,Ci} T_{Ci,Mi} \quad (43)$$

We use the Denavit-Hartenberg D-H algorithm to determinate the transformations. The parameters are presented in Table 6.

The homogeneous transformation matrix according to Denavit-Hatenberg is:

$$T_{i,j} = \begin{bmatrix} c(\gamma_j) & -s(\gamma_j)c(\alpha_j) & s(\gamma_j)s(\alpha_j) & \alpha_j c(\gamma_j) \\ s(\gamma_j) & c(\gamma_j)c(\alpha_j) & -c(\gamma_j)s(\alpha_j) & \alpha_j s(\gamma_j) \\ 0 & s(\alpha_j) & c(\alpha_j) & d_j \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (44)$$

By using the D-H parameters of Table 6 in the eq. 43 and eq. 44 we obtained the equation eq. 45 to wheels one and two. The kinematics to each wheel subset was obtained using the matrix operations in eq. 45.

$$T_{R,Mi} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & dz_r \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c(\beta_i) & 0 & s(\beta_i) & dx d_i c(\beta_i) \\ s(\beta_i) & 0 & -c(\beta_i) & dx d_i s(\beta_i) \\ 0 & 1 & 0 & dz d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c(\rho_i) & -s(\rho_i) & 0 & dx s_i \\ s(\rho_i) & c(\rho_i) & 0 & 0 \\ 0 & 0 & 1 & dz d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \\ \begin{bmatrix} c(\Psi_i) & 0 & -s(\Psi_i) & 0 \\ s(\Psi_i) & 0 & c(\Psi_i) & 0 \\ 0 & -1 & 0 & dz s_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c(\theta_i) & 0 & -s(\theta_i) & 0 \\ s(\theta_i) & 0 & c(\theta_i) & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c(\zeta_i) & -s(\zeta_i) & 0 & R_w \theta_i c(\zeta_i) \\ s(\zeta_i) & c(\zeta_i) & 0 & R_w \theta_i s(\zeta_i) \\ 0 & 0 & 1 & R_w \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (45)$$

In order to obtain the wheel Jacobian matrix, we must express the motion of the rover (derivatives of rover reference position and orientation) to the wheel motion (wheel

rotation velocity, rocker and bogie angular rates, etc.). This is done by applying the instantaneous transformation $T_{\hat{R}, \hat{M}_i}$ as follows.

$$\dot{T}_{\hat{R}, R} = T_{\hat{R}, \hat{M}_i} \dot{T}_{M_i, R} \quad i = 1, \dots, 4 \quad (46)$$

Derivative of transformation matrices and instantaneous transformations are discussed in Muir e Neuman (1987). Using Z - Y - X Euler angles yaw φ (rotation about the Z -axis), pitch ρ (rotation about the Y axis), and roll r (rotation about the X axis), from eq. 46 the derivative of the rover coordinate frame is found to have the following form eq. 47.

$$\dot{T}_{\hat{R}, R} = \begin{bmatrix} 0 & -\dot{\phi} & \dot{\rho} & \dot{x} \\ \dot{\phi} & 0 & -\dot{r} & \dot{y} \\ -\dot{\rho} & \dot{r} & 0 & \dot{z} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (47)$$

The transformations on the right hand side of eq. 47 are obtained using eq. 46 and Table 6, taking the derivatives of the resulting transformations, and noting that $T_{M_i, R} = (T_{R, M_i})^{-1}$. Once these operations are performed, the right hand side of eq. 46 gives a 4x4 matrix whose elements are functions of D-H parameters, bogie, rocker and steering angles β , ρ , Ψ and the angular rates $\dot{\theta}$, $\dot{\Psi}$, $\dot{\beta}$, $\dot{\rho}$, $\dot{\zeta}$ the results for wheels 1 and 2 are found to be:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \dot{\phi} \\ \dot{\rho} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} R_w c(\beta_i) c(\Psi_i) & 0 & b_i d_{si} c(\beta_i) \\ R_w s(\Psi_i) & 0 & a_{si} \\ b_i R_w s(\beta_i) c(\Psi_i) & 0 & d_{si} s(\beta_i) \\ 0 & 0 & -c(\beta_i) \\ 0 & b_i & 0 \\ 0 & 0 & b_i s(\beta_i) \end{bmatrix} \begin{bmatrix} \dot{\theta}_i \\ \dot{\beta}_i \\ \dot{\eta}_i \end{bmatrix} \quad i = 1, 2 \quad (48)$$

Where $b_1=-1$, $b_2=1$, d_{si} and a_{si} are geometrical parameters defined by D-H and $\dot{\eta}_i = \dot{\zeta}_i + \dot{\Psi}_i$ slip and steering rates.

The middle wheels 3 and 5 have the follow kinematic equations:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \dot{\phi} \\ \dot{\rho} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} R_w c(\sigma_1) & 0 & -a_{\rho 1} s(\gamma_{\rho 1}) & d_{s1} c(\sigma_1) \\ 0 & 0 & 0 & K_i \\ R_w s(\sigma_1) & 0 & -a_{\rho 1} c(\gamma_{\rho 1}) & d_{s1} s(\sigma_1) \\ 0 & 0 & 0 & -c(\sigma_1) \\ 0 & -1 & -1 & 0 \\ 0 & 0 & 0 & -s(\sigma_1) \end{bmatrix} \begin{bmatrix} \dot{\theta}_i \\ \dot{\beta}_i \\ \rho_1 \\ \dot{\eta}_i \end{bmatrix} \quad i = 3, 5 \quad (49)$$

Where $\sigma_1 = \rho_1 - \beta$, ρ_1 is the left rocker angle, $K_i = a_{Ai}c(\gamma_{Ci}) + a_{\rho 1}c(\gamma_{Ci} + \gamma_{Ai})$ $i=3,5$, d_{s1} , a_{Ai} , γ_{Ci} , $a_{\rho i}$ and γ_{Ai} are the kinematics parameter of D-H Table. The back wheels kinematic model is presented in the eq 50.

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \dot{\phi} \\ \dot{\rho} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} R_w c(\sigma_2) & 0 & -a_{\rho 1} s(\gamma_{\rho 2}) & d_{s1} c(\sigma_2) \\ 0 & 0 & 0 & K_i \\ R_w s(\sigma_2) & 0 & -a_{\rho 1} c(\gamma_{\rho 2}) & d_{s1} s(\sigma_2) \\ 0 & 0 & 0 & -c(\sigma_2) \\ 0 & -1 & -1 & 0 \\ 0 & 0 & 0 & -s(\sigma_2) \end{bmatrix} \begin{bmatrix} \dot{\theta}_i \\ \dot{\beta}_i \\ \rho_2 \\ \dot{\eta}_i \end{bmatrix} \quad i = 4, 6 \quad (50)$$

Where $\sigma_2 = \rho_2 - \beta$, ρ_2 is the left rocker angle, $K_i = a_{Ai}c(\gamma_{Ci}) + a_{\rho 2}c(\gamma_{Ci} + \gamma_{Ai})$ $i=3,5$, d_{s1} , a_{Ai} , γ_{Ci} , $a_{\rho i}$ and γ_{Ai} are the kinematics parameter of D-H Table.

3.4.1.4 Crab and Exo-Mars approaches

The models were simplified to 2D models they are presented in the blue dashes lines at Figure 41 (a) Crab, (b) ExoMars RB, (THUEER; SIEGWART, 2010).

Figure 41: Kinematics simplified models (THUEER; SIEGWART, 2010).

The modeling of Exomars (RB) was straight forward, no simplifications were necessary. The suspension consists of a rocker and a bogie. They are linked by a pivot which is

at a defined height above ground and at half distance between center and front wheel (Figure 41 (b)). The CRAB has kinematic loops in their suspensions, the parallelogram bogies, which are basically more difficult to model but can be simplified. While the regular bogie rotates about the pivot (Figure 42 (a)), the parallelogram bogie rotates about an instantaneous center of rotation between the wheels at the same height as the wheel center (Figure 42 (b)).

Figure 42: Motion comparison regular (a) and parallelogram (b) bogie. The regular bogie rotates about the pivot. The parallelogram bogie rotates about the instantaneous center of rotation at wheel center level. (THUEER; SIEGWART, 2010).

Since the distance between the wheels remains constant, the parallelogram bogie can be replaced in the kinematic model by a rigid link between the wheels and a pivot at the location of the instantaneous center of rotation.

Setting up the kinematic equations is explained using RB as an example. The system is defined by the constant dimensions AD , DB , and DC , the wheel ground contact angles γ_i , and the orientation of rocker α and β bogie with respect to the inertial system (see Figure 42(b)). The unknown parameters are the magnitudes of the velocities in A, B, C, and D, given that the wheels always touch the ground, as well as the rotational velocities of rocker ω_1 and bogie ω_2 . The velocity in D is not of interest; therefore it does not appear as a parameter and is expressed by means of the other velocities yielding an equation system with four equations and five unknowns. As it was mentioned before, rovers have one DoF in 2D which means that one velocity can be chosen as input. Thus the equation system has exactly one solution.

Below, ϑ_D is expressed in inertial system coordinates through the velocities in A, B, and C.

$$\vartheta_{DA} = \vartheta_A + w_1 \times_1^0 R(\alpha)^1 \bar{A}\bar{D} \quad (51)$$

$$\vartheta_{DB} = \vartheta_B + w_2 \times_2^0 R(\beta)^2 \bar{D}\bar{B} \quad (52)$$

$$\vartheta_{D_C} = \vartheta_C + w_2 \times_2^0 R(\beta)^2 \bar{D}\bar{C} \quad (53)$$

Where ϑ_i : velocity in i inertial system, ω_i : rotational velocity of system i inertial system, ${}^j_i R(\alpha)$: transformation from system j to i by rotation of angle α , ${}^i\bar{X}\bar{Y}$: vector from X to Y expressed in coordinate system i .

