Modeling and Control of the UGV Argo J5 with a Custom-Built Landing Platform

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Modeling and Control of the UGV Argo J5 with a Custom-Built Landing Platform

A Dissertation

Presented to

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In Partial Fulfillment

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Abstract

This thesis aims to develop a detailed dynamic model and implement several navigation controllers for path tracking and dynamic self-leveling of the Argo J5 Unmanned Ground Vehicle (UGV) with a custom-built landing platform. The overall model is derived by combining the Argo J5 driveline system with the wheels-terrain interaction (using terramechanics theory and mobile robot kinetics), while the landing platform model follows the Euler-Lagrange formulation. Different controllers are, then, derived, implemented to demonstrate: i.) self-leveling accuracy of the landing platform, ii.) trajectory tracking capabilities of the Argo J5 when moving in uneven terrains. The novelty of the Argo J5 model is the addition of a vertical load on each wheel through derivation of the shear stress depending on the point’s position in 3D space on each wheel.

Static leveling of the landing platform within one degree of the horizon is evaluated by implementing Proportional Derivative (PD), Proportional Integral Derivative (PID), Linear Quadratic Regulator (LQR), feedback linearization, and Passivity Based Adaptive Controller (PBAC) techniques. A PD controller is used to evaluate the performance of the Argo J5 on different terrains. Further, for the Argo J5 -landing platform ensemble, PBAC and Neural Network Based Adaptive Controller (NNBAC) are derived and implemented to demonstrate dynamic self-leveling. The
emphasis is on different controller implementation for complex real systems such as Argo J5 - Landing platform.

Results, obtained via extensive simulation studies in a Matlab/Simulink environment that consider real system parameters and hardware limitations, contribute to understanding navigation performance in a variety of terrains with unknown properties and illustrate the Argo J5 velocity, wheel rolling resistance, wheel turning resistance and shear stress on different terrains.
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Abbreviations

MR: Mobile Robot.
PD: Proportional Derivative.
UGV: Unmanned Ground Vehicle.
PID: Proportional Integral Derivative.
LQR: Linear Quadratic Regulator.
PBAC: Passivity Based Adaptive Controller.
UAV: Unmanned Aerial Vehicle.
UAS: Unmanned Aircraft System.
SSMP: Skid Steering Mobile Platform.
SSMR: Skid Steering Mobile Robot.
DMR: Differential Mobile Robot.
WMR: Wheeled Mobile Robot.
MEC: Model Error Compensator.
EKF: Extended Kalman Filter.
GA: Genetic Algorithm.
FL: Fuzzy Logic.
NN: Neural Network.
ICR: Instantaneous Center of Rotation.
ODG: Ontario Drive and Gear Limited.
MRP: Mobile Robot Platform.
SIM: Simulation.
PMAC: Permanent Magnetic Alternative Current.
PM: Permanent Magnetic.
AC: Alternative Current.
COM: Center of Mass.
DC: Direct Current.
SM: Sliding Mode.
MMP: Mobile Manipulator Platform.
PBA: Passivity Based Adaptive.
NNBAC: Neural Network Based Adaptive Controller.

Nomenclature

ℓ: Lagrangian.
K: The total kinetic energy.
P: The potential energy.

\( J_P \): Moment of inertia of the landing plate surface (kg.m^2).
\( J_L \): Moment of inertia of the linear actuator (kg.m^2).
\( J_C \): Moment of inertia of the thrust tube/shaft (kg.m^2).
\( \dot{\theta} \): The angular velocity of the landing platform (rad/s).
\( \dot{\gamma} \): The angular velocity of the linear actuator (rad/s).
\( m_L \): The mass of the linear actuator (kg).
\( m_C \): The mass of the thrust tube/shaft (kg).
\( v_L \): The linear velocity of the linear actuator (m/s).
\( v_C \): The linear velocity of the thrust tube/shaft (m/s).
\( v \): The linear velocity (m/s).
\( r \): The radius (m).
\( \omega \): The angular velocity (rad/s).
\( \theta_L \): The leveling angle (°).
\( \gamma \): The linear actuator angle (\(^o\)).

\( m_P \): The mass of the landing platform (kg).

\( g \): The gravity constant (m/s\(^2\)).

\( y_L \): The vertical distance between the Center Of Mass of the part to the base (m).

\( y_P \): The vertical distance between the Center Of Mass of the part to the base (m).

\( y_C \): The vertical distance between the Center Of Mass of the part to the base (m).

\( L_Z \): The vertical length between the landing platform and its base (m).

\( G_r \): The gear ratio.

\( \theta_m \): The angle of the DC motor of the linear actuator (\(^o\)).

\( L_a \): The total length of the linear actuator (m).

\( L_A \): The length of the linear actuator body (m).

\( \tau_L \): The applied torque on the landing platform (N.m).

\( \tau \): The generated torque (N.m).

\( B_L \): The landing platform friction coefficient.

\( J_m \): Moment of inertia of the DC motor (kg.m\(^2\)).

\( \ddot{\theta} \): The angular acceleration of the DC motor (rad/s\(^2\)).

\( B_m \): The friction coefficient of the DC motor.

\( k_m \): The torque constant of the DC motor.

\( V \): The armature voltage of the DC motor (V).

\( R \): The armature resistance of the DC motor (\(\Omega\)).

\( m \): The mass of the Argo J5 (kg).

\( I \): Moment of inertia of the Argo J5 (kg.m\(^2\)).

\( \theta_w \): The angle of the wheel (\(^o\)).

\( \dot{\theta}_w \): The angular velocity of the wheel (rad/s).

\( \ddot{\theta}_w \): The angular acceleration of the wheel (rad/s\(^2\)).
\( F_S(\dot{\theta}_w) \): The resultant reactive force (N).

\( F_L(\dot{\theta}_w) \): The resultant reactive force (N).

\( M_r(\dot{\theta}_w) \): The resultant reactive torque, (N.m).

\( \mu_{s_i} \): The dry friction coefficient for \( i^{th} \) wheel in longitudinal and lateral directions.

\( \mu_{L_i} \): The dry friction coefficient for \( i^{th} \) wheel in longitudinal and lateral directions.

\( N_i \): The reactive vertical force (N).

\( \dot{\vartheta}_x \): The longitudinal velocity of Argo J5 (m/s).

\( \dot{\vartheta}_y \): The lateral velocity of Argo J5 (m/s).

\( r_w \): The radius of the wheel (m).

\( \phi \): The turning angle of the Argo J5 (°).

\( B \): The vertical distance between the center of the tire and COM of the Argo J5 (m).

\( A(\theta_w) \): The nonholonomic constraints vector.

\( \lambda \): Lagrange multipliers scalar.

\( S \): Full rank matrix.

\( C(q, \dot{q}) \): Coriolis and centrifugal matrix.

\( D(q) \): Gravity vector.

\( F_w \): The traction force at the wheel (N).

\( m_{lp} \): The whole mass of the landing platform (kg).

\( F_{wind} \): The air drag force (N).

\( F_R \): The rolling resistance force (N).

\( \theta_G \): The slope angle (°).

\( C_{r_1} \): The friction coefficient depending on tires and road conditions.

\( C_{r_2} \): The friction coefficient depending on tires and road conditions.

\( \tau_w \): The wheel’s torque (N.m).
\( \tau_{fricw} \): The wheel’s internal friction load (N.m).

\( b_a \): The damping coefficient.

\( \omega_L \): The angular velocity of the left wheel (rad/s).

\( \omega_R \): The angular velocity of the right wheel (rad/s).

\( \theta_{1i} \): The wheel’s entry angle (°).

\( k_c \): The sinkage pressure moduli of the terrain.

\( k_d \): The sinkage pressure moduli of the terrain.

\( n \): The sinkage exponent.

\( c \): The terrain’s cohesion.

\( \phi_f \): The internal friction angle (°).

\( K_p \): The constant gain.

\( K_i \): The constant gain.

\( K_d \): The constant gain.

\( \theta_{Ld} \): The desired level angle (°).

\( \Gamma \): Positive constant.

\( Y \): The regressor.

\( L_{de} \): The length of the tire deflation (m).

\( w_{de} \): The width of the tire deflation (m).

\( p_t \): The air pressure in the tire (Pa).

\( V_t \): The volume of the gas.

\( T \): The temperature of the air (K).

\( r_{ring} \): The radius of the ring (m).

\( w_{ring} \): The width of the ring (m).

\( M_a \): The molar mass of air (J/mol.K).

\( A_h \): The area of the orifice in the tire (mm²).
Chapter 1

Background and Introduction

The term “robot” first appeared in 1921 [1]. The main objective of using a robot in a workspace environment is to help humans when performing difficult tasks in dangerous environments. Mobile Robots (MRs) refer basically to UGVs [1, 2] and research mostly focuses on mobility, localization, navigation, planning, and communication [3] as shown in Fig. 1.1 and Fig. 1.2. Each focus area addresses a pivotal part of UGV technologies for diverse applications.

Mobility refers to the ability of free movement; it depends on the specific robot mechanism, implemented sensor-base control techniques, and wheel-terrain interaction. Localization centers on specifying the robot location with respect to a fixed coordinate frame - it also deals with robot position/location estimation. Navigation relates to creating and updating a workspace map where the MR moves - sensor data/information is essential. Planning relates to deriving waypoints, trajectories, to be followed by the MR when moving from one location to another. It includes path planning and motion planning. Path planning relates to finding a path between two positions, i.e., initial and goal point; motion planning explores the path between...
two positions where only the initial position is known. Communication basically refers to robot to robot interaction or to robot interaction with human operators.

When focusing on autonomous or semi-autonomous UGVs operating in uncertain and dynamic environments, accurate modeling followed by sensor-based navigation and control are crucial when interactions with a human operator are limited. Thus, MR physical and component limitations (actuators, sensors, batteries, etc.) must be taken into account. In addition, MR wheel-terrain interaction [5, 6] must be included in derived models, and this is the case for the Argo J5 that is the testbed vehicle studied in this thesis, see Fig. 1.3. Terramechanics theory is used to study the behavior of any MR by finding stress distributions under wheels.

For the research in this thesis, the testbed is the in-house custom-built landing platform on top of the Argo J5 UGV as shown in Fig. 1.4. Leveling requirements are the ability to level within 1° of the horizon, and to operate in rough terrains (off-road) up to 25° off the horizon [7, 8, 9, 10].
The ensemble base UGV-landing platform functions as an enhanced ground robotic vehicle, for which accurate dynamic models, navigation controllers, and platform leveling controllers need to be derived and implemented. Further, functionality-wise, at a minimum, take-off/landing must take place when the vehicle is either stationary or moving.

The focus of this thesis is on deriving the Argo J5 dynamic model followed by testing and implementing different controllers for trajectory tracking and static and dynamic platform leveling. The Argo J5 driveline, wheel-terrain interaction and landing platform limitations are considered.
1.1 Motivation and Problem Statement

The thesis motivation centers on developing an Argo J5 - landing platform ensemble that may be used as a mobile ‘platform’ for helicopters and quadrotors to land, takeoff, and possibly recharge, which is operational on different terrains.

A detailed mathematical model is derived, followed by deriving, implementing and testing controllers for self-leveling and trajectory tracking on different types of terrains.

1.2 Proposed Solution

The landing platform model is derived following the Euler-Lagrange formulation. The Argo J5 model is derived based on terramechanics theory and kinetics in 3D space, also including wheel-terrain interactions.
Once the overall dynamic model is derived, controllers are derived and tested, including PBAC and NNBAC, which ensure stability, robustness, and fast settling time.

The driveline of Argo J5 consists of a permanent magnet alternative current motor, chains, and four wheels, which is similar to a standard car. Knowledge of all information about components is key to predicting the behavior of Argo J5 in moving and turning and plays a sensitive role in controller design.

For this type of robot, the effective variables that have to be controlled are position and velocity. Furthermore, the controller has to guarantee the stability, robustness, and convergence to overcome each external disturbance and response errors.

The study of the contact surface between Argo J5 wheels and the soil plays an important role to achieve full autonomy and safe locomotion for Argo J5. Thus,
the dynamic response of Argo J5 can be expected in different terrains that have substantial effects on traction development, motion, and turning resistance of the Argo J5.

Combining the two models of Argo J5 and the landing platform in one mathematical formulation and applying the PBAC and NNBAC for dynamic self-leveling are the final work of this research.

1.3 Contributions

The main contributions of this dissertation are summarized as follows:

1. The landing platform dynamic model is derived following the Euler-Lagrange approach. Different controllers are implemented to test the leveling capabilities of the platform, and most importantly, how fast level is achieved without violating stability, starting from 5°, 10°, 15°, and 20° off-level. The goal is to understand how the platform behaves, what are the physical limitations of the design that may prevent use, and what needs to be done to overcome observed limitations.

2. The Argo J5 model is derived and developed by combining the driveline model with wheel-terrain interaction equations by applying the terramechanics theory. The final model describes the dynamic motion of Argo J5 in a composed manner by taking the terrain effects in the derivation. PD controller is used for trajectory tracking of the UGV Argo J5.

3. Three modeling methods of the Argo J5 are presented and compared for accuracy and evaluation purposes.
4. The model of the landing platform is combined with the Argo J5 model and two controllers, PBAC and NNBAC are implemented for dynamic self-leveling to evaluate performance of the overall system ensemble as shown in Fig. 1.4. The objective is to level the landing platform within 1° of the horizon (starting from different off-level angles) while the Argo J5 moves in uneven/rough terrains at different speeds. Testing and evaluation are based on actual physical system limitations and constraints and on actual parameter values. Finally, tire deflation analysis is considered to illustrate its effectiveness on dynamic self-leveling by using NNBAC.

In summary, complete mathematical model of whole system is provided and several controllers are implemented (PD, PID, LQR, feedback linearization and PBAC) for static self-leveling of the landing platform, while PBAC and NNBAC controllers are implemented to compare the dynamic self-leveling performance for the landing platform.

### 1.4 Dissertation Outline

The rest of this dissertation is organized as follows:

Chapter two summarizes related works and includes the literature reviews. It focuses on three areas: modeling of SSMR and the landing platform, controllers, and terrain interaction.

Chapter three presents prototype robotic vehicle and the landing platform properties, which describes the shape, dimension, weight, and size of Argo J5 and the landing platform.
In Chapter four, the landing platform and Argo J5 models are derived. The dynamics of the landing platform and Argo J5 are explained in detail. The model of tire deflation is derived.

Chapter five introduces the controllers’ techniques that are used for the landing platform and Argo J5.

Implementation details and analysis studies are discussed in chapter six.

Chapter seven shows the results of the studies in chapter six.

Chapter eight concludes the dissertation and highlights the next steps to be followed.
Chapter 2

Literature Review

In this chapter, an overview of the related work and literature surveys are summarized. Research relevant to modeling and control of MRs is presented in the first section. The second section summarizes types of MR. Then, research related to modeling landing platforms and to self-leveling is shown. Limitations of existing approaches are presented in the last section of this chapter.

2.1 Related Work

Research related to modeling and control of MRs may be found in [12, 13, 14, 15, 16, 17, 18], while vehicle-terrain interaction is found in [19, 20, 21]. This modeling research is based on modeling the wheels using Newton’s second law. Vehicle-terrain interaction modeling ensures vehicle safety when it moves on different types of terrain with unknown dynamic properties. Research on Differential Mobile Robots (DMRs) may be found in [22, 23]. Modeling and control of a DMR
is also presented in [24] for outdoor navigation, while in [25] an overview of navigation control of MR is explained.

Wheeled Mobile Robots (WMRs) are used in several applications [16], [26, 27, 28, 29]. Wheeled mobile platforms [14] are treated as independent robots or as means to transport parts of complex robotics systems [30]. Skid steering wheeled mobile platforms are preferred [31] because of the ability to adjust the moving direction by assigning different velocities between two side wheels [17].

From the control perspective, several approaches center on backstepping, Sliding Mode (SM), and velocity control of SSMRs, as presented in [32, 33, 34]. A motion control for trajectory tracking and for finding a model for SSMR is presented in [14]. Particle swarm optimization and genetic algorithms are used in [35] to evaluate SSMR performance. SSMR modeling and SM control based on extended state observer are presented in [36]. Model Error Compensator (MEC) and Extended Kalman Filter (EKF) are used to reduce the system noise on rough and unpaved roads. In [37], optimal control is used for path following without ignoring wheel slip. Genetic Algorithm (GA) [38], Fuzzy Logic (FL) [39, 40, 41], or Neural Network (NN) [42] are proposed for the controller designs accounting for slip conditions [38], [43, 44, 45, 46, 47]. In [31] a new method of utilizing Instantaneous Center of Rotation (ICR) is introduced to derive SSMR dynamics. A modeling methodology to predict SSMR kinematic motion is introduced in [48]. For fast autonomous SSMR on soft terrain, a model based control method is developed in [49]. By using artificial force concept, a new modeling method is proposed in [30, 50]. Additional research on SSMR may be found in [51, 52, 53]. Reported research in [54, 55, 56] focuses on modeling/control of Mobile Manipulator Platforms (MMPs). Research on SSMRs with a different number of wheels may be
found in [42, 57, 58, 59, 60, 61, 62, 63]. In [64, 65, 66, 67], different techniques and a novel approach to verify and investigate SSMR behavior and performance are presented, while a LQR controller is used in [64] to compensate nonlinearities in the dynamic drive model. In [65], SSMR modeling is done by rotating the wheels independently, using factitious forces for the controller, and assuming no wheel slipping. However, in [66], the effect of wheel slipping is considered for the modeling/control purposes. In [67], a study of torque and power analysis are presented in detail to evaluate performance of a small SSMR.

When centering on wheel-terrain interaction and terramechanics theory, vehicle-terrain interaction knowledge is crucial to predict the vehicle behavior for navigation on different terrains, to keep the vehicle safe, and to derive an effective motion control. For a comprehensive study of skid steering mechanics see [68], while [69] summarizes skid steering mechanics in steady maneuvers that utilize lateral forces to find vertical loads on each of the wheels. Then, the assumption that these loads are equally distributed on each wheel is considered to make the analysis more precise. This serves as the first step to verify the shear stress development, which can be calculated from the load on the specific wheel. Extensions of the work reported in [69] may be seen in [70]. Regardless, in both, the wheel shear stress obeys Coulomb’s friction law, i.e., when the wheel starts to move, the shear stress can vary from zero to a maximum value. Last, but not least, there is considerable research that investigates the principle of wheel and soil interaction mechanics, the interaction of wheel on loose soil, and the empirical models of the stress distributions under the wheels [71, 72, 73]. Table 2.1 summarizes different approaches found in the literature reviews. Table 2.2 compares different approaches found in literature with the proposed one in this thesis.
Table 2.1: A detailed review for modeling of UGV.

<table>
<thead>
<tr>
<th>Reference Number</th>
<th>Approach</th>
<th>Advantage</th>
<th>Disadvantage</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>[74]</td>
<td>Euler-Lagrange</td>
<td>Constraints</td>
<td>Load variation (tracking error converge to zero)</td>
<td>SIM, SIM, EXP</td>
</tr>
<tr>
<td>[75]</td>
<td>Euler-Lagrange</td>
<td>Constraints</td>
<td>Slow convergence of NN weights (time-consuming)</td>
<td>SIM</td>
</tr>
<tr>
<td>[15]</td>
<td>Euler-Lagrange</td>
<td>External disturbance</td>
<td>Do not consider the full dimension of MR</td>
<td>SIM</td>
</tr>
<tr>
<td>[14]</td>
<td>Euler-Lagrange</td>
<td>Steering action</td>
<td>Complicated</td>
<td>SIM</td>
</tr>
<tr>
<td>[16]</td>
<td>Euler-Lagrange</td>
<td>/</td>
<td>Complicated</td>
<td>SIM</td>
</tr>
<tr>
<td>[17]</td>
<td>Euler-Lagrange</td>
<td>/</td>
<td>/</td>
<td>Complicated</td>
</tr>
</tbody>
</table>
Table 2.1: A detailed review for modeling of UGV.

<table>
<thead>
<tr>
<th>Reference Number</th>
<th>Approach</th>
<th>Advantage</th>
<th>Disadvantage</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>[31]</td>
<td>Euler-Lagrange</td>
<td>ICR new method</td>
<td>Complicated</td>
<td>SIM</td>
</tr>
<tr>
<td>[32]</td>
<td>Euler-Lagrange</td>
<td>ICR</td>
<td>Complicated</td>
<td>SIM</td>
</tr>
<tr>
<td>[33]</td>
<td>Euler-Lagrange</td>
<td>ICR</td>
<td>Complicated</td>
<td>SIM, EXP</td>
</tr>
<tr>
<td>[34]</td>
<td>Kinematics</td>
<td>Simple</td>
<td>/</td>
<td>SIM, EXP</td>
</tr>
<tr>
<td>[48]</td>
<td>Kinematics</td>
<td>/</td>
<td>/</td>
<td>SIM, EXP</td>
</tr>
<tr>
<td>[35]</td>
<td>Kinematics</td>
<td>Slip effect</td>
<td>/</td>
<td>SIM</td>
</tr>
<tr>
<td>[36]</td>
<td>Euler-Lagrange</td>
<td>Preventing excessive skidding</td>
<td>/</td>
<td>SIM</td>
</tr>
<tr>
<td>[49]</td>
<td>Wheel-terrain interaction</td>
<td>Slip and skid</td>
<td>For soft soil only</td>
<td>SIM, EXP</td>
</tr>
<tr>
<td>[50]</td>
<td>Force analysis</td>
<td>Speed control</td>
<td>/</td>
<td>SIM</td>
</tr>
<tr>
<td>[51]</td>
<td>Kinematics</td>
<td>Price</td>
<td>/</td>
<td>SIM</td>
</tr>
<tr>
<td>[52]</td>
<td>FW and INV kinematics</td>
<td>Information</td>
<td>/</td>
<td>SIM</td>
</tr>
<tr>
<td>[53]</td>
<td>Euler-Lagrange</td>
<td>Application(cleaning)</td>
<td>/</td>
<td>SIM</td>
</tr>
</tbody>
</table>
Table 2.1: A detailed review for modeling of UGV.