Equations 51 to 53 can be rearranged to:

$$\vartheta_{D_A} = \vartheta_{D_B} \quad \vartheta_{D_A} = \vartheta_{D_C} \quad (54)$$

Finally, the equation system can be written as:

$$A_x = b \quad \text{with} \quad x = (\vartheta_B, \vartheta_C, \omega_1, \omega_2)^T \quad (55)$$

Eq 55 can be solved for x with ϑ_A as input. If the velocity input is given at B or C , the system has to be modified such that ϑ_B or ϑ_C appear in b .

The CRAB model is even simpler with only two vectors to represent the simplified suspension.

$$\vartheta_{B_A} = \vartheta_A + w_1 \times_1^0 R(\alpha)^2 \bar{A}\bar{B} \quad (56)$$

$$\vartheta_{B_C} = \vartheta_C + w_2 \times_2^0 R(\alpha)^2 \bar{B}\bar{C} \quad (57)$$

3.4.2 Rovers characteristics and simulations

In this section rover characteristics are presented based on bibliographic review, all rovers are different and were development to different tasks, using the rover characteristics, CAD models were developed, and they were scaled. The parameters established to scale were wheel diameter, bogie dimension and mass. The diameter wheel dimension selected was 0.13 m it dimensions corresponds to Rocky 7 NASA rover. CAD model of CRAB was made and its mass was the parameter as well as bogie dimension. The rovers were simulated using a step way and obtained the maximum step to climb and get off, all simulations were carried out using 10 RMP (PEDERSEN et al., 2006). Five rovers were used: Crab, Shrimp, the Rocker bogie (Spirit and Curiosity) and Exo-Mars.

3.4.2.1 Crab

The Crab characteristics were given by Krebs, Pradalier e Siegwart (2010) and Thueer e Siegwart (2010). Crab has two parallel bogies connected to the bottom through the middle wheel and at the top with a rotational joint to prevent hyper-statism. The characteristics are presented in Table 7 and Table 8 respectively.

Table 7: Crab dimensions. (KREBS; PRADALIER; SIEGWART, 2010).

Parameter	Value	Unit
Width	0.773	m
Distance front to middle	0.324	m
Distance middle to back	0.324	m
Ground clearance	0.2	m
Wheel diameter	0.196	m
Wheel width	0.1	m
Weight	37.25	kg
Speed autonomous	0.06	m/s

Table 8: Crab dimension. (THUEER; SIEGWART, 2010).

Parameter	Value	Unit
Total mass	17.5	kg
CoG X	0.228	m
CoG Y	0.0	m
CoG Z	0.123	m
Track length	0.456	m
Track width	0.38	m
Wheel stance	0.228	m
Wheel diameter	0.11	m
Wheel width	0.07	m
Max. torque	5.49	Nm
Max. speed	0.15	m/s
Max step obstacle (kinematics)	>0.11	m

Similar parameters were presented by Thueer e Siegwart (2010) with some differences and additional data. See Table 8.

The differences between these two references are due to modifications in the prototypes, the prototype used by Thuer is presented in Figure 43.

Figure 43: Crab prototype (THUEER; SIEGWART, 2010).

The CAD model of crab is presented at Figure 44.

Figure 44: CRAB CAD model

The parameters presented by Krebs and Thueer were used to develop the scaled CAD model and were used to design tables. One example of these tables is presented in Figure 45

WHEEL CRAB			
WHEEL DIAMETER [mm]	130	ANGULAR VELOCITY (RPM)	10
WIDTH WHEEL (mm)	30	LINEAR VELOCITY (m/s)	0,136
HORIZONTAL BAR		VERTICAL BAR	
TOTAL LENGTH (mm) TL	250	TOTAL HEIGHT [mm]	140
WIDTH (mm)	5	HOLE DISTANCE	35
HOLE LENGTH (mm) HL	160		
PROPORTION	0,66666667		
	2/3 TL - 10		
L BAR		TOTAL DIMENSIONS OF CRAB	
L LENGTH (mm) LL	180	LENGTH (mm)	590
THICKNESS (mm)	5	HEIGHT (mm)	240
L HEIGHT (mm) LH	100	WEIGHT (kg)	1,806
	HL+2*10		

Figure 45: Design table example

In the simulation, we used a step obstacle. The maximum step obstacle to climb and maximum step obstacle to get off were obtained. See Figure 46. For Crab, we obtained a value of 1.85 times the wheel diameter to climb, and the maximum step to get off was of 1.4 times the wheel diameter. With these values the wheels-soil contact was maintained.

Figure 46: Simulation of Crab using step obstacle.

3.4.2.2 Shrimp

Shrimp's characteristics are presented by Siegwart et al. (2002). This rover is based on rhombus mechanism at the front and in the bogie; the shrimp has one wheel mounted in a fork in the front, one wheel in the rear and two bogies on each side. The characteristics are presented in Figure 47. The weight is 3.1 kg, including the battery. According to the designers, Shrimp is able to overcome obstacles of up to two times the wheel diameter. (Siegwart et al 2002)

Figure 47: Shrimp's dimensions (SIEGWART et al., 2002)

Shrim's length is calculated using the fork front mechanism and the following equations 58 to 67. The mechanism has two DOF. Then, we need two data inputs. Assuming that inputs are the angle α and Y_i and based on Figure 48, the model is:

$$A_i + Y_i = E \sin(\Psi) + F \cos(\alpha) \quad (58)$$

$$\sin(\Psi) = \frac{(A_i + Y_i) - F \cos(\alpha)}{E} \quad (59)$$

$$X_i = E \cos(\Psi) + F \sin(\alpha) \quad (60)$$

$$\tau = 360 - \beta - \gamma - \theta \quad (67)$$

In the simulation we used a step obstacle. The maximum step obstacle to climb and maximum step obstacle to get off were obtained. See Figure 50. To climb, we obtained a value of 2.4 times the wheel diameter, whereas the maximum step to get off was of 0.58 times the wheel diameter. With these values the wheels-soil contact was maintained.

WHEEL PARAMETERS		FORK F SUPERIOR	
WHEEL DIAMETER [mm]	130	LENGTH	65
WHEEL WIDTH [mm]	30	TOTAL LENGTH TLFF	130
		F	110
HORIZONTAL CENTRAL BAR		FORK C INFERIOR	
MIDDLE LENGTH [mm]	110	LENGTH	70
TOTAL LENGTH [mm]	220	TOTAL LENGTH TLFC	140
HOLE DIAMETER	10	C	120
DISTANCE HOLE CENTER TO END	10		
VERTICAL CENTRAL BAR		FORK ED RIGTH	
MIDDLE HEIGHT [mm]	70	LENGTH TLED	110
TOTAL HEIGHT [mm] TVH	140	TOTAL LENGTH	220
DISTANCE HOLE [mm]	40	D1	85
CHASIS		D	75
LENGTH REAR WHEEL DRWL	120	E	125
HEIGTH REAR WHEEL DRWH	100		
BODY LENGTH BL	220	ROVER	
CENTER LENGHT ROVER LCR	80	A	120
HEIGHT FRONT BAR HBF	110	FI	1,287
HEIGHT HOLE FRONT BAR HHBF	60	TOTAL LENGTH	610,6
CENTER HEIGHT ROVER HCR	60	TOTAL HEIGHT	257
B	50	WEIGHT [kg]	1,771

Figure 49: Parameters of Shrimp

Figure 50: Shrimp simulation.

3.4.2.3 MER – Mars Exploration Rovers

MER rovers use the Rocker – bogie mechanism. The principal characteristics were presented by Lindemann e Voorhees (2005). They have 6-wheel drive, 4-wheel steered and a rocker bogie suspension system. The rover is presented in Figure 51.

The parameters are summarized in Figure 52.

We used the parameters presented by Lindemann to scale Spirit's. Afterwards, CAD model was developed. See Figure 53.

All Mars Explorer Rovers have the same kind of suspension called "Rocker-bogie".

Figure 51: MER. (LINDEMANN; VOORHEES, 2005)

MER				
WHEEL PARAMETERS				
WHEEL DIAMETER [mm]	130	WHEEL DIAMET	8,95	130
WIDTH WHEEL (mm)	30	SCALE FACTOR	14,5251397	
		TOTAL LENGTH	45,8	665
		TOTAL WIDTH	21,66	315
CHASIS				
LENGTH [mm] LC	230	BOGIE		
WIDTH [mm] WCH	300	HEIGHT	5,39	78
		LENGTH	14,22	207
LINK MER				
LENGTH	292	ROCKER		
DIAMETER	10	BETA	-0,33979407	1,9
		LENGTH1	29,95	435
BOGIE MER				
LENGTH LBM	210	LENGTH1 TO HC	17,39	253
HIGHT HBM	80	LENGTH 2	8,49	123
		HEIGHT 1	5,39	78
ROCKER MER				
LENGTH 1	435			
LENGTH 1 TO HOLE	253			
LENGTH 2	123			

Figure 52: MER's Parameters.

Figure 53: MER CAD model.

JPL (Jet Propulsion Laboratory – NASA) included a differential mechanism to link the rockers. We designed them according to Figure 54. The differential offers a relation of 4:1 and the rockers turn in opposite direction.

	Z	Dp	WIDTH FACE CUBE	AXIS DIAMETER
RING	40	40	10	
PLANET	15	15	10 A	5
SUN	10	10	10 A	5
N	2			
R+S/N	25			
M	1			
IF WR=0	WPP/WS=	0,2	WS/WPP=	5
IF WS=0	WPP/WR=	0,8	WR/WPP=	1,25
IF WPP=0	WR/WS=	-0,25	WS/WR=	-4

Figure 54: Differential model.

Likewise, in the simulation we used a step obstacle. The maximum step obstacle to climb and maximum step obstacle to get off were obtained. See Figure 55. To climb, we obtained a value of 3.46 times the wheel diameter. The maximum step to get off was of 1.4 times the wheel diameter. With these values, the wheels-soil contact was maintained.

Figure 55: Step results.

3.4.2.4 MSL Curiosity

The characteristics of the Mars Science Laboratory, as known as Curiosity, were published by Welch 2013 and by the JPL. See Figure 56. Rover has six drive wheels, four steering wheels and Rocker-Bogie suspension.

Figure 56: Curiosity JPL NASA.

The scaled parameter found was 3.714. It was calculated using the wheel diameter of the picture and the result was 130 mm. It corresponds to the wheel diameter parameter chosen to this simulation. See Figure 57.

CURIOSITY				
WHEEL				
WHEEL DIAMETER	35	130		
PROPORTION	3,71428571			
BOGIE				
HEIGHT1	37,5	139,285714	140	109,756098
angle 1	84,1			
LENGTH1	45,53	169,111429	170	133,258537
length2	39,45	146,528571	147	115,463415
angle	157,5			
height2	14	52		40,9756098
ROCKER				
LENGTH1	62,43	231,882857	232	182,721951
ANGLE1	149			
LENGTH2	67,47	250,602857	251	197,473171
ANGLE 2	102			
HEIGHT1	40	148,571429	149	117,073171
vertical support	16	59,4285714		46,8292683

Figure 57: Parameters of Curiosity.

In the simulation we used a step obstacle. The maximum step obstacle to climb and maximum step obstacle to get off were obtained. See Figure 58. To climb we obtained the value of 1.85 times the wheel diameter. The maximum step value to get off was 1.05 times the wheel diameter. With these values the wheels-soil contact was maintained.

Figure 58: Step results.

3.4.2.5 Exo -Mars

The rover is presented in Figure 59. The geometric characteristics were obtained from Patel, Slade e Clemmet (2010).

Figure 59: ExoMars (ESA).

ExoMars uses three-bogies concept. Two bogies are in the lateral and the other bogie is in the rear. The rover has six drive wheels and six steering and tactile wheels. The proportions are according to Curiosity. It uses the same wheel diameter and overall dimensions. The respective CAD model uses the three-bogie concept and is presented in the Figure 60. The body of the robot was designed in the CAD model to maintain the same mass.

The rover can climb obstacles of 2.86 times the wheel diameter and get off obstacles of 0.194 times the wheel diameter. Figure 61.

Figure 60: CAD Model ExoMars.

Figure 61: ExoMars step simulation.

3.4.3 Tests

3.4.3.1 EESC USP Robot

Tests in agricultural uneven terrain were performed using a robot developed to LARS challenge 2012. The robot was developed as part of Mobile robotics introduction discipline of PhD in Mechanical Engineering Program chaired by Professor Marcelo Becker at EESC –USP. The CAD model of the robot is presented in Figure 62. The robot has two propulsion motors that correspond to differential configuration ID according to table 1.1.

Figure 62: USP robot (FURLANETTI et al., 2012)

The robot was tested in uneven agriculture terrain, in the National Laboratory of Precision Agriculture (LaNAPre) of Embrapa. The soils used were soil to non-perennial crop in the moment of seeding and soil to perennial crop. Figure 63.

Figure 63: Tests in LaNAPre.

According to our findings the robot presented difficulties in non-perennial crop due to chassis height and could not traverse the non-perennial terrain. In perennial terrain the robot should travel in a straight fashion. However, it could not follow the straight line. Due to its differential configuration, the robot also presents difficulties in curves.

3.4.3.2 Agribot

The Agriculture robot was developed by USP, Embrapa, and Agricultural Machines Jacto S.A., in a MCT/FINEP/CT-Agro project. Agribot may be seen in Figure 64. It is classified as ITSS according to table 1.1. Propulsion tests were performed. After the tests, Agribot was put in operation. The steering and propulsion controls were developed as well as a supervisory system. Several tests were carried out in the steering system, and the steering hydraulics system was improving (TORRES, 2014b).

Tests in the propulsion system were performed at LaNAPre. The results will be presented in chapter 5. In general, the robot presented difficulties to overcome obstacles. See Figure 65.

The Agribot could not overcome the slope. Agribot was developed as multipurpose platform and its dimensions are $3 \times 2.25 - 2.40 \times 1.8$ m. Transporting this robot is not an easy task. When it is lifted, it tends to slant way. It takes 4 people to keep it balanced when the robot is being transferred to a truck. See Figure 66.

Four steering systems give Agribot high maneuverability in agricultural uneven terrain. It was presented at Agrishow 2013 and Diaz et al. (2013).

Figure 64: AgriBot

Figure 65: Test to overcome obstacle

Figure 66: Transporting Agribot.

3.4.3.3 Mirã

Mirã rover was developed to Embrapa as a platform to test LIBS portable technology. It was presented in SIAGRO 2014 (ARCHILA et al., 2014) and was used as a platform for pelican quadcopter to land and take off. Figure 67.

Figure 67: Mirã Rover presented in SIAGRO 2014.

Mirã was presented at 67th SBPC ExpoTec to demonstrate LIBS technology operation. Figure 68 shows the moment that the LIBS shoot over aluminum alloy and the spectrum was read. Specific LIBS mounting used in Mirã requires focal distance of 0.08 m of soil.

Figure 68: LIBS test in SBPC 2015.

Mirã was used as a platform to test other technologies to be used in scouting tasks. In this case, thermal cameras were used to identify fruits (PEDRAZA, 2015). Figure 69 presents Mirã and the thermal camera subsystem used in Maringa Farm.

Mirã was a platform used to test devices to scouting tasks. It was possible to embed the technology purposed and the results were presented in SIAGRO 2015, SBPC, 2015 and in Pedraza (2015). Tests of performance of Mirã in uneven terrain were performed and will be presented in chapter 5.

Figure 69: Thermal cameras.

3.5 Proposal

The proposal of R2A (Rover to Agriculture) was a result of the application of the methodology. It contemplates the development of a platform with capabilities to move on even and uneven terrain. It also considers energy consumption as a significant aspect of the rover. The fact that the rover has different subsystems was also taken into account. The mechanics and electronics configurations, as well as the computational system will be described, as follows.

3.5.1 Mechanics Configuration

The mechanics configuration of R2A is composed by a suspension system, propulsion system, steering system and chassis. A general view of R2A presented in Figure 70 shows the suspension system (9), propulsion systems (1, 2, 3, 4), steering system (5, 6, 7, 8), and the chassis (10).

Figure 70: R2A

The suspension system is composed by a spatial mechanism linked by cylindrical and spherical joints as Figure 71 shows.

Figure 71: Suspension system concept.

The cylindrical joints are linked to the chassis, and the spherical joints are linked to the bars. This configuration allows the weight to be distributed on the wheels and utilizes the motor torque to assist the robot movement. Table 9 presents the rover concept evolution. It include: steering system, height change system and stiffness change system.

Table 9: Rover concept evolution.

CONCEPT	SCHEMATIC DRAWING
Initial Rover Concept	
Steering System	
Height Change System	
Stiffness Change System	

The lateral systems include two four bars mechanism. This mechanism is used to adjust the height of the rover. Flexible and/or rigid components may be included whenever it is necessary, e.g. when the robot needs to be adapted to specific terrain characteristics. See Figure 72.

Figure 72: R2A Suspension.

Figure 72 presents two four-bar mechanism: one in each side of the rover and, in this case, bar 11 was included to fix the height of suspension. Figure 73 presents the inclusion of flexible elements (12) in the suspension. Among these elements there are springs, dampers, and intelligent shock absorbers (EDWARDS; YEYATI, 2005).

Figure 73: Flexible elements (12) in the suspension.

The propulsion system is composed by 4 wheels. Each wheel consists of a transmission system and a motor. This configuration gives independent power to each wheel. See Figure 70. The steering system is composed of a motor, a gearbox, guidance and support. Each system is linked directly to each wheel providing them independent steering systems, as shown in Figure 74.

Figure 74: Steering system.

The chassis is supported by three suspension points. It may fit different sensors and configurations. See Figure 75.

Figure 75: Chassis configuration.

Figure 75 shows the suspension set-up. As one may see, when there is change in the height, consequently one dimension is altered Figure 76. This amounts to saying that, according to the desired height, some adjustments are made. It is possible due to the fact that the chassis is constructed with a modular profile. The configuration of the chassis

may be changed accordingly. The chassis has the modular profile used in Mirã and allows the inclusion of devices as LIBS, Cameras, Sensors, land and take off platform to drones, batteries, among others.

Figure 76: Change in the height and length in R2A.

3.5.2 Electronics Configuration

The electronics configuration of R2A is composed by 9 systems. There are four independent propulsion systems, 4 steering systems. See Figure 77. These systems are commanded by a central controller that synchronizes the rover operation. Each system has independent power and distributed control.

The electronic propulsion system is presented in Figure 78. It is composed by power, controller, motor and sensor.