<table>
<thead>
<tr>
<th>Reference Number</th>
<th>Approach</th>
<th>Advantage</th>
<th>Disadvantage</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>[22]</td>
<td>Kinematics</td>
<td>/</td>
<td>/</td>
<td>SIM</td>
</tr>
<tr>
<td>[54]</td>
<td>Spatial vectors algebra</td>
<td>/</td>
<td>Disturbances and oscillations because of the arm</td>
<td>SIM</td>
</tr>
<tr>
<td>[55]</td>
<td>Euler-Lagrange</td>
<td>/</td>
<td>Complicated</td>
<td>SIM</td>
</tr>
<tr>
<td>[56]</td>
<td>Euler-Lagrange</td>
<td>/</td>
<td>/</td>
<td>SIM</td>
</tr>
<tr>
<td>[58]</td>
<td>Kinematics</td>
<td>Six wheels</td>
<td></td>
<td>SIM</td>
</tr>
<tr>
<td>[60]</td>
<td>Kinematics</td>
<td>Twelve wheels, slip, and friction</td>
<td>/</td>
<td>SIM</td>
</tr>
<tr>
<td>[42]</td>
<td>Euler-Lagrange</td>
<td>Two MRs</td>
<td>/</td>
<td>SIM</td>
</tr>
<tr>
<td>[62]</td>
<td>Kinematics</td>
<td>Slip with ICR</td>
<td>/</td>
<td>SIM, EXP</td>
</tr>
<tr>
<td>[64]</td>
<td>Euler-Lagrange</td>
<td>/</td>
<td>/</td>
<td>SIM</td>
</tr>
<tr>
<td>[65]</td>
<td>Euler-Lagrange</td>
<td>Decoupled wheels</td>
<td>No slip</td>
<td>SIM</td>
</tr>
</tbody>
</table>
### Table 2.1: A detailed review for modeling of UGV.

<table>
<thead>
<tr>
<th>Reference Number</th>
<th>Approach</th>
<th>Advantage</th>
<th>Disadvantage</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>[39]</td>
<td>Kinematics</td>
<td>Rough terrain, disturbance factor, and motion constraint</td>
<td>Rough terrain only</td>
<td>SIM</td>
</tr>
<tr>
<td>This research</td>
<td>Driveline, terramechanics</td>
<td>Adding terrain interaction effect to the model</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>
Table 2.2: Closely related approaches-comparison.

<table>
<thead>
<tr>
<th>Reference number</th>
<th>Year</th>
<th>Wheel type</th>
<th>Analysis dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>[76]</td>
<td>1967</td>
<td>Rigid wheel</td>
<td>1 dimension (x)</td>
</tr>
<tr>
<td>[68]</td>
<td>2001</td>
<td>Rigid wheel</td>
<td>2 dimensions (x,y)</td>
</tr>
<tr>
<td>[77]</td>
<td>2005</td>
<td>Rigid wheel</td>
<td>1 dimension (x)</td>
</tr>
<tr>
<td>[78]</td>
<td>2007</td>
<td>Rigid wheel</td>
<td>2 dimensions (x,y)</td>
</tr>
<tr>
<td>[79]</td>
<td>2009</td>
<td>Rigid wheel</td>
<td>1 dimension (x)</td>
</tr>
<tr>
<td>[21]</td>
<td>2012</td>
<td>Rigid wheel</td>
<td>2 dimensions (x,y)</td>
</tr>
<tr>
<td><strong>Proposed</strong></td>
<td>2018</td>
<td><strong>Rigid wheel</strong></td>
<td><strong>3 dimensions (x,y,z)</strong></td>
</tr>
</tbody>
</table>

2.2 Mobile Robots Drive Types

Drive types of WMRs are differential drive, tricycle, omnidirectional, synchro drive, Ackerman steering, and skid steering as shown in Figs. 2.1-2.6, respectively.

Figure 2.1: Differential drive mobile robot [80].
Figure 2.2: Tricycle mobile robot [81].

Figure 2.3: Omnidirectional mobile robot [82].

Figure 2.4: Synchro drive mobile robot [83].
2.3 Landing Platforms

During the last decade, landing platform related research has become a challenging research topic in robotics. The main reasons are high load capacity, high stiffness, and ability to level. Kinematics and dynamics analysis of serial and parallel manipulators provide the fundamentals for accurate landing platform modeling [86, 87, 88, 89, 90, 91]. Well-known modeling approaches include:
- Euler-Lagrange and variations [92, 93, 94, 95, 96, 97, 98, 99]. The advantage of this approach is that it is straightforward, but it is not appropriate if there are external force effects on the landing platform.

- Newton-Euler equations [100, 101, 102, 103, 104]. This approach is time-consuming and complicated. However, it results in an exact model that considers the external forces and disturbances.

- Principle of Hamilton [92]. Limited research has been reported on this approach because it depends solely on the kinematics of the landing platform.

- Principle of virtual work [91, 105, 106]. This approach relies on screw theory and it has the same advantages and disadvantages of the Newton-Euler approach mentioned above.

- Lagrange-D’Alembert formulation [107, 108]. This approach is known to be a tree system where the calculation is done by converting the parallel manipulator into a serial manipulator. Then, the D’Alembert principle is applied to obtain the motion representation. This approach is simple but does not provide modeling accuracy.

In [7], a mobile landing platform is designed for self-leveling angles up to $25^\circ$. The study in [109] emphasizes the relationship between the design practicality and cost. In [110], the design of high torque platforms and their ability to carry heavy weights is discussed. In [111], work is performed on a self-leveling system with two degrees of freedom. In [8] and [112], the self-leveling landing platform and mobile platform are designed together to make a mobile self-leveling landing platform to
serve as an integrated landing station in unsuitable locations. Table 2.3 summarizes different approaches found in the literature reviews.

In this research, the Euler-Lagrange approach is applied to the landing platform of Fig. 1.4 as the main objective is to study how fast leveling is achieved.
Table 2.3: A detailed review of the landing platform model.

<table>
<thead>
<tr>
<th>Reference Number</th>
<th>Approach</th>
<th>Advantage</th>
<th>Disadvantage</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>[92]</td>
<td>Euler-Lagrange</td>
<td>Simple and general</td>
<td>There is no result</td>
<td>/</td>
</tr>
<tr>
<td>[93]</td>
<td>Euler-Lagrange</td>
<td>Simple</td>
<td>Can not deal with external force or weight</td>
<td>SIM</td>
</tr>
<tr>
<td>[94]</td>
<td>Euler-Lagrange</td>
<td>Simple</td>
<td>Can not deal with external force or weight</td>
<td>SIM</td>
</tr>
<tr>
<td>[95]</td>
<td>Euler-Lagrange</td>
<td>Simple</td>
<td>Can not deal with external force or weight</td>
<td>SIM</td>
</tr>
<tr>
<td>[98]</td>
<td>Euler-Lagrange</td>
<td>Simple</td>
<td>Can not deal with external force or weight</td>
<td>SIM</td>
</tr>
</tbody>
</table>
Table 2.3: A detailed review of the landing platform model.

<table>
<thead>
<tr>
<th>Reference Number</th>
<th>Approach</th>
<th>Advantage</th>
<th>Disadvantage</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>[100]</td>
<td>Newton-Euler</td>
<td>Can deal with external force or weight</td>
<td>Complicated</td>
<td>SIM</td>
</tr>
<tr>
<td>[101]</td>
<td>Newton-Euler</td>
<td>Can deal with external force or weight</td>
<td>Complicated</td>
<td>SIM</td>
</tr>
<tr>
<td>[102]</td>
<td>Newton-Euler</td>
<td>Can deal with external force or weight</td>
<td>Complicated</td>
<td>SIM</td>
</tr>
<tr>
<td>[103]</td>
<td>Newton-Euler</td>
<td>Can deal with external force or weight</td>
<td>Complicated</td>
<td>SIM</td>
</tr>
<tr>
<td>[104]</td>
<td>Newton-Euler</td>
<td>Can deal with external force or weight</td>
<td>Complicated</td>
<td>SIM</td>
</tr>
<tr>
<td>[105]</td>
<td>Principle of virtual work</td>
<td>/</td>
<td>/</td>
<td>SIM</td>
</tr>
<tr>
<td>[106]</td>
<td>Principle of virtual work</td>
<td>/</td>
<td>/</td>
<td>SIM</td>
</tr>
<tr>
<td>[107]</td>
<td>Lagrange-D'Alembert formulation</td>
<td>/</td>
<td>/</td>
<td>SIM</td>
</tr>
<tr>
<td>[108]</td>
<td>Lagrange-D'Alembert formulation</td>
<td>/</td>
<td>/</td>
<td>SIM</td>
</tr>
</tbody>
</table>
Table 2.3: A detailed review of the landing platform model.

<table>
<thead>
<tr>
<th>Reference Number</th>
<th>Approach</th>
<th>Advantage</th>
<th>Disadvantage</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>This research</td>
<td>Euler Lagrange</td>
<td>Leveling and dealing with real Drone</td>
<td>/</td>
<td>SIM</td>
</tr>
</tbody>
</table>
2.4 Limitations of Existing Approaches

Unprepared terrain\textsuperscript{1}, see Figs. 2.7-2.11, is one of the crucial issues that most other modeling works have not considered. This means that previous modeling methods require prior knowledge about the terrain or do not add the terrain effect to the model. Also, these methods do not derive reaction forces from the analytical relationship between shear stress, shear displacement, and vertical load. Therefore, vehicle behavior is very difficult to predict in different terrains. This leads to the second limitation that relates to the velocity of the mobile platform to be controlled, especially without having any information about the nature of the terrain. The third limitation is the load that the mobile platform can hold without negative effect on the vehicle. These three limitations are overcome when using terramechanics theory for modeling purposes.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{moon_surface.png}
\caption{Moon surface [113].}
\end{figure}

\textsuperscript{1}Unprepared terrain: is a term that is used to describe unknown terrain. This means the dynamic properties of the terrain are unknown, i.e., mud, asphalt, sand, etc. Also, it could mean that this is the first time the MR has moved on this terrain.
Figure 2.8: Sand surface [114].

Figure 2.9: Mud surface [115].

Figure 2.10: Undefined surface [116].
Figure 2.11: Street represents an example of prepared terrain [117].
Chapter 3

The Prototype Robotic Vehicle

This chapter introduces detailed information about Argo J5 configuration. The first section shows the configuration components of Argo J5. The second section describes Argo J5 driveline parts. The third section presents Argo J5 specifications. In the fourth section, the control tool of Argo J5 is explained. Vehicle-terrain interaction is presented in the fifth section. Finally, terramechanics theory is explained and clarified.

3.1 Argo J5 Configuration

Argo J5 is a ground vehicle that is manufactured by Ontario Drive and Gear Limited (ODG), established in 1967, and located in New Hamburg, Ontario, Canada. Argo J5 is 4*4 skid steer electrical Mobile Robot Platform (MRP) that has an electrical motor instead of a mechanical engine. Argo J5 is used in different fields such as agriculture, military, and academic applications. The dimensions of this vehicle are as shown in Figs. 3.1-3.5.
Figure 3.1: Front view of Argo J5 with external dimensions [118].

Figure 3.2: Top view of Argo J5 with external dimensions [118].
Figure 3.3: Top, front, and side views of Argo J5 with external dimensions [119].
Figure 3.4: Front and side views of Argo J5 with external dimensions [119].
CONFIGURATION #2: One Common Payload Zone

In this configuration, any payload mounted on the chassis that extends over the Drive Units, MUST BE kept a minimum of 16 inches above the chassis top deck. This will allow sufficient clearance between the over-hanging payload and the Drive Units when the Drive Units have articulated to their maximum rotation as they sometimes do when traversing rough terrain.

Figure 3.5: Front view of Argo J5 [119].
3.1.1 Battery System

Argo J5 contains two battery packs, which are connected in parallel. Each battery pack typically consists of $4 \times 12\, \text{V}$ with specific base dimension as shown in Figs. 3.6 and 3.7, respectively. Two kinds of 48 V batteries can be used in Argo J5, which are 35 A h and 112 lbs for lead acid or 50 A h and 68 lbs for lithium ion.

Figure 3.6: Battery location and connection [119].
Figure 3.7: Battery base dimension [119].
3.1.2 Motors

This motor is a 3-phase and Y-connected permanent magnet synchronous motor with an axial air gap. It has a built-in bidirectional cooling fan and internal temperature sensor [119]. It is also known as a Permanent Magnet Alternative Current (PMAC) Motor. Motor specifications are shown in Table 3.1. The shape of this motor and its dimensions are presented in Figs. 3.8 and 3.9.

Table 3.1: Motor specifications [119].

<table>
<thead>
<tr>
<th>Motor specifications</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>22 lbs</td>
</tr>
<tr>
<td>Power</td>
<td>6 Hp continuous, 19 Hp peak</td>
</tr>
<tr>
<td>Voltage</td>
<td>24-48V DC</td>
</tr>
<tr>
<td>Max current</td>
<td>300 A/1min</td>
</tr>
<tr>
<td>Part number</td>
<td>ME1117</td>
</tr>
<tr>
<td>Max RPM</td>
<td>5000</td>
</tr>
<tr>
<td>Phase to phase winding resistance</td>
<td>0.013 Ohms</td>
</tr>
</tbody>
</table>

Figure 3.8: ME1117 PMAC motor [119].
Figure 3.9: ME1117 synchronous AC motor drawing [119].
3.1.3 Tires

Argo J5 has four tires, which can affect the performance of Argo J5 in land and water, see Fig. 3.10.

![Figure 3.10: Wheel orientation [119].](image)

3.2 Driveline Parts

The driveline is a group of parts of the mobile platform, which is responsible for the movement system. The driveline transfers the kinematic energy from the motor to the wheels through the chains. Argo J5 does not have mechanical parts as cars or trucks do. The basic configuration of the driveline of Argo J5 consists of motor, chain, and wheels in each side as shown in Fig. 3.11. Much research deals with the model of the driveline [120, 121, 122, 123, 124, 125]. However, the driveline model of an electrical mobile platform for skid steering vehicles has not been incorporated.
3.2.1 Motors

The PMAC motor, as shown in Fig. 3.8, is widely used because of its high performance and smoothness of torque [126, 127, 128, 129]. Sinusoidal and trapezoidal are the two major classes of the PMAC; it is a synchronous motor in that its rotor spins at the same speed as its internal rotating magnetic field [130, 131, 132]. This motor can be constructed to provide up to 200 hp [132]. PMAC, Permanent Magnet (PM) synchronous, and brushless AC are synonymous terms [129].

3.2.2 Chains

Chains are used to transfer the power from the motors to the wheels and to provide smooth wheel rotation. Chains can be modeled as a gear ratio $G_r$. This can be expressed by ignoring the backlash.
3.2.3 Wheels

Drive wheels can be combined and modeled as one wheel by ignoring the difference in rotational speeds. Newton’s second law is used to describe the wheel dynamics in both forms of rotational and linear motions [133]. The supplied torque from the motor of the mobile platform to the wheels through the chains, after overcoming the internal and external friction torques, provides the corollary wheel acceleration. The external friction torques provide the necessary force for the mobile platform to overcome the rolling resistance, air drag, and gravitational force of the wheel [78].

3.3 Argo J5 Specifications

This vehicle is fully amphibious, which can move on soft and challenging/rugged surfaces on land with max speed 18 km/h or water with max speed 4 km/h. Also, this MRP carries large payloads with a max payload on land of 600 lbs. More specifications are shown in Table 3.2.

Table 3.2: Argo J5 specifications [119].

<table>
<thead>
<tr>
<th>Argo J5 specifications</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traction</td>
<td>24” Argo tire</td>
</tr>
<tr>
<td>Part number</td>
<td>ME1117</td>
</tr>
<tr>
<td>Base weight</td>
<td>280 kg</td>
</tr>
<tr>
<td>Battery capacity</td>
<td>Expandable to 7.2 kW hr</td>
</tr>
<tr>
<td>External dimensions</td>
<td>1.52 L × 1.38 W × 0.83 H m</td>
</tr>
<tr>
<td>Gross vehicle weight</td>
<td>590 kg</td>
</tr>
<tr>
<td>Operating/Storage temperature</td>
<td>-20 to 40° C / -40 to 50° C</td>
</tr>
</tbody>
</table>
3.4 Control Tool

Argo J5 has a remote control as shown in Fig. 3.12 for teleoperation working with wireless radio frequency 2.4 GHz or 5.8 GHz for less than 1 Km.

![Remote control of Argo J5](image)

Figure 3.12: Remote control of Argo J5[119].

3.5 Landing Platform

The landing platform of Argo J5 consists of a wide plate surface and three linear actuators that can control the movement level in the 3D space. Two of these linear actuators that have a linear motion along the x and y-axes are made by Duff-Norton as shown in Fig. 3.13 with 500 lbs capacity. The components of Duff-Norton linear actuator are shown in Fig. 3.14.
3.6 Vehicle-Terrain Interaction

Vehicle-terrain interaction knowledge is fundamental to predict the behavior of vehicle navigation on different terrains, to keep the vehicle safe, and to find effective
motion control. For a comprehensive theory of skid steering mechanics, [68] is an example that explains the behavior of tracked vehicles. However, research is lacking in the comprehensive analysis of the mobile platform. The analysis of skid steering mechanics in steady maneuvers is presented in [69] that utilizes lateral forces to find vertical loads on each wheel. After that, the analysis becomes more precise by assuming these loads are equally distributed on each wheel in the same row. This point can be considered as the first step to verify the shear stress development, which can be calculated from the load on that wheel. Later on, an extension applied by taking into consideration the difference of vertical load on each wheel lies in the same row [70]. In fact, in both works the shear stress of the wheel obeys Coulombs friction law, which refers to the value of the shear stress that can vary from zero to maximum value during movement.

3.7 Terramechanics

Many works investigate the principle of wheel-soil interaction mechanics, the interaction of wheels on loose soil, and the empirical models of the stress distributions under the wheels. Terramechanics is the study of soil properties, specifically the interaction of wheeled or tracked vehicles on various surfaces [71, 72, 73].

Based on terramechanics theory [134, 135], skid steering kinetic equations [68], and wheeled vehicle vertical load [71], analysis of Argo J5 terrain interaction is shown later in this dissertation. Reaction forces are calculated by using vertical load, shear displacement, and shear stress. Depending on the position of each wheel of Argo J5, the vertical load can be determined. By taking slip velocity integrals for a specific point on each wheel that makes contact with the ground, shear dis-
placement can be obtained. Also, from shear displacement, shear stress can be derived for the same contact point. Finally by deriving the Argo J5 kinetics, the performance of Argo J5 can be predicted for different terrains.
Chapter 4

Dynamic Models

In this chapter, the landing platform and Argo J5 dynamic models are derived. The first section of this chapter shows the landing platform model. The second section presents the Argo J5 dynamic model, which is derived by applying Euler-Lagrange formulation with and without the potential field. Section three displays the dynamic model of the Argo J5 by explaining the driveline models and by deriving the vehicle-terrain interaction equations. Terramechanics theory is applied to complement the model of Argo J5 and to study the terrain effect on the vehicle's movement. Section four contains the dynamic model of the Argo J5 with the custom-built landing platform. Section five illustrates the dynamic model of tire deflation of Argo J5 and the impact on dynamic self-leveling.

4.1 Dynamic Model of Landing Platform

From Fig. 4.1, leveling in the x-direction is considered. The platform dimension along the x-axis is $2BC$, while the height of the platform with respect to the base,
UGV, as shown in Fig. 1.4, is $AB$. $AC$ is the length of the linear actuator, then

\[ \ell = K - P \]  

(4.1)

where $\ell$ is Lagrangian, $K$ is the total kinetic energy of the platform, and $P$ is the potential energy of the platform. Then

\[
K = \frac{1}{2} J_P \dot{\theta}_L^2 + \frac{1}{2} J_L \dot{\gamma}^2 + \frac{1}{2} m_L \dot{v}_L^2 + \frac{1}{2} J_C \dot{\gamma}_C^2 + \frac{1}{2} m_C \dot{v}_C^2
\]  

(4.2)

where $J_P$, $J_L$, and $J_C$ are moments of inertia of the landing plate surface, the linear actuator, and the thrust tube/shaft, respectively. $\dot{\theta}_L$ and $\dot{\gamma}$ are the angular velocities.
of the landing platform and the linear actuator, respectively. $m_L$ and $m_C$ are the masses of the linear actuator and the thrust tube/shaft, respectively. $v_L$ and $v_C$ are the linear velocities of the linear actuator and the thrust tube/shaft.