The motor is a Brushless DC motor of 250 W with three phases. The sensors are hall sensors. There is one driver that is embedded within the controller. The power unit is a lithium battery of 40 V DC. The steering electronic system is presented in the Figure 79. It is composed by power, controller, driver, steering DC motor and sensor.

The steering system consists of a DC motor with a position control. The sensor takes the data of angular position and sends this information to the controller. The controller sends the signal to the driver that sends it to the motor. The power unit is a battery of 12 V and 7 Ah. The electronic suspension system consists of sensors that send the information to the central controller. This way, the configuration of the robot suspension is acknowledged by the controller.

3.5.3 Computational System

The computational system is composed by the principal program and two subprograms. The principal program receives the assigned task and translates it to commands.

Figure 77: Electronic architecture of R2A.

Figure 78: Propulsion System.

Figure 79: Steering System.

The commands are sent to the subprograms and define the robot parameters such as movements, velocities, and steering angles. The principal program receives data from,

steering and propulsion systems that uses them to know the state of the robot. Figure 80. The programs use the kinematics and dynamics models that are presented in detail in the next section.

Figure 80: Computational system.

The computational systems include the distributed controller to steering and propulsion. There are four steering subsystems and four propulsion subsystems as presented in Figure 77. Each one with its own controller. In this work, a traditional PID control strategy was used. However, it is possible to use other control algorithms. A brief of the control diagram is presented in Figure 81.

Figure 81: Control diagram.

This control system is used in the steering and propulsion systems. The angular position is a control variable in the case of steering system. When it comes to the propulsion system, the variable is the angular velocity.

There are four steering systems and they have independent controllers. However, all this systems use the same control program. Regarding the propulsion system, there are also four independent controllers that use the same control program. This means that there are two control programs.

3.6 Mechatronic CAE model

The mechatronic CAE models are computer aided engineering models used to study and develop R2A. In this study, we used four tools: computer aided design; multibody dynamics, finite elements analysis (FEA) and electronic. They are presented below. The first tool used the computer aided design (CAD). It was used to develop the structure and parts of robot. The second tool is the multibody dynamics. It uses CAD and includes the motors to propulsion and steering. For flexible suspension, we use springs. The propulsion system the model uses the motors presented in the Figure 82. They are integrated to wheels and give the robot propulsion.

Figure 82: Propulsion motors.

In the multibody analysis, springs were included to study the rigid and flexible suspensions options. See Figure 83.

Figure 83: Spring inclusion in CAE model.

The steering system is also included in the multibody analysis. See Figure 84, where one has the steering motor, an angular position sensor (potentiometer), and the gears that are linked to the motor axis, as well as to the potentiometer axis.

Finally, the multibody system was tested in regular and uneven terrain to obtain the performance and tendency Figure 85. Simulation data were collected to use FEA and to select the structural material to be used.

One example of use of FEA in the rover development is presented in the Figure 86 in this case applied to lateral support.

The fourth CAE tool used was the electronic simulation. It was applied to propulsion and steering systems. The electronic descriptions of the propulsion and steering systems

Figure 84: Steering motor and sensor.

Figure 85: Environments.

Figure 86: FEA to lateral support.

were presented in 3.5.2. In Figure 87, we present the schematic of the steering system. This system is composed by a DC motor, a driver, two potentiometers, and a controller.

The propulsion system uses a brushless three-phases motor, a driver to each phase, one potentiometer, and one controller. The system is presented in Figure 88.

As presented in the 3.5.2 the electronics configuration of R2A is composed by 8 systems. There are four independent propulsion systems, and 4 steering systems. These systems are commanded by a central controller that synchronizes the rover operation. Each system has independent power and distributed control. Figure 89 presents a possi-

Figure 87: Steering system.

Figure 88: Propulsion system.

ble configuration using a controller to command the propulsion and steering systems.

CAE tools allow us to study different configurations to know the tendency and possible performance of R2A. They were important to choose the actuators, electronics, dimensions

Figure 89: Possible configuration to R2A command.

and materials to the rover. The results of the simulations will be presented in the.

Results

In this chapter, the results of this work are described in details. The first one is the comparison between R2A concept and some rovers in simulated environment. The second one is a specific simulation of R2A in step and agricultural uneven terrain. Then, R2A prototype is presented and tested. Finally, a comparison among AgriBot, Mirã and R2A is offered.

4.1 Simulations Comparative

The R2A suspension concept was compared with other passive suspensions. The selected suspensions were the ones in Shrimp, Crab, Roker Bogie (MER and Curiosity), Exo – Mars. The rovers mentioned above have different dimensions. Therefore, they were scaled to obtain similar dimensions so the comparison could be carried out as presented in section 3.4. R2A was simplified using a rigid suspension as the others Rovers and scaled so the wheel diameter was 130 mm. Overall dimensions were similar to the other rovers, as well as the mass, the velocity was 10 rpm for all rovers. The robot CAD simplified is presented in Figure 90.

Figure 90: R2A CAD Model simplified.

R2A can climb step of 3.25 times the wheel diameter and get off the same step. Figure 91.

Figure 91: R2A step simulation.

The results of step simulations are presented in Table 10. The best climbing performance was MER's with 3.46 wheels diameter. The second best one is R2A's with 3.25 wheels diameter. Additionally, R2A showed the best getting off ability.

Table 10: Comparison of Rovers (Step).

ROVER	MAXIMUM STEP (CLIMB) [Wheel diameters]	MAXIMUM STEP (GET OFF) [Wheel diameters]
CRAB	1.85	1.40
SHRIMP	2.40	0.58
MER	3.46	1.40
MSL	1.85	1.05
Exo-Mars	2.86	1.19
R2A	3.25	3.25

New simulations were performed. The rovers were tested using the same obstacle. The obstacle used has two steps. The first one is 75 mm high and the second is 240 mm high. These dimensions make it possible for all the rovers to overcome the steps. Subsequently, we present the results of the simulations of each rover type using torque as a comparative parameter. The velocity was 10 rpm according Pedersen et al. (2006).

4.1.1 Crab

The results of Crab simulations are presented in Figure 92. The maximum torque value presented was approximately 5 N-m. However, this value corresponds to one singularity in the simulation.

The 5 N-m is due to the impact of the wheels against the obstacle. This kind of situations should be avoided in a real application. See Figure 93.

Figure 92: Torque of motors.

Figure 93: Impact of the wheels against the step.

As the singularities were deleted, we obtained the results disregarding impact conditions. See Figure 94.

Figure 94: Results of simulation to Crab in ideal condition.

4.1.2 Shrimp

The simulation of Shrimp presents peaks or singularities that are similar to those that happened in Crab's. The values are incremented due to the impact between the rover and the obstacles. See Figure 95.

Figure 95: Results of Shrimp simulation.

The peak corresponds to impact of the wheels against the obstacle. An example is presented in Figure 96.

Figure 96: Shrimp overcomes an obstacle.

The maximum value is 8.97 N-m in motor 4. In this case, there are other peaks. Nevertheless, the highest value is clear. It corresponds to the impact situation. When these impacts are deleted, we obtain the results shown in Figure 97.

The maximum torque presented was of 1.47 N-m. It was in motor 2. In this case, there are other peak values due to climbing and getting off moments.

Figure 97: Torque in the motors of Shrimp in step obstacles.

4.1.3 MER

The simulation of MER is presented in Figure 98. Unexpectedly, there are not evident singularities. However, the impact appears with sudden changes in the values of torque. See Figure 98.

Figure 98: Torque in the motors of MER in step obstacles.

The maximum torque value is 1.46 N-m to motor 1 and 2. When these peaks are eliminated, we obtain the results shown in Figure 99.

The maximum torque value is 1.1 N-m to motors 3 and 2. In this simulation, it is possible to identify the peaks that correspondent to climbing and getting off stages. The maximum values correspond to climbing the highest step.

Figure 99: Torque in the motors of MER in step obstacles.

4.1.4 MSL

MSL simulation presented two peaks. See Figure 100. Likewise, they correspond to impact or singularities.

Figure 100: Torque in the motors of MSL in step obstacles.

The maximum torque value is 9.12 N-m, eliminating the peaks; we obtain the Figure 101.

The maximum torque value was 1.68 N-m to motor 3 when it achieves the highest step. In the results of this simulation it is difficult to identify climbing and getting off stages.

4.1.5 ExoMars

Simulations were carried out in a step terrain. Figure 102 that illustrates the climbing ability also presents the simulation results.

Figure 101: Torque in MSL's motors overcoming obstacles.

Figure 102: Exo Mars Climb test.

The maximum torque value was 1.98 N-m to the middle motor.

4.1.6 R2A

Figure 103 presents the results for the simulation of R2A. The torque values may also be observed. The maximum value is 0.69 N-m to the rear motor M2 and 0.53 N-m to the front motor.

The simulation presents a maximum torque value of 0.69 to rear motor (M2).

4.1.7 Comparison of rovers

The simulations were carried out to compare and contrast the rovers. The results are presented in Table 11.

Figure 103: R2A Climb test.

Table 11: Comparison of Rovers (Torque).

ROVER	STEP (CLIMB) [Wheel diameters]	STEP (GET OFF) [Wheel diameters]	MAXIMUM TORQUE [N-m]	AVERAGE TORQUE [N-m]
CRAB	1.85	0.58	2.22	0.12
SHRIMP	1.85	0.58	1.51	0.13
MER	1.85	0.58	1.10	0.13
MSL	1.85	0.58	1.68	0.14
Exo- Mars	1.85	0.58	1.96	0.19
R2A	1.85	0.58	0.69	0.10

Table 4.8 presents the torque values using a step of 0.58 wheel diameter and a 1.85 wheel diameter. These dimensions allow all rovers to overcome the step. In these simulations the maximum torque was 2.22 N-m, which corresponds to CRAB's. The minimum torque value was 0.69, which is R2A's. One may observe in the average torque column that the minimum torque was presented by R2A. The value is 0.1 N-m. Exo-Mars presented the maximum value, which is 0.19.

The R2A was compared with rovers Crab, Shrimp, MER, MSL and Exo-Mars. The rovers were scaled modeled and simulated in ideal conditions such as: friction coefficient of 1, constant velocity, and rigid suspensions. These comparisons aimed to evaluate passive suspension systems in step terrain. It is important to highlight that all rovers studied present different characteristics. They were developed to specific tasks and the comparison did not attempt to establish that one is better than other. The simulations were carried out to understand the mechanical behavior of the suspension systems as well as the differences among the suspension mechanisms. The description of each one was presented. R2A presented considerable capacity to overcome obstacles. Additionally, R2A presents a symmetric performance when it is climbing and getting off obstacles,

differently from the other rovers. The torque of R2A was the lowest which indicates less energy consumption.

4.2 Kinematics and dynamics R2A

In the following section, we will show the general kinematics model for R2A that uses homogeneous matrix transformation.

Figure 104: General geometric robot parameters.

Figure 104 presents the inertial coordinate system $\{X_o, Y_o, Z_o\}$. One may observe that the frame of the robot's gravity center $\{X_R, Y_R, Z_R\}$ is colored in green. In blue, one has the frames of the steering system $\{X_s, Y_s, Z_s\}$ and, in yellow, the frames of the propulsion system $\{X_p, Y_p, Z_p\}$.

$$T_{R,Ai} = T_{R,D} T_{D,Si} T_{S,Ai} \quad (68)$$

Eq. 68 represents the transformation from $\{X_R, Y_R, Z_R\}$ frame to wheel coordinate frame $\{X_{Ai}, Y_{Ai}, Z_{Ai}\}$, including the steering angle Ψ_i , and the rotation wheel angle θ_i .

To consider the wheel slip ζ_i and the translation along Z_{Ai} axis to the ground in a distance of R_w (wheel radius), it is necessary to include more transformation matrices. Figure 105 presents the coordinate frames $\{X_{Ai}, Y_{Ai}, Z_{Ai}\}$, $\{X_{Ci}, Y_{Ci}, Z_{Ci}\}$ and $\{X_{Mi}, Y_{Mi}, Z_{Mi}\}$ necessary to include slip conditions and wheels variables according to Denavit Hartenberg.

Figure 105: Coordinate frames from the wheel's center to the ground.

Table 12: D-H Parameters.

FRAME	Γ	d	a	A
D	0	D_{zr}	0	-90
S_i	$\pm\beta$	$d_z d_i$	$d_x d_i$	90
A_i	Ψ_i	d_{zsi}	0	-90
C_i	θ_i	0	0	-90
M_i	Z_i	$-R_w$	$-R_w \theta_i$	0

$$T_{R,Mi} = T_{R,D} T_{D,Si} T_{S,Ai} T_{Ai,Ci} T_{Ci,Mi} \quad (69)$$

Eq. 69 summarizes the coordinate transformations from the robot's gravity center frame to each wheel subsystem. We use Denavit-Hartenberg D-H algorithm to determine the transformations. The parameters are presented in Table 12.

The homogeneous transformation matrix according to Denavit-Hartenberg is:

$$T_{i,j} = \begin{bmatrix} c(\gamma_j) & -s(\gamma_j)c(\alpha_j) & s(\gamma_j)s(\alpha_j) & \alpha_j c(\gamma_j) \\ s(\gamma_j) & c(\gamma_j)c(\alpha_j) & -c(\gamma_j)s(\alpha_j) & \alpha_j s(\gamma_j) \\ 0 & s(\alpha_j) & c(\alpha_j) & d_j \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (70)$$

By using the D-H parameters of Table 12 in the eq. 68 and 69, we obtained the equations 70. The kinematics to each wheel subset was obtained using the matrix operations

in eq. 71.

$$T_{R,M_i} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & dzr \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c(\beta_i) & 0 & s(\beta_i) & dx d_i c(\beta_i) \\ s(\beta_i) & 0 & -c(\beta_i) & dx d_i s(\beta_i) \\ 0 & 1 & 0 & dz d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c(\Psi_i) & 0 & -s(\Psi_i) & 0 \\ s(\Psi_i) & 0 & c(\Psi_i) & 0 \\ 0 & -1 & 0 & dz s_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \\ \begin{bmatrix} c(\theta_i) & 0 & -s(\theta_i) & 0 \\ s(\theta_i) & 0 & c(\theta_i) & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c(\tau_i) & -s(\tau_i) & 0 & R_w \theta_i c(\tau_i) \\ s(\tau_i) & c(\tau_i) & 0 & R_w \theta_i s(\tau_i) \\ 0 & 0 & 1 & R_w \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (71)$$

In order to obtain the wheel Jacobian matrix, we must express the motion of the rover (derivatives of rover reference position and orientation) to the wheel motion (wheel rotation velocity, rocker and bogie angular rates, etc.). This is done by applying the instantaneous transformation $T_{\hat{R},\hat{M}_i}$ as follows. Adapted of McDermott e Tarokh (2005).

$$\dot{T}_{M_i,R} = T_{\hat{R},\hat{M}_i} \dot{T}_{\hat{R},R} \quad i = 1, \dots, 4 \quad (72)$$

$$\dot{T}_{\hat{R},R} = T_{\hat{R},\hat{M}_i} \dot{T}_{M_i,R} \quad i = 1, \dots, 4 \quad (73)$$

It is also possible to obtain the relationships as follow:

$$\dot{T}_{R,M_i} = T_{\hat{R},\hat{M}_i} \dot{T}_{\hat{R},R} \quad i = 1, \dots, 4 \quad (74)$$

$$\dot{T}_{\hat{R},R} = T_{\hat{M}_i,\hat{R}} \dot{T}_{R,M_i} \quad i = 1, \dots, 4 \quad (75)$$

Derivative of transformation matrices and instantaneous transformations are discussed in Muir e Neuman (1987). Using Z-Y-X Euler angles yaw ϕ (rotation about the Z-axis), pitch ρ (rotation about the Y axis), and roll r (rotation about the X axis), from eq. 72 the derivative of the rover coordinate frame is found to have the following form eq. 76.

$$\dot{T}_{\hat{R},R} = \begin{bmatrix} 0 & -\dot{\phi} & \dot{\rho} & \dot{x} \\ \dot{\phi} & 0 & -\dot{r} & \dot{y} \\ -\dot{\rho} & \dot{r} & 0 & \dot{z} \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (76)$$

The transformations on the right hand side of eq. 69 are obtained using eq. 74. To eq. 76 and Table 12, taking the derivatives of the resulting transformations, and noting

that $T_{Mi,R} = T_{R,Mi} - 1$. Finally, Jacobean matrix to R2A is obtained replacing in eq. 76. Jacobean matrix is presented in equation 77.

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \dot{\phi} \\ \dot{\rho} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} R_w c(\beta_i) c(\Psi_i) & 0 & b_i d_{si} c(\beta_i) \\ R_w s(\Psi_i) & 0 & a_{si} \\ b_i R_w s(\beta_i) c(\Psi_i) & 0 & d_{si} s(\beta_i) \\ 0 & 0 & -c(\beta_i) \\ 0 & b_i & 0 \\ 0 & 0 & b_i s(\beta_i) \end{bmatrix} \begin{bmatrix} \dot{\theta}_i \\ \dot{\beta}_i \\ \dot{\eta}_i \end{bmatrix} \quad i = 1, 2 \quad (77)$$

The dynamic model is presented briefly in the equations 78 to 85. Where m is the total mass, F_{fi} the friction force in the wheel i , I the inertia, l the wheel axis length and τ_i the motors torque and i is the wheel number (1, 2, 3, 4):

$$m\ddot{x}_g + ma_g (\ddot{\theta} \sin(\theta) + \dot{\theta}^2 \cos(\theta)) - (F_{f1} + F_{f2}) \sin(\theta) - \cos(\theta)(f_{f3} + F_{f4}) = 0 \quad (78)$$

$$m\ddot{y}_g + ma_g (\ddot{\theta} \cos(\theta) + \dot{\theta}^2 \sin(\theta)) - (F_{f1} + F_{f2}) \cos(\theta) - \sin(\theta)(f_{f3} + F_{f4}) = 0 \quad (79)$$

$$I\ddot{\theta} - ma_g \ddot{y}_g \cos(\theta) + ma_g \ddot{x}_g \sin(\theta) - a_g (F_{f1} - F_{f2}) + l(F_{f3} - F_{f4}) = 0 \quad (80)$$

$$I_{wy} \ddot{\varphi}_1 + F_{f1} r = \tau_1 \quad (81)$$

$$I_{wy} \ddot{\varphi}_1 + F_{f2} r = \tau_2 \quad (82)$$

$$I_{wy} \ddot{\varphi}_2 + F_{f3} r = \tau_3 \quad (83)$$

$$I_{wy} \ddot{\varphi}_2 + F_{f4} r = \tau_4 \quad (84)$$

Where $m = m_r + 4m_w + m_l$ and $I = I_r + m_r(a - a_g)^2 + 4I_{wz} + m_w(l^2 + a_g^2) + I_l + m_l(b + a_g)^2$