Also

$$v = r\omega$$

$$r = L$$

where $v$, $r$, $\omega$, and $L$ are the linear velocity, the radius, the angular velocity, and the length, respectively.

By using angular relationships, a relationship between $\theta_L$, which is a leveling angle, and $\gamma$, which is linear actuator angle, may be found, as shown in Fig. 4.1, as

$$\gamma = \frac{\theta_L + 90}{2}$$

$$\dot{\gamma} = \frac{1}{2}\dot{\theta}_L$$

Substituting (4.3) and (4.4) into (4.2) yields

$$K = \frac{1}{2}(J_P + \frac{1}{4}J_L + \frac{1}{4}m_LL_m^2 + \frac{1}{4}J_C + m_CL_z^2)\dot{\theta}_L^2$$

(4.5)

which can be written as

$$K = \frac{1}{2}J\dot{\theta}^2$$

(4.6)

with

$$J = (J_P + \frac{1}{4}J_L + \frac{1}{4}m_LL_m^2 + \frac{1}{4}J_C + m_CL_z^2)$$

(4.7)
The potential energy is derived as

\[ P = m_L g y_L + m_P g y_P + m_C g y_C \]  \hspace{1cm} (4.8)

where \( m_P \) is mass of the landing platform, \( g \) is gravity, and \( y_L, y_P, \) and \( y_C \) are the vertical distance between the Center of Mass (COM) of each part, respectively, to the base. Further

\[ y_L = L_L \sin \gamma \]
\[ y_P = L_Z \]
\[ y_C = (L_L + L_C + \Delta L) \sin \gamma \]  \hspace{1cm} (4.9)

where \( L_Z \) is the vertical length between the landing platform and its base. Also, \( L_Z \) is equal to the half-length of the landing platform as shown in Fig 4.2.

Substituting (4.9) into (4.8) gives

\[ P = m_L g L_L \sin \gamma + m_P g L_Z + m_C g (L_L + L_C + \Delta L) \sin \gamma \]  \hspace{1cm} (4.10)

Substituting (4.4) into (4.10) yields
\[ P = m_L g L_L \sin \frac{\theta_L + 90}{2} + m_P g L_Z + m_C g(L_L + L_C + \Delta L) \sin \frac{\theta_L + 90}{2} \]  

(4.11)

with

\[ \Delta L = G_r \theta_m \]  

(4.12)

where \( G_r \) is the gear ratio and \( \theta_m \) is the angle of the DC motor of the linear actuator.

Substituting (4.12) into (4.11) gives

\[ P = m_L g L_L \sin \frac{\theta_L + 90}{2} + m_P g L_Z + m_C g(L_L + L_C + G_r \theta_m) \sin \frac{\theta_L + 90}{2} \]  

(4.13)

Now, a relationship between \( \theta_m \) and \( \gamma \) must be derived by finding a polar equation for the circle of the radius \( L_Z \) centered at \( A(L_Z, \pi/2) \). Let \( C(L_a, \gamma) \) be a point on the circle, then by applying the law of cosines to triangle ABC yields

\[ L_Z^2 = L_Z^2 + L_a^2 - 2 L_Z L_a \cos \gamma - \frac{\pi}{2} \]  

(4.14)

where \( L_a \) is the total length of the linear actuator and can be represented as

\[ L_a = 2 L_Z \sin \gamma \]  

(4.15)

Also

\[ L_a = L_A + \Delta L \]  

(4.16)
where $L_A$ is the length of the linear actuator body. See Fig. 4.2 for details.

Substituting (4.16) into (4.15) yields

$$L_A + \Delta L = 2L_Z \sin \gamma$$

(4.17)

Substituting (4.4) into (4.17) yields

$$L_A + G_r \theta_m = 2L_Z \sin \frac{\theta_L + 90}{2}$$

(4.18)

or

$$\theta_m = \frac{1}{G_r} \left( 2L_Z \sin \frac{\theta_L + 90}{2} - L_A \right)$$

(4.19)

Substituting (4.19) into (4.13) gives

$$P = m_L g L_L \sin \frac{\theta_L + 90}{2} + m_P g L_Z + m_C g (L_L + L_C + 2L_Z \sin \frac{\theta_L + 90}{2} - L_A) \sin \frac{\theta_L + 90}{2}$$

(4.20)

Finally, $\ell$ is obtained by substituting (4.6) and (4.20) into (4.1), which results in

$$\ell = \frac{1}{2} J \dot{\theta}_L^2 - (m_L g L_L \sin \frac{\theta_L + 90}{2} + m_P g L_Z + m_C g (L_L + L_C + 2L_Z \sin \frac{\theta_L + 90}{2} - L_A) \sin \frac{\theta_L + 90}{2})$$

(4.21)

Since the dynamic equation of motion is

$$\tau_L = \frac{d}{dt} \frac{\partial \ell}{\partial \dot{\theta}} - \frac{\partial \ell}{\partial \theta}$$

(4.22)
where $\tau_L$ is the applied torque on the landing platform, then the final equation is

$$
\tau_L = J \ddot{\theta}_L + \frac{1}{2}(m_L g L_L + m_C g (L_L + L_C + 4L_Z \sin \frac{\theta_L + 90}{2} - L_A) \cos \frac{\theta_L + 90}{2})
$$

(4.23)

or

$$
\tau_L = J \dot{\theta}_L + G_1(\theta_L)
$$

(4.24)

where $G_1(\theta_L) = \frac{1}{2}(m_L g L_L + m_C g (L_L + L_C + 4L_Z \sin \frac{\theta_L + 90}{2} - L_A) \cos \frac{\theta_L + 90}{2})$.

$$
\tau_L = \tau - B_L \dot{\theta}_L
$$

(4.25)

where $\tau$ is the generated torque and $B_L$ is the landing platform friction coefficient.

Therefore, excluding the actuator model

$$
\tau = J \ddot{\theta}_L + B_L \dot{\theta}_L + G_1(\theta_L)
$$

(4.26)

Next, the dynamic model of the actuator as shown in Fig. 4.3 is

$$
J_m \ddot{\theta}_m + B_m \dot{\theta}_m = k_m \frac{V}{R} - \frac{\tau}{k_G}
$$

(4.27)

where $J_m$, $\dot{\theta}_m$, $B_m$, $\theta_m$, $k_m$, $V$, and $R$ are the moment of inertia, angular acceleration, motor friction coefficient, angular velocity, torque constant, armature voltage, and armature resistance of the DC motor, respectively. Then,

$$
\tau = G_r(k_m \frac{V}{R} - J_m \dot{\theta}_m - B_m \dot{\theta}_m)
$$

(4.28)
combining the two models from (4.26) and (4.28) yields

\[ u_1 = G_rJ_m\ddot{\theta}_m + J\dddot{\theta}_L + k_GB_m\dot{\theta}_m + B_L\dot{\theta}_L + G_1(\theta_L) \]  \hspace{1cm} (4.29)

where \( u_1 = G_rk_m\frac{V}{R} \). Moreover, from (4.19), (4.30) and (4.31) one obtains

\[ \dot{\theta}_m = \frac{1}{G_r}L_Z\cos\left(\frac{\theta_L + 90}{2}\right)\dot{\theta}_L \]  \hspace{1cm} (4.30)

\[ \ddot{\theta}_m = -\frac{L_Z}{G_r}\left(\sin\frac{\theta_L}{2}\ddot{\theta}_L - \frac{1}{2}\dot{\theta}_L^2 \sin \frac{\theta_L + 90}{2}\right) \]  \hspace{1cm} (4.31)

Substituting (4.30) and (4.31) into (4.29), the final model is

\[ u_1 = (J - J_mL_Z\sin\frac{\theta_L}{2})\dddot{\theta}_L + (B_L + B_mL_Z\cos\frac{\theta_L + 90}{2})\dot{\theta}_L + G_1(\theta_L) \]  \hspace{1cm} (4.32)
which can be written as

\[ u_1 = M_1(\theta_L)\ddot{\theta}_L + C_1(\theta_L, \dot{\theta}_L)\dot{\theta}_L + G_1(\theta_L) \quad (4.33) \]

with \( M_1(\theta_L) = J - J_mL_Z\sin\frac{\theta_L}{2} \), and \( C_1(\theta_L, \dot{\theta}_L) = B_L + B_mL_Z\cos\frac{\theta_L+90}{2} - \frac{1}{2}J_mL_Z\sin\frac{\theta_L+90}{2}\dot{\theta}_L \).

### 4.2 Argo J5 Dynamic Model by Using Euler Lagrange Principle

In this section, Argo J5, as shown in Fig 4.4, dynamic model is derived by (4.22), neglecting the potential field and by adding the potential field. Several assumptions are made for this derivation, which are

- The geometric location of COM of Argo J5 is shown in Fig. 4.4.
- The two wheels on each side of the Argo J5 have the same rotation speed because of the chain connection.
- The wheels are always connected to the ground during Argo J5 movement.

#### 1. Potential Field = 0

When \( P=0 \) because of the path planer, then \( \ell = K \) and the model of Argo J5 [53] is

\[ M(\theta_w)\ddot{\theta}_w + F(\dot{\theta}_w) = B(\theta_w)\tau + A^T(\theta_w)\lambda \quad (4.34) \]
where

$M(\theta_w) = \begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & I \end{bmatrix}$

$m$ is the mass of the Argo J5,
$I$ is moment of inertia of Argo J5,
$\theta_w$, $\dot{\theta}_w$, and $\ddot{\theta}_w$ are the angle, velocity, and acceleration of the wheel, respectively,

$F(\dot{\theta}_w) = \begin{bmatrix} F_S(\dot{\theta}_w) \cos \phi - F_L(\dot{\theta}_w) \sin \phi \\ F_S(\dot{\theta}_w) \cos \phi + F_L(\dot{\theta}_w) \sin \phi \\ M_r(\dot{\theta}_w) \end{bmatrix}$
\( FS(\dot{\theta}_w) \) and \( FL(\dot{\theta}_w) \) are resultant reactive forces,

\( Mr(\dot{\theta}_w) \) is resultant reactive torque,

\[
FS(\dot{\theta}_w) = \sum_{i=1}^{4} F_{Si}(\dot{\theta}_w)
\]

\[
FL(\dot{\theta}_w) = \sum_{i=1}^{4} F_{Li}(\dot{\theta}_w)
\]

\[
FS(\dot{\theta}_w) = \mu_{Si}.N_i.sgn(\vartheta_{ix})
\]

\[
FL(\dot{\theta}_w) = \mu_{Li}.N_i.sgn(\vartheta_{iy})
\]

\( \mu_{si} \) and \( \mu_{li} \) are dry friction coefficients for \( i^{th} \) wheel in longitudinal and lateral directions,

\( N_i \) is a reactive vertical force, which acts on wheel,

\( \vartheta_x \) is the longitudinal velocity of Argo J5,

\( \vartheta_y \) is the lateral velocity of Argo J5,

\[
B(q) = \frac{1}{r_w} \begin{bmatrix}
\cos \phi & \sin \phi \\
\sin \phi & \cos \phi \\
-B & B
\end{bmatrix}
\]

\( r_w \) is the radius of the wheel,

\( \phi \) is the turning angle of the Argo J5,
$B$ is the vertical distance between the center of the tire and COM of the Argo J5,

$A(\theta_w)$ is nonholonomic constraints vector,

$\lambda$ is Lagrange multipliers scaler,

$$\tau = \begin{bmatrix} \tau_L \\ \tau_R \end{bmatrix} \quad (4.35)$$

Rearranging (4.34), multiplying both sides by $S^T$, and simplifying, yields

$$S^T M S \dot{\xi} + S^T M \dot{\dot{\xi}} + S^T F = S^T B \tau \quad (4.36)$$

or

$$\bar{M} \dot{\xi} + \bar{C} \xi + \bar{F} = \bar{B} \tau \quad (4.37)$$

where $S$ is a full rank matrix.