Writing a matrix from eq. 85:

$$\begin{aligned}
 & \begin{bmatrix} m & 0 & ma_g \sin(\theta) & 0 & 0 & 0 & 0 \\ 0 & m & -ma_g \cos(\theta) & 0 & 0 & 0 & 0 \\ ma_g \sin(\theta) & -ma_g \cos(\theta) & I & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & I_{wy} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & I_{wy} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & I_{wy} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & I_{wy} \end{bmatrix} \begin{bmatrix} \ddot{x}_g \\ \ddot{y}_g \\ \ddot{\theta} \\ \ddot{\varphi}_1 \\ \ddot{\varphi}_2 \\ \ddot{\varphi}_3 \\ \ddot{\varphi}_4 \end{bmatrix} + \dots \\
 & \dots + \begin{bmatrix} 0 & 0 & ma_g \dot{\theta} \cos(\theta) & 0 & 0 & 0 & 0 \\ 0 & 0 & ma_g \dot{\theta} \sin(\theta) & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{x}_g \\ \dot{y}_g \\ \dot{\theta} \\ \dot{\varphi}_1 \\ \dot{\varphi}_2 \\ \dot{\varphi}_3 \\ \dot{\varphi}_4 \end{bmatrix} + \begin{bmatrix} -\sin(\theta) & -\sin(\theta) & -\cos(\theta) & -\cos(\theta) \\ \cos(\theta) & \cos(\theta) & -\sin(\theta) & -\sin(\theta) \\ -a_g & a_g & 1 & -1 \\ r & 0 & 0 & 0 \\ 0 & r & 0 & 0 \\ 0 & 0 & r & 0 \\ 0 & 0 & 0 & r \end{bmatrix} \begin{bmatrix} F_{f1} \\ F_{f2} \\ F_{f3} \\ F_{f4} \end{bmatrix} = \dots \quad (85) \\
 & \dots = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \end{bmatrix}
 \end{aligned}$$

4.3 R2A Simulations

Several simulations were performed using the CAD and CAE models. They were presented in the previous sections. Based on these models, three simulations were performed: The first one uses step terrain, the second one uses uneven terrain and the third presents FEA. First simulation was performed to find the maximum step R2A is able to climb up and down using real dimensions and mass values. In this simulation, the mass used was 65kg, the friction coefficient was equals 1 and the constant wheel velocity was 20 RPM. The goal of this simulation was to define the limits of the suspension system in ideal conditions. Figure 106 presents the environment of the simulation.

Figure 106: Step simulations.

These simulations consider several steps to find the maximum step to climb up and down. See Figure 107. The first step was used to test the ability of climbing down and the second step to test the ability of climbing up. Results show that the maximum step

to climb down was 1 time the wheel diameter and the maximum step to climb up was 1 times the wheel diameter. Before finding the maximum steps, different stiffness conditions were tested represented by the spring constant K . Figure 107 shows that the results to stiffness corresponds to 0.1 N/m in the springs of suspension.

Figure 107: Step simulation results.

Both front wheels and both back wheels behave the same way since the robot is symmetric and the terrain has two dimensions. Figure 108 shows the torque of front (Blue) and rear (Red) wheels. The maximum torque values are when the R2A is climbing the steps. There are unexpected peaks. They occur when the front or rear wheels get an abrupt change. During the simulations the abrupt changes occur in the next conditions: when the wheels hit the step, when the wheels finish climbing the step and when the wheel gets off the terrain and achieves the floor. See Figure 107

Figure 108: Peaks conditions in the simulation.

Figure 109 presents the results of the simulations. Different stiffness may be observed as follows: (a) K 0.1 N/m, (b) K 1 N/m, (c) K 10 N/m, (d) K 100 N/m, (a) K 1000 N/m.

Figure 109: Results of simulation to different stiffness conditions

The highest torque was 88.70 N-m to the front wheel when the spring constant was 0.1 N/m. The minimum values were 57.13 N-m when stiffness was 100 N/m to front wheel, and the 53.20 N-m to front wheel, when stiffness was 1000 N/m.

Table 13 summarizes the results of the simulations in different stiffness conditions. The maximum average torque was 13.63 to the front wheel and $K = 1$ N/m. The lowest torque value was of 11.60 N-m to front wheel, when stiffness was 100 N/m. However, if

Table 13: Results of step simulations using different stiffness

Stiffness	Front Wheel		Rear Wheel		Mean	
K [N/m]	Maximum Torque [N-m]	Average Torque [N-m]	Maximum Torque [N-m]	Average Torque [N-m]	Maximum Torque [N-m]	Average Torque [N-m]
0.1	88.70	12.28	86.28	13.11	87.49	12.70
1	71.03	13.63	73.95	13.39	72.49	13.51
10	58.75	11.71	62.83	12.15	60.79	11.93
100	57.13	11.60	61.56	12.20	59.34	11.90
1000	57.20	11.63	61.77	12.13	59.48	11.88

we consider the average and medium values regarding the last three stiffness conditions, the values were the minimum ones and were very similar.

When non-rigid suspension was used in the step terrain simulation, it was found that the maximum and average torque values increased as stiffness suspension values decreased. Table 13 presents these findings. Non-rigid suspension stores energy in the springs before delivering it. However, the energy is delivered in moments that the robot can not benefit from it, for example. See the Figure 110.

Figure 110: Suspension system of R2A.

The situation presented in Figure 110 generates the increment in the maximum and average torque values in the R2A. It happens because of stiffness suspension value decreases in step terrain. Average torque presents a maximum difference of -7.48% and maximum torque the maximum difference was -35.59%. See Table 14

Table 14: Results of step simulations using different stiffness in percentages.

Stiffness	Front Wheel		Rear Wheel		Mean	
K [N/m]	Maximum Torque [%]	Average Torque [%]	Maximum Torque [%]	Average Torque [%]	Maximum Torque [%]	Average Torque [%]
0.1	100	100	100	100	100	100
1	80.08	110.99	85.71	102.14	82.86	106.38
10	66.23	95.36	72.82	92.68	69.48	93.94.
100	64.41	94.46	71.35	93.06	67.82	93.70
1000	64.49	94.71	71.59	92.52	67.98	93.54

The second simulation was made in uneven terrain considering the topography of the terrain in street 16th of Maringá farm. See Figure 111.

Figure 111: Maringá Farm and CAD model. Courtesy Citrosuco.

In these simulations, we obtained the behavior of R2A in a realistic environment. Figure 112 presents the simulation environment.

The simulations were made with constant wheel velocity of 20 RPM. The friction coefficient was 1 and the spring constant change between 0.1 N/m to 100 N/m. Figure 113 presents the torque when stiffness was 0.1 N/m. The motors were numbered as follows: the front right wheel is number one; the rear right is number 2; the front left is 3 and the last one is 4.

Figure 112: Simulation of R2A in Maringa farm topography.

Figure 113: Torque of motors in Maringa topography.

In order to understand the behavior of the torque in each motor, see Figure 114. In the first graphic, one may observe the torque for motors 1 and 4. In the second graphic, we have oscillations of the torque values for motors 2 and 3. In this graphics, it is possible to see the effect of the suspension on the torque.

Figure 114 shows the effect of the suspension system. It shows how the torque behaves in the motors with similar values between the motors one and four, as well as between motors two and tree. The results of the simulations are presented in Table 15.

Table 15 presents the torque by motor shown the maximum and average values with different stiffness values for all motors. The highest torque value was 37.44 N-m to motor two when stiffness was 10 N/m. The minimum was 34.97 N-m to motor one, when stiffness was the same. The maximum average was 14.66 N-m to motor four at k 100 N/m and the minimum average 11.5 N-m to motor 1 at K 0.1 N-m. In general, the values are very similar even when we have different stiffness values.

Figure 114: Torque of motors in Street. 16th Maringa farm.

Table 15: Results of simulations using different stiffness

Stiffness	Torque M1		Torque M2		Torque M3		Torque M4	
K [N/m]	Max Torque [N-m]	Avg Torque [N-m]	Max Torque [N-m]	Avg Torque [N-m]	Max Torque [N-m]	Avg Torque [N-m]	Max Torque [N-m]	Avg Torque [N-m]
0.1	37.12	11.91	35.41	13.08	35.02	12.57	35.28	11.15
1	35.11	12.00	37.36	14.61	35.86	14.39	36.58	11.44
10	34.97	11.97	37.44	14.65	36.52	14.57	37.03	11.48
100	35.03	11.96	37.34	14.66	36.47	14.33	37.20	14.63

In the simulations, the relation between stiffness (K) and path traveled by the robot were also analyzed. The parameters used were the same in the four simulations. Stiffness varies from 0.1 [N/m] to 100 [N/m]. The most significant difference in the paths occurred when stiffness values varied between K 100 and K 10. See that Figure 115 presents different paths. The blue path is related to K 0.1 N/m, the red path to K1 N/m, the green path to K 10 N/m, and the yellow path to K 100 N/m. The values for the distances the robot traveled are presented in Figure 116 and Figure 117.

To show the differences between paths, we present the principal views in Figure 115. The first one is a lateral view presented in Figure 116. It illustrates different heights of the paths. The blue and red paths present the same height. The value is 0.025 m for the green path. It is slightly above the previous paths at the final point. The height for the yellow path is 0.086 m, which is above the height for the green path at the final point.

The top and front views of Figure 115 are presented in Figure 117. Regarding the top view, there are differences around 0.010 m. They are small when compared to the robot dimensions. When it comes to the front view, the behavior is similar, except when k is 100.