2. **Potential Field** $\neq 0$

When $P \neq 0$, the dynamic equation of Argo J5 [30] is

$$M(\theta_w) \ddot{\theta}_w + C(\theta_w, \dot{\theta}_w) \dot{\theta}_w + D(\theta_w) + F(\dot{\theta}_w) = B(\theta_w) \tau + A^T(\theta_w) \lambda \quad (4.38)$$

where

$C(q, \dot{q})$ is a Coriolis and centrifugal matrix, and

$D(q)$ is a gravity vector.

Rearranging (4.38), multiplying both sides by $S^T$, and simplifying, yields

$$S^T M S \dot{\xi} + (S^T M \dot{S} + S^T CS) \xi + S^T D + S^T F = S^T B \tau \quad (4.39)$$
\[ \ddot{M} \ddot{\xi} + C\dot{\xi} + D + F = B\tau \] (4.40)

4.3 Argo J5 Dynamic Model by Using Driveline Components and Terramechanics Theory

The main purpose of this section is to introduce the development model of Argo J5 by applying driveline model and vehicle-terrain interaction. In the vehicle-terrain interaction, fundamentals of terramechanics theory is explained in detail, and the analysis of wheel-terrain interaction is shown.

4.3.1 Driveline Model of Argo J5

The driveline of Argo J5 consists of motor, chains, and four wheels as shown in Fig. 4.5

![Figure 4.5: One side of Argo J5 driveline subsystems.](image)

1. Motor

Argo J5 has two PMAC motors, one on each side. The features and characteristics of this motor are explained in chapter three. For control purposes, the torque of the motor, \( \tau_m \), is

\[ \tau_m = J_m\dot{\omega}_m \] (4.41)
where

\( J_m \) is motor moment of inertia,

\( \omega_m \) is angular velocity of the motor.

2. **Chains**

Chains can be modeled as a gear ratio, \( G_r \).

3. **Wheels**

The force analysis of Argo J5 movement as shown in Fig 4.6. The model of one wheel of the UGV Argo J5 with a rigid landing platform that has 0° off-level can be derived as

\[
F_w = m\ddot{x} + F_{\text{wind}} + F_R + mg \sin \theta_G + m_l p g \sin \theta_G \tag{4.42}
\]

Figure 4.6: The force analysis of Argo J5 movement.
where

$F_w$ is the traction force at the wheel,

$m$ is the mass of Argo J5,

$m_{lp}$ is the whole mass of the landing platform,

$\dot{\vartheta}_x$ is the linear velocity at the COM along the x direction,

$F_{wind}$ is the air drag force,

$F_R$ is the rolling resistance,

$g$ is gravity,

and $\theta_G$ is a slope angle.

The rolling resistance can be determined by

$$F_R = m(C_{r_1} + C_{r_2}\dot{\vartheta}_x)$$ (4.43)

where $C_{r_1}$ and $C_{r_2}$ are friction coefficients depending on tires and road conditions [78]. Also, $F_{wind}$ can be ignored.

Substituting (4.43) into (4.42) yields

$$F_w = m\dot{\vartheta}_x + m(C_{r_1} + C_{r_2}\dot{\vartheta}_x) + mg\sin(\theta_G) + m_{lp}g\sin(\theta_G)$$ (4.44)

Also, the total load torque on a wheel can be found

$$\tau_w = J_w\ddot{\vartheta}_w + \tau_{fricw} + r_w F_w$$ (4.45)

The model of one wheel of the UGV Argo J5 is
\[
\tau_w = J_w \dot{\omega}_w + \tau_{fricw} + mr_w^2 \dot{\omega}_w + mr_w(C_{r_1} + C_{r_2} r_w \omega_w) \\
+ mr_w g \sin(\theta_G) + m_l g r_w \sin(\theta_G) \tag{4.46}
\]

where

- \( \tau_w \) is the wheel’s torque,
- \( J_w \) is the wheel’s moment of inertia,
- \( \omega_w \) is the wheel’s angular velocity,
- \( \tau_{fricw} \) is the wheel’s internal friction load,
- \( r_w \) is the radius of the wheel.

Adding the model of the motor to the model of the wheel and substituting the wheel’s internal friction load, yields

\[
u_2 - \tau_m = (J_w + mr_w^2) \dot{\omega}_w + b_w \omega_w + mr_w(C_{r_1} + C_{r_2} r_w \omega_w) \\
+ m r_w g \sin(\theta_G) + m_l g r_w \sin(\theta_G) \tag{4.47}
\]

where \( u_2 = \frac{V}{R} \), \( V \) is the rotor voltage, and \( R \) is the rotor resistance of the motor.

Rearranging (4.47) and substituting the motor’s torque, resulting

\[
u_2 = J_m \dot{\omega}_w \frac{1}{G_r} + (J_w + mr_w^2) \dot{\omega}_w + b_w \omega_w + mr_w(C_{r_1} \tag{4.48} \\
+ C_{r_2} r_w \omega_w) + m r_w g \sin(\theta_G) + m_l g r_w \sin(\theta_G)
Then

\[ u_2 = \left( \frac{J_m}{G_r} + J_w + mr_w^2 \right) \dot{\omega}_w + (b_w + mr_w^2 C_{r_2}) \dot{\omega}_w \]
\[ + mr_w C_{r_1} +mgr_w \sin(\theta_G) + mLpg_r w \sin(\theta_G) \]  

(4.49)

which can be written as

\[ u_2 = M_2 \ddot{\theta}_w + C_2 \dot{\theta}_w + G_2 \]  

(4.50)

where \( M_2 = \frac{J_m}{G_r} + J_w + mr_w^2 \), \( C_2 = b_w + mr_w^2 C_{r_2} \), \( G_2 = mr_w C_{r_1} + mgr_w \sin(\theta_G) + mLpg_r w \sin(\theta_G) \), \( b_w \) is the damping coefficient and \( \theta_w \) is the angle of the wheel.

Thus, the left and right wheels models of the vehicle are

\[ u_{2L} = M_2 \ddot{\theta}_{wL} + C_2 \dot{\theta}_{wL} + G_2 \]  

(4.51)

\[ u_{2R} = M_2 \ddot{\theta}_{wR} + C_2 \dot{\theta}_{wR} + G_2 \]

The model of Argo J5 (4.50) is used for controller derivation and the models of the wheels (4.51) are applied for trajectory tracking application.

### 4.3.2 Wheel-Terrain Interaction Analysis

The vehicle-terrain interaction analysis is derived in Cartesian coordinates that include shear displacement, shear stress, normal stress, reaction force, vehicle kinetics, and vertical load distribution. This analysis is derived according to the COM of Argo J5 [119], and is applied to the four wheels as described in Fig. 4.8. The
The following assumptions are used to simplify the comprehensive analysis and derivation:

- The tires of Argo J5 can be considered rigid wheels.
- The landing platform is considered a rigid body with 0° level angle in x and y directions.
- The area of the ground beneath Argo J5 is flat, i.e. θ = 0°, and homogeneous.
- The bulldozing effect is ignored.
- The lower value of the integration of the contact angle is very small, so it can be considered as 0°. This means θ1i always lies in the front sinkage region.

1. **Shear Displacement**

Consider a point \( P_i \), as shown in Fig. 4.8, which lies on the middle outer surface of the wheel, where \( i \) refers to the number of the tire. Thus \( i = 1, 2, 3, 4 \). Each one of these points \( P_i \) has its own frame that is relative to the robot frame.
Figure 4.8: Side and top views of Argo J5.
Consider $a$ and $B$ to be the distances between the center of the tires on the same side along the x-axis and the center of the tire and the COM along the y-axis, respectively. Let $h$ be the vertical distance between the ground and the COM along the z-axis. The position of the points $P_i$ can be calculated as

$$P_i = X_i i + Y_i j + Z_i k$$

$$X_i = \left(\frac{1}{2} - \text{INT}\left(\frac{i - 1}{2}\right)\right)a + x_i$$

$$Y_i = (-1)^{i+1}B + y_i$$

$$Z_i = -(h - r_w + z_i)$$

where $X_i$, $Y_i$, and $Z_i$ are the Cartesian coordinates of the point $P_i$; $i$, $j$, and $k$ are the unit vectors along the x, y, and z-axes, respectively; $\text{INT}$ is the integer function. Also, the values of $x_i$, $y_i$, and $z_i$ are determined as

$$x_i = r_w \sin(\theta_i)$$

$$y_i = x_i \tan(\phi)$$

$$z_i = r_w \cos(\theta_i)$$

where $\theta_i$ is the contact angle of the wheel-terrain at the point $P_i$ and $\phi$ is the turning angle of Argo J5.

Assuming that $V$ is the linear velocity of Argo J5 and $\Omega$ is the turning rate of Argo J5 that equals $\dot{\phi}$, then

$$V = V_x i + V_y j + \Omega k$$
For the SSMP, the longitudinal and lateral velocities of the COM of the vehicle can be calculated from kinematic analysis [1]. The relationship between the linear and angular velocities is \( V = r_w \omega \).