In the simulations in uneven terrain, the suspension effect maintains the torque distribution among the four motors. Nevertheless, the effect of stiffness variations is around $\pm 5.65\%$ to maximum torque and among 0 to 15.91% to average torque. In this case, due to the terrain topology, the energy stored by springs is fully exploited. Consider-

Figure 115: Path follow by R2A.

Figure 116: Lateral view of Paths follows by R2A.

ing the path, the maximum Euclidean distance between 100 and 0.1 stiffness suspension was of 0.016 m. This corresponds to 0.27%, which might be consistent with different topographic features.

Figure 117: Top and front views of Path follow by R2A.

Third simulation presents FEA application to select the materials that will be used in R2A prototype. Using the results of step dynamic simulations, it was possible to obtain the torques and forces acting on the parts of the robot. Finite element analyses were performed after having the force values. Then the materials to construct the robot were chosen. One example of the results obtained is presented in Figure 118.

Figure 118 presents Von Mises equivalent stresses and the safety factor according the selected material. For lateral support, 1060 aluminum alloy was selected and the safety factor was 2.2. Firstly, a step simulation was carried out. In this simulation, a maximum force of 1500 N was used to obtain the safety factor. In a simulation where the terrain is uneven, a maximum load around 650 N is expected to this part of the robot.

4.4 The Prototype

In this section, the final prototype of R2A is presented. The materials were machined and milled in a lathe BLC-1244B See Figure 119(a), and milling machine XL5036B, as shown in Figure 119(b).

Once the machining and milling of parts were carried out, we started assembling R2A. The first system that was assembled was the steering one. See Figure 120(a). The second one was the suspension axis, as in Figure 120(b), and, finally, the chassis, shown in Figure 120(c).

The electronics is presented in Figure 121. The electronics steering system, the electronic propulsion system, and start and safe system are shown in Figure 121, respectively.

Finally, a general view of the R2A is presented in Figure 122.

PARAMETER	Lateral support
<p>Von Mises equivalent stress:</p> <p>Maximum value: 61.508 <u>KPa</u></p> <p>Minimum Value: 12.5 MPa</p>
<p>Safety Factor:</p> <p>Material selected: AL 1060</p> <p>Minimum value: 2.2</p>

Figure 118: Example of FEA to R2A.

Figure 119: Machining process.

4.5 Tests

R2A was tested in order to obtain its principal parameters, i.e. motors and sensors. The parameters were used to controllers and programs. Once the parameters were ob-

Figure 120: Assembly

Figure 121: Electronics R2A.

Figure 122: R2A.

tained tests in even and uneven terrain were run. Finally, R2A was compared with the rover Mirã and Agribot

4.5.1 Motors tests

Initially, the motors were tested without load in order to obtain its velocity values according to the control signal. All the motors have different velocities with the same control signal. The results are presented in Figure 123.

Figure 123: Velocity of motors without load.

The control signal value is between 0 and 5 volts. The left front motor (lfm) starts with a control signal of 1.36 volts. It was the first to start. The last one to start was the right front motor (rfm) with a control signal of 1.4 volts. All motors start at different control signal and have different velocity values. It is important to highlight that, despite being equal according to the manufacturer, the motors need different control signals. The values were linearized and presented in the equations shown in Figure 123.

4.5.2 Sensors tests

R2A uses hall sensors, potentiometers, and current sensors. The potentiometers are used to steering control. Hall sensors are used for propulsion control, whereas the current sensors are used to obtain the data of consumption of the rover.

The potentiometer gives volt signals. These signals in the steering subsystem correspond to an angular position. The values were parameterized according to Figure 124.

Figure 124: Potentiometer data.

Figure 123 presents the values of volts and their respective values in degree. The response is polynomic. However, it is possible to use a linear function as presented in Figure 124.

When it comes to current sensors, ACS712-30A sensors were used. Their scales are between 0 and 5 volts. Nevertheless, they sense positive and negative current using the middle of scale as zero reference. The sensor signal at zero amperes is presented in Figure 125.

Figure 125: Current sensors data at zero amperes.

To use the sensors, it is necessary to take the Root Mean Square value (RMS) of a data sample. In the case of R2A, the sensors were used to obtain the current consumption of the motors. One example is presented in Figure 126.

Figure 126 presents the change in the current with the change in motor velocity. In this example, there is no load in the motors. The x axis in the figure is velocity in rpm.

4.5.3 Even terrain tests

A supervisory program was developed to perform tests. The interface is presented in Figure 127. The supervisory sends the set points to R2A. It shows the values for current consumption of motors and also save them.

Figure 126: Current consumption versus control signal motors.

Figure 127: Supervisory program interface to tests.

The first test starts sending the set point to the motors. The values are incremented slowly until R2A starts to move. The motor current is presented in Figure 128.

Figure 128: The beginning of the movement.

In this test, the set point was incremented slowly. Only one sensor was used in each test to obtain the minimum set point to move R2A. The current consumption of each motor to the minimum set point to move the rover was 1.4 volts. The current consumption was

Table 16: Minimum velocity in even terrain.

d [m]	t [s]	v [m/s]	w [rad/s]	v [km/hr]	w [rpm]
0.9	3.5	0.257	1.714	0.926	16.37

between 0.48 and 0.63 Amp. It is important to highlight that the peaks correspond to the start set point. The consumption, then, falls to around 0.14 amperes. In this test, the minimum velocity value was obtained. This value was 0.257 m/s. See Table 16.

4.5.4 Uneven terrain tests

Some tests were also performed in uneven terrain. The first one aimed to obtain the velocity of the rover according to the set point in this terrain type. The results are presented in Figure 129.

Figure 129: Velocity of R2A in uneven terrain.

One example is presented in Figure 130. It is the results of current consumption in the four propulsion motors. These values are related to two different rover velocities. The maximum value was for motor 4 with 0.503 Amp.

Figure 130: Current consumption to R2A in uneven terrain.

Current consumption is increased according to velocity increment. See Table 17. The maximum value was of 0.837 amperes for 0.83 m/s and the minimum 0.503 for 0.25 m/s.

Table 17: R2A's Current and velocity values

Velocity [m/s]	Maximum current [A]
0.25	0.503
0.33	0.530
0.47	0.540
0.58	0.554
0.83	0.837

4.5.5 Step and climb tests

Tests in step terrain were performed. The results of current consumption are presented in Figure 131. As one may see, it presents a maximum current consumption of 1.1 A to motor 1. Both motors 2 and 3 present maximum values of 0.4 and 0.48 A, respectively.

Figure 131: Step results test.

Different values were found in the climbing tests. The values were 3.7 amp and 3 to motors 2 and 4, respectively. These values correspond to a climb angle of 30 degrees. The rover stopped and the wheels started skidding. Before it started skidding the panic button was pushed and the rover was turned off. See Figure 132.

Figure 132: Current consumption in the climbing test.

Tests were performed to motors sensors and passive suspension. The motors and sensors have the same manufactures. Even so, their behavior was different. It was important to learn about their characteristics and collect these data to use them in the controllers and supervisory program. Once the controllers and supervisory system were adjusted, it was possible to test the suspension. Tests validated the suspension behavior. The suspension distributes the loads among four wheels as presented in Figure 131. The velocity of the rover was tested to values of 0.25 to 0.83 m/s. They are typical values to agriculture applications (Pedersen et al 2006). Tests validate the capability to overcome obstacles and 30 degree is the limit in sloping terrain.

4.6 Comparison Tests

After characterizing R2A parameters, it is important to compare it with Mirã rover and AgriBot. This comparisons are relevant to validate the parameters and contrast them with these agricultural plataforms. Tests were performed and the results are presented below.

4.6.1 Mirã

Mirã rover was developed by LabRoM - USP and Embrapa as a preliminary prototype of the present work to validate the capability to support Laser Induced Breakdown Spectroscopy (LIBS) technology into a mobile robot (DIAZ et al., 2015). Figure 133. Presents Mirã.

Figure 133: Mirã.

The prototype has two motors that provide differential traction. Mirã was tested in uneven terrain. The test aimed to measure the current consumption. These current measurements were carried out using ACS712-30A current sensor. The results of tests are presented in Figure 134.

Table 18 shows the maximum current consumption and the torque per motor.

Figure 134: Current consumption of each motor in forward-backward maneuver. a) right motor measured value b) left motor measured value.

Table 18: Experimental results.

Motor	I max (A)	T max (N)	I Average (A)
Right	6.99	6	4.4
Left	6.73	5.8	4.52

Mirã uses batteries of 12 volts 7Ahr. It presents an average power consumption of 52.8 watts and 54.24 watts for right and left motors, respectively. The overall dimensions of Mirã are 0.65x0.5x0.4 m and mass is 35 kg. Maximum velocity is 0.7 m/s. (ARCHILA et al., 2014) and it has autonomy of 512 m.

4.6.2 Agribot

The AgriBot is the abbreviation of Agricultural Robot developed by Embrapa, USP and Jacto. It was put in operation as part of the present work with the objective to study the principal characteristics of this agricultural robot. The steering and propulsion system were improved. The controllers to the steering system and a supervisory system were developed. See Figure 135

Agribot is a 4WS/4WD and the actuators are hydraulics (ARCHILA; SILVEIRA; BECKER, 2013). However, it has two propulsion pumps. The hydraulic power of each pump is distributed between two hydraulic motor wheels. Agribot was tested in uneven terrain in LaNAPre (National Lab of Precision Agriculture) of Embrapa. The results of test are presented in Table 19.

Table 19 presents the values of wheel angular velocity W , robot velocity V , pressure drop in P motors, as well as the flow rate in the motors. When one has maximum pressure and flow rate, maximum velocity corresponds to 2.827 m/s. The overall dimensions of AgriBot are 3x2.4x1.8 m and mass is 2779 kg (TABILE et al., 2011). The principal energy supply is a diesel tank whose capacity is 140 liters. It has a diesel 76 Hp motor. The

Figure 135: AgriBot and supervisory system.

Table 19: Test AgriBot.

W [RPM]	V [m/s]	P [Bar]	Flow Rate [m ³ /s]
7.50	0.397	30	0.00005875
15.00	0.785	25	0.00011750
26.09	1.365	25	0.00020435
30.00	1.571	40	0.00023500
37.50	1.963	70	0.00029375
46.15	1.963	100	0.00036154
48.46	2.416	150	0.00037962
50.00	2.537	200	0.00039167
54.00	2.827	250	0.00042300

power is distributed among the steering and propulsion systems. Each propulsion motor may use no more than 14 Hp.

4.6.3 R2A

R2A was developed by LabRoM – USP, Embrapa, IFSP and UIS. It uses passive suspension and configuration 4WS/4WD. See Figure 136.

R2A has overall dimensions of 1.1x0.8x0.75 m, mass is 65 kg. It uses four batteries of 40 volts 7 Ah Li-ion for the propulsion systems. Two batteries of 12 volts 7 Ah for the steering system. The maximum velocity is 20 km/h - 250 watts per motor. The autonomy of R2A is 25 km.

Figure 136: R2A CAD and Real Prototype.

4.6.4 Comparison

Mirã, AgriBot and R2A were tested. With the results in Table 20, it is possible to obtain the propulsion power in kwatt, the weight per kilowatt, autonomy in meters, and maximum and minimum velocity

Table 20: Comparison of R2A, AgriBot and Mirã

	Weight [kg]	Power [kW]	Weight/Power [kg/kW]	Autonomy [m]	Min Vel [m/s]	Max Vel [m/s]
Mirã	35	0.17	208.33	512	0.15	0.70
AgriBot	2,776	41.78	66.45	203,544	0.40	2.83
R2A	65	1.12	58.04	25,000	0.25	5.56

Table 20 presents that the maximum velocity is of 5.56 m/s to R2A followed by AgriBot with 2.83 m/s. The relation weight/power to R2A is 58.04 kg/kw. This value is the minimum of the three robots. The relation weight power in Brazilian tractors is 58 kg/kW according to Schlosser et al. (2005). AgriBot presents autonomy of 203,544 m. It was calculated considering the tank capacity of 140 lts (Diesel) and 20 hours of autonomy (Jacto, 2012). If AgriBot works at maximum velocity, it can achieve 203,544 m. In the case of R2A, autonomy is of 25,000 m. It has four batteries of 40 volts 7 Ah. It is possible to improve this autonomy. One may use more batteries. Nevertheless, it is important to evaluate it according to the task to be performed.

R2A characteristics in association with other technologies such as: LIBS, Thermal and multispectral cameras, and collaborative robotics using drones, among others will offers possible advantages and improvements in agriculture engineering. The possible applications and advantages are described below.

R2A may be applied in agricultural environment. The wheel diameter and suspension allow it to overcome obstacles of 0.75 times the wheel diameter and slopes of 30 degrees. These characteristics are easily found during all crop phases.

R2A's autonomy is 25,000 m in even terrain and maximum slope of 7 degrees. In an orange crop, for instance, in Maringa farm, the rover can travel along 250 crop streets. This autonomy may be useful when LIBS technology is being applied. It is possible to map the soil composition more accurately and in real time. Information about nutrition necessities of crops, variable taxes of fertilizers may also be given. It could reduce quantities of supply, improving the productivity and reducing the costs.

When thermal cameras are imbedded in R2A, it will be able to detect fruits and diseases. Fruit detection provides more accurate quantity estimative and this is relevant datum to be used when prices in the market are being determined. In the case of diseases thermal and multispectral cameras could be used to detect abnormalities in sprees, trunk, fruits, or branches detecting possible damage and diseases.

Additionally, R2A may serve as a useful platform to transport and recharge batteries of drones. R2A and drones, using collaborative robotics, are able to better plan navigation stage and study and control diseases in the crops, for instance.

Conclusions

A bibliographic review contemplated outdoor robots, agricultural robots, rovers and agricultural rovers. Outdoor robots were classified according to their locomotion system. The classification uses five categories: Coupled differential (CD), Independent differential (ID), independent traction steerable systems (ITSS), Legged and hybrid robots (L&HR) and others. Applications and general architectures of agricultural robots were described. Mechanical characteristics of explorations rovers were presented. Finally, three tables that classify the robots according passive and active suspension were described. The tables highlight the mechanical characteristics, the simplified CAD diagram and chronological development.

The methodology to develop and evaluate agricultural robots, rovers and agricultural rovers was delineated. The methodology was based on mechanic and mechatronic methodologies and the phases contemplated were: problem statement, informational/conceptual design and detailed design. The problem statement is composed by: tasks, bibliographic review and environment. The informational/conceptual design is composed by benchmarking (Mathematical models, simulations, and tests) and proposal. The detailed design is composed by mechatronic CAD and CAE models, virtual prototype, real prototype and tests. The methodology was used to develop three prototypes they were: EESC - USP robot, Mirã and R2A, and to evaluate and put in operation the AgriBot.

Kinematic and dynamic models for R2A were developed and presented. The models used homogenous transformations, Denavit-Hartenberg parameters, instantaneous transformations and Newton-Euler method. The models presented were: the Jacobean matrix used to supervisory and control system, the geometric transformation to transform coordinates points referenced into the robot coordinate system to inertial coordinate system, and the general dynamics equations used to estimate the torques.

Mechatronics CAE models were developed using four tools, Computer Aided Design CAD, Multibody Dynamics, Finite Element Analysis (FEA) and electronics simulations. They were used to evaluate and dimension the rover. CAE models offered a prevision of the behavior of rover. Through CAE models it was possible to identify some flaws during

detailed design phases.

A new rover to agriculture (R2A) was developed. It is composed by a four propulsion motors, four steering wheels, passive suspension, electronic subsystem and distributed control subsystem. All subsystems are integrated in a supervisory system used to test and drive the robot. The rover has the ability of overcoming obstacles of 0.75 times the wheel diameter and move in even and uneven terrain. The suspension has the option to change its height and stiffness and the energy supply is electric using rechargeable batteries. R2A overall dimensions are 1.1x0.8x0.75 m and weight is 65 kg, including four propulsion batteries and two steering and general purpose batteries.

R2A concept was compared in simulation environment with rovers: Crab, Shrimp, MER, MSL and Exo-mars. The simulation conditions were friction coefficient of 1, constant velocity, equal dimensions in wheels and bogies, equal weight and rigid suspensions. The results obtained shows its capacities to overcome obstacles of 3.25 times the wheel diameter followed by MER with 3.46 times the wheel diameter. R2A was the one that presents symmetry to climb and get off the steps and presents less energy consumption than the others rovers used in the simulations.

R2A behavior was validated first in simulations and after in experimental tests. The results show a capacity to climb a slope of 30 degree and overcome obstacles of 0.75 time the wheel diameter; minimum velocity of 0.25 m/s and maximum of 5.5 m/s. The suspension distributed the weight in the four wheels and support the moves of the rover in uneven terrain.

R2A was compared with Mirã and Agribot. It presented better relation weight/power the value is 58.04 kg/kw. Its maximum velocity is 5.5 m/s and it is able to overcome obstacles. AgriBot has 66.45 kg/kw and maximum velocity of 2.8 m/s and Mirã has 190 kg/kw and maximum velocity of 1 m/s. Agribot and Mirã were not developed aiming to overcome obstacles. Autonomy estimated to R2A is 25,000 m to AgriBot is 203,544 m, and Mira 512 m. LIBS and thermal cameras were tested in Mirã successfully. It was also tested as a taking off and landing platform to a pelican quadcopter. Likewise, R2A has the capability of supporting these agricultural devices.

5.1 Future works

R2A is a promising platform. Developing its application is one the next steps of this investigation. It corresponds to embedding navigation system. Therefore, this embedded electronics may be improved with the use of a robust computer and controllers. Other navigation devices such as sensors and instruments e.g. laser, IMU, GPS, cameras, encoders may be included. Future works in control area could be developed to implement different control strategies to enhance steering, propulsion and navigation. Studies on portable LIBS may profit from the research carried out in Mirã. Since R2A has more

autonomy and its platform is more stable, LIBS technologies may find this rover considerably adequate for future investigations. When it comes to Mechanics, it is possible to study the influence of stiffness variations in the performance of robot in uneven terrain. The stiffness could be changed if springs, dampers or intelligent shock absorbers are included. Load capacity is another mechanic characteristic to be evaluated. A new chassis and parts may be designed to support other tasks that involve heavier loads.

Activities developed and publications

Disciplines

Reference	Discipline	Cred.	Freq.	Conc.	Situation
SEM5911-1/7	Mobile Robotics Introduction	12	100	A	Concluded
SEM5740-5/4	Mathematics for Engineers	12	100	A	Concluded
SEM5892-7/6	Methodology and Bibliographic Research	6	100	A	Concluded
SEM5875-5/2	Robotics Systems Control	12	100	A	Concluded
SEM5910-1/5	Introduction to Project Methodology in Engineering	12	90	A	Concluded

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15.1.3161.18.4

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