Now, the velocity at the point \( P_i \) with respect to the COM is

\[
V_i = V \times P_i = (V_x - \Omega Y_i)i + (V_y + \Omega X_i)j
\]

\[
= (V_{xi}, V_{yi})
\]

Also, the velocity at the point \( P_i \) can be decomposed into three components: [4] normal, tangential, and lateral velocities, respectively, and can be calculated as

\[
\begin{align*}
V_{ni} &= V_{xi} \sin(\theta_i) \\
V_{ti} &= r_w \omega_i - V_{xi} \cos(\theta_i) \\
V_{li} &= V_{yi}
\end{align*}
\]

where

\[
\omega_i = \begin{cases} 
\omega_L & \text{if } i \text{ is odd} \\
\omega_R & \text{if } i \text{ is even}
\end{cases}
\]
where $\omega_L$ and $\omega_R$ are the angular velocities of the left and right sides, respectively. Therefore, the slip velocity of the point $P_i$ can be found as

$$V_{jxi} = -V_{ti} \cos(\theta_i)$$
$$V_{jyi} = V_{ti}$$
$$V_{jzi} = -V_{ti} \sin(\theta_i)$$

Additionally, the components of the shear displacement can be calculated as

$$j_{xi} = \frac{1}{\omega_i} \int_{\theta_i}^{\theta_{1i}} V_{jxi} d\theta_i$$
$$j_{yi} = \frac{1}{\omega_i} \int_{\theta_i}^{\theta_{1i}} V_{jyi} d\theta_i$$
$$j_{zi} = \frac{1}{\omega_i} \int_{\theta_i}^{\theta_{1i}} V_{jzi} d\theta_i$$

where $\theta_{1i}$ is the wheel’s entry angle, which makes the contact angle.

The shear displacement is obtained as

$$j_i = \sqrt{j_{xi}^2 + j_{yi}^2 + j_{zi}^2}$$

2. Normal Stress

The normal stress of a rigid wheel that runs on the deformable ground of the front region can be calculated as

$$\sigma_i = \left( \frac{k_c}{b} + k_\phi \right) \sigma_w^n (\cos \theta_i - \cos \theta_{1i})^n$$
where $k_c$, $k_\phi$ are the sinkage pressure moduli of the terrain, and $n$ is the sinkage exponent.

Also, the normal stress of a rigid wheel that runs on the deformable ground of the rear region can be calculated as

$$
\sigma_i = \left( \frac{k_c}{b} + k_\phi \right) r_i^n (\cos(\theta_{1i} - \theta_i) - \cos\theta_{1i})^n
$$

(4.61)

The difference of calculating the normal stress is caused by the method of finding the sinkage $z$.

3. Shear Stress

Shear stress is an exponential relationship that depends on the shear displacement $j$ with the normal stress $\sigma_i(\theta_i)$, and it is expressed as

$$
\tau_i = (c + \sigma_i(\theta_i)\tan(\phi_f))(1 - e^{-j_i/K})
$$

(4.62)

where $c$ and $\phi_f$ are the terrain’s cohesion and internal friction angle, respectively, and $K$ is the shear deformation modulus.

The shear stress components at point $P_i$ can be expressed as

$$
\begin{align*}
\tau_{xi} &= -\tau_i \cos\alpha_i \sin\beta_i \\
\tau_{yi} &= -\tau_i \sin\alpha_i \sin\beta_i \\
\tau_{zi} &= -\tau_i \cos\beta_i
\end{align*}
$$

(4.63)
where $\alpha_i$ and $\beta_i$ are angles and are determined as

$$\alpha_i = \tan^{-1} \frac{V_{jiy}}{V_{jxi}}$$

$$\beta_i = \tan^{-1} \sqrt{\frac{V_{jxi}^2 + V_{jiy}^2}{V_{jzi}}}$$  \hspace{1cm} (4.64)$$

On the other hand, the normal stress components are determined as

$$\sigma_{xi} = -\sigma_i(\theta_i) \sin \theta_i$$

$$\sigma_{yi} = 0$$

$$\sigma_{zi} = \sigma_i(\theta_i) \cos \theta_i$$  \hspace{1cm} (4.65)$$

4. **Reaction Force**

The reaction force components are determined by integrating the result of combining the normal stress component with the shear stress component that has the same direction, thus

$$F_{xi} = r_w \int_{\theta_1}^{\theta_2} \int_{-b/2}^{b/2} (\tau_{xi} + \sigma_{xi}) dy_i d\theta_i$$

$$F_{yi} = r_w \int_{\theta_1}^{\theta_2} \int_{-b/2}^{b/2} (\tau_{yi} + \sigma_{yi}) dy_i d\theta_i$$

$$F_{zi} = r_w \int_{\theta_1}^{\theta_2} \int_{-b/2}^{b/2} (\tau_{zi} + \sigma_{zi}) dy_i d\theta_i$$  \hspace{1cm} (4.66)$$

5. **Argo J5’s Kinetics**

During the movement of Argo J5, the reaction force components are responsible for the acceleration, rolling resistance, weight balance, and moment of
turning resistance. Thus, the acceleration components are calculated as

$$\sum_{i=1}^{4} F_{xi} = r_w \sum_{i=1}^{4} \int_{0}^{\theta_{i1}} \int_{-b/2}^{b/2} (\tau_{xi} + \sigma_{xi}) dy_i d\theta_i$$

$$= ma_x$$

(4.67)

$$\sum_{i=1}^{4} F_{yi} = r_w \sum_{i=1}^{4} \int_{0}^{\theta_{i1}} \int_{-b/2}^{b/2} \tau_{yi} dy_i d\theta_i = ma_y$$

(4.68)

While the distributed weight balance on the wheels are determined as

$$\sum_{i=1}^{4} F_{zi} = r_w \sum_{i=1}^{4} \int_{0}^{\theta_{i1}} \int_{-b/2}^{b/2} (\tau_{zi} + \sigma_{zi}) dy_i d\theta_i$$

$$= \sum_{i=1}^{4} W_i = W = mg$$

(4.69)

Next, the rolling resistance is calculated as

$$R_r = r_w \sum_{i=1}^{4} \int_{0}^{\theta_{i1}} \int_{-b/2}^{b/2} \sigma_i(\theta_i) \sin\theta_i dy_i d\theta_i$$

(4.70)

Additionally, the rolling moments along the $x$ and $y$-axes are derived as

$$M_x = r_w \sum_{i=1}^{4} \int_{0}^{\theta_{i1}} \int_{-b/2}^{b/2} [Y_i(\tau_{xi} + \sigma_{xi}) - Z_i(\tau_{zi} + \sigma_{zi})] dy_i d\theta_i$$

(4.71)

$$M_y = r_w \sum_{i=1}^{4} \int_{0}^{\theta_{i1}} \int_{-b/2}^{b/2} [Z_i(\tau_{zi} + \sigma_{zi}) - X_i(\tau_{xi} + \sigma_{xi})] dy_i d\theta_i$$

(4.72)

$$M_z = r_w \sum_{i=1}^{4} \int_{0}^{\theta_{i1}} \int_{-b/2}^{b/2} [X_i\tau_{yi} - Y_i(\tau_{xi} + \sigma_{xi})] dy_i d\theta_i$$

(4.73)

$$= I_z \dot{\Omega}$$
Next, the moment of turning resistance is derived as

\[ M_r = -r_w \sum_{i=1}^{4} \int_{0}^{b/2} \int_{-b/2}^{b/2} X_i \tau_{yi} dy_i d\theta_i \] (4.74)

6. Vertical Load Distribution

Consider that the reaction force along the \( z \)-axis on each wheel has a linear relationship with its current position at the point \( P_i \), thus

\[ F_{zi} = C_1 + C_2 X_i + C_3 Y_i \] (4.75)

where \( C_1, C_2, \) and \( C_3 \) are constants that can be calculated as

\[
C_1 = \frac{mg}{4} \\
C_2 = \frac{-hma_x}{a^2} \\
C_3 = \frac{-hma_y}{4B^2}
\] (4.76)

Therefore, the vertical load on each wheel is

\[
W_1 = \frac{m}{4aB} (aBg - 2Bha_x - aha_y) \\
W_2 = \frac{m}{4aB} (aBg - 2Bha_x + aha_y) \\
W_3 = \frac{m}{4aB} (aBg + 2Bha_x - aha_y) \\
W_4 = \frac{m}{4aB} (aBg + 2Bha_x + aha_y)
\] (4.77)

which can be used to obtain the \( \theta_{1i} \) in (4.69).
4.4 Dynamic Model of the Argo J5 with the Custom-Built Landing Platform

From 4.33 and 4.50, the combined model is

\[ u = M(\theta)\ddot{\theta} + C(\theta, \dot{\theta})\dot{\theta} + G(\theta) \]  

(4.78)

where

\( u \in \mathbb{R}^{2 \times 1} \) is the applied torque on the landing platform and the Argo J5, respectively,

\[ u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \]

\( M(\theta) \in \mathbb{R}^{2 \times 2} \) is the inertia matrix,

\[ M(\theta) = \begin{bmatrix} M_1 & 0 \\ 0 & M_2 \end{bmatrix} \]

\( C(\theta, \dot{\theta}) \in \mathbb{R}^{2 \times 2} \) is the Coriolis and centrifugal matrix,

\[ C(\theta, \dot{\theta}) = \begin{bmatrix} C_1 & 0 \\ 0 & C_2 \end{bmatrix} \]
\( G(\theta) \in \mathbb{R}^{2+1} \) is the gravitational vector,

\[
G(\theta) = \begin{bmatrix} G_1 \\ G_2 \end{bmatrix}
\]

and

\[
\theta = \begin{bmatrix} \theta_L \\ \theta_w \end{bmatrix}
\]

(4.78) represents the dynamic model of Argo J5 with a custom-built landing platform as shown in Figs. 4.9 and 4.10.

For control purposes, the combined dynamic model, (4.78), in state space form is

\[
\dot{x} = A(x) + B(x)u(t)
\]  

(4.79)

where

\[
x = \begin{bmatrix} \theta \\ \dot{\theta} \end{bmatrix}
\]

\[
A(x) = \begin{bmatrix} \dot{\theta} \\ -M^{-1}(\theta)(C(\theta, \dot{\theta})\dot{\theta} + G(\theta)) \end{bmatrix}
\]  

(4.80)
and

$$B(x) = \begin{bmatrix} 0 \\ -M^{-1}(\theta) \end{bmatrix}$$ (4.81)

Figure 4.9: Front view of Argo J5 with landing platform.

Figure 4.10: Side view of Argo J5 with landing platform.
4.5 Tire Deflation Model of the Argo J5

In this section, a model of tire deflation, as shown in Fig.4.11, is derived to investigate the effects of tire deflation on dynamic self-leveling. The main goal is to find the deflation radius of the tire, a mathematical representation that has the radius of the tire and the temperature, and the volume of the gas as explained below.

![Figure 4.11: Tire deflation physical side and bottom views.](image)

The length of the tire deflation \[136\] is

\[ L_{de} = \frac{w_{de}}{p_t b} \]  \hspace{1cm} (4.82)

where \( L_{de} \) is length of the tire deflation, \( w_{de} \) is the width of the tire deflation, \( p_t \) is the air pressure in the tire, \( b \) is the normal width of the tire.
To obtain the radius of the tire deflation, trigonometric relationship can be applied as

$$\sin \theta_{de} = \frac{L_{de}/2}{r_w}$$  \hspace{1cm} (4.83)

Substituting (4.82) into (4.83), obtained

$$\sin \theta_{de} = \frac{w_{de}}{2r_w p_t b}$$  \hspace{1cm} (4.84)

Then,

$$\theta_{de} = \sin^{-1} \frac{w_{de}}{2r_w p_t b}$$  \hspace{1cm} (4.85)

$$\cos \theta_{de} = \frac{r_{de}}{r_w}$$  \hspace{1cm} (4.86)

Then,

$$r_{de} = r_w \cos \theta_{de}$$  \hspace{1cm} (4.87)

Substituting (4.85) into (4.87), yields

$$r_{de} = r_w \cos(\sin^{-1} \frac{w_{de}}{2r_w p_t b})$$  \hspace{1cm} (4.88)

Applying the ideal gas law [137], which is

$$p_t V_t = nRT$$  \hspace{1cm} (4.89)

where $V_t$ is the volume of the gas, $n$ is the amount of substance of air, $R$ is the ideal air constant, and $T$ is the temperature of the air. To find the volume of the air,

$$V_t = V_{outer} - V_{inner}$$  \hspace{1cm} (4.90)
\[ V_t = r_u^2 \pi b - r_{\text{ring}}^2 \pi w_{\text{ring}} \]  

(4.91)

where \( r_{\text{ring}} \) is the radius of the ring and \( w_{\text{ring}} \) is the width of the ring.

The pressure of tire deflation [138] is expressed

\[ p_{\text{det}}(t) = p_t e^{-t/c_k} \]  

(4.92)

where

\[ c_k = \frac{V_t}{A_h} \sqrt{\frac{2M_a}{RT}} \]  

(4.93)

where \( M_a \) is the molar mass of air and \( A_h \) is the area of the orifice.

To summarize the work of this chapter, Table 4.1 presents the dynamic models that are derived through this chapter.

Table 4.1: Dynamic models.

<table>
<thead>
<tr>
<th>Dynamic models</th>
<th>Corresponding equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landing platform model</td>
<td>4.33</td>
</tr>
<tr>
<td>Argo J5 by Euler-Lagrange without potential field</td>
<td>4.34</td>
</tr>
<tr>
<td>Argo J5 by Euler-Lagrange with potential field</td>
<td>4.38</td>
</tr>
<tr>
<td>Argo J5 by driveline components and terramechanics theory</td>
<td>4.50, 4.62, 4.70, and 4.74</td>
</tr>
<tr>
<td>The whole robot</td>
<td>4.78</td>
</tr>
<tr>
<td>Tire deflation</td>
<td>4.88 and 4.92</td>
</tr>
</tbody>
</table>
This chapter centers on derivation and implementation of different controllers on the landing platform, on the Argo J5, and the combined system. Section one depicts several controller techniques implemented on the landing platform to show the fast leveling with and without external disturbances. Five different controllers are tested to compare performance during leveling achievement. Section two presents a PD controller that is implemented to show trajectory tracking of the Argo J5. Section three details a PBAC and NNBAC for dynamic self-leveling of the combined, Argo J5 - landing platform.

5.1 Landing Platform Controller Development

In this section, different controllers are derived to test performance with respect to the leveling process. PD and PID controllers are developed because their sim-
plicity and wide applicability. A LQR is then derived, which ensures the stability of
the landing platform and minimizes energy usage, due to battery limitations. Then,
feedback linearization evaluates performance degradation due to transforming the
nonlinear system to a linearized one. Finally, a PBAC is also developed to test
system robustness.

5.1.1 PD, and PID

Consider the following control laws for PD, and PID, respectively

\[ u_1 = -K_p \tilde{\theta}_L - K_d \dot{\theta}_L + G_1(\theta_L) \]  \hspace{1cm} (5.1)

\[ u_1(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{d(e)}{dt} \]  \hspace{1cm} (5.2)

where \( K_p, K_d, \) and \( K_i \) are constant gains, \( \tilde{\theta}_L = \theta_L - \theta_{Ld}, e(t) = \theta_{Ld} - \theta_L, \) and \( \theta_{Ld} \) is the desired level angle.

There are several methods to choose values of constant gains, such as Ziegler-
Nichols tuning method; however, in this paper, constant gains are chosen by the
Matlab toolbox to ensure a faster settling time as shown in Table 5.1.

<table>
<thead>
<tr>
<th>Gain Value</th>
<th>Rise Time (sec)</th>
<th>Settling Time (sec)</th>
<th>Over Shoot</th>
<th>Steady-State Error (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_p )</td>
<td>Decrease</td>
<td>Small Change</td>
<td>Increase</td>
<td>Decrease</td>
</tr>
<tr>
<td>( K_i )</td>
<td>Decrease</td>
<td>Increase</td>
<td>Increase</td>
<td>Decrease</td>
</tr>
<tr>
<td>( K_d )</td>
<td>Small Change</td>
<td>Decrease</td>
<td>Decrease</td>
<td>No Change</td>
</tr>
</tbody>
</table>

Table 5.1: General effects of PID’s constant gains tuning on a closed-loop system
The above control laws (5.1) and (5.2) achieve zero steady-state error [139]. By considering a Lyapunov function to be

\[ V = \frac{1}{2} \dot{\theta}_L^T M_1(\theta_L) \ddot{\theta}_L + \frac{1}{2} \ddot{\theta}_L^T K_p \ddot{\theta}_L \]  

(5.3)

one may see that

\[ \dot{V} = \dot{\theta}_L^T M_1(\theta_L) \ddot{\theta}_L + \frac{1}{2} \dot{\theta}_L^T M_1(\theta_L) \dot{\theta}_L - \dot{\theta}_L^T K_p \ddot{\theta}_L \]  

(5.4)

Substituting (4.33) into (5.4) and simplified yields

\[ \dot{V} = \dot{\theta}_L^T (u_1 - K_p \ddot{\theta}_L) \]  

(5.5)

Substituting (5.1) into (5.5) yields

\[ \dot{V} = -\dot{\theta}_L^T K_d \dot{\theta}_L \leq 0 \]  

(5.6)

Applying LaSalle’s Theorem, assuming that \( \dot{V} \equiv 0 \), then (5.6) implies that \( \dot{\theta}_L \equiv 0 \) and hence \( \ddot{\theta}_L \equiv 0 \), and (4.33) and (5.1) imply \( \dot{\theta}_L = 0 \), when \( \dot{\theta}_L = 0 \). So, the equilibrium is asymptotically stable and the landing platform will level.

5.1.2 Linear Quadratic Regulator

Since the dynamic system (4.33) is controllable, LQR can be applied [140] and the platform can be linearized at a fixed point (equilibrium point), represented in term of the following state-space equation

\[ \dot{x} = Ax + Bu_1 \]  

(5.7)
where $x$ is the state vector, $A$ is the system matrix, $B$ is the input vector, and $u_1$ is the controller vector. Then, a linear control law can be chosen as

$$u_1 = -K_L x$$ \hspace{1cm} (5.8)

that minimizes the cost function

$$C_f = \int_0^\infty (x^T Q x + u^T R u) dt$$ \hspace{1cm} (5.9)

where $K_L$ is a vector $\in \mathbb{R}^{1 \times 2}$, $x$ is the state vector. $Q$, a positive diagonal matrix with a big value, shows how bad of a penalty it is if the state is not where it should be, and $R$ is a positive scaler with a small value that refers to a penalty of control expenditure.

This means that by selecting the linear controller (5.8) that minimizes the quadratic cost function (5.9), the state of the landing platform will be regulated and stabilized to the equilibrium point, thus achieving leveling.

### 5.1.3 Feedback Linearization

Feedback linearization [141] may be applied to classes of nonlinear systems if such systems can be represented in a controller canonical form. For example

$$\dot{x} = f(x) + g(x) u_1$$ \hspace{1cm} (5.10)

where $x = [\theta_L \dot{\theta}_L]^T \in \mathbb{R}^2$ is the state of the landing platform, and
\[
f(x) = \begin{bmatrix} \dot{\theta}_L \\ -M_1^{-1}(\theta_L)(C_1(\theta_L, \dot{\theta}_L)\dot{\theta}_L + G_1(\theta_L)) \end{bmatrix}
\]
(5.11)

\[
g(x) = \begin{bmatrix} 0 \\ -M_L^{-1}(\theta_L) \end{bmatrix}
\]
(5.12)

Assume there is a state transformation \( T : x \mapsto z \) with \( z \in \mathbb{R}^2 \) and \( T(0) = 0 \). \( z = T(x) \) is continuously differentiable, invertible, and its inverse is also continuously differentiable. This can make the system dynamics transform into

\[
\dot{z} = Az + B(\psi(x) + \beta(x)u)
\]
(5.13)

where \( A, B \) are controllable, \( \beta(x) \) is invertible. For the landing platform, let

\[
u = \beta^{-1}(x)(-\psi(x) + \mu)
\]
(5.14)

and substituting (5.14) into (5.13) yields

\[
\dot{z} = Az + B\mu
\]
(5.15)

Now, choose \( \mu = -K_Fz \) so that \( A - BK_F \) is Hurwitz. Where \( z_1 = x_1, z_2 = x_2 \), 
\[ \psi(x) = -M_1^{-1}(x_1)(C_1(x_1, x_2)x_2 + G_1(x_1), B = [0 1]^T, \beta(x) = M_1^{-1}(x_1), K_F \]
a vector \( \in \mathbb{R}^{1 \times 2} \), and \( A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \).
5.1.4 Passivity Based Adaptive Controller

To develop the PBAC [139], consider that

\[ M_1(\theta_L)\ddot{\theta}_L + C_L(\theta_L, \dot{\theta}_L)\dot{\theta}_L + G_1(\theta_L) = Y(\theta_L, \dot{\theta}_L, \ddot{\theta}_L)\Theta \quad (5.16) \]

where \( Y(\theta_L, \dot{\theta}_L, \ddot{\theta}_L) \) is the regressor, then \( u \) can be chosen as

\[ u = Y(\theta_L, \dot{\theta}_L, \nu, a)\hat{\Theta} - K_B r \quad (5.17) \]

where \( \nu = \dot{\theta}_{Ld} - \Lambda \ddot{\theta}_L, a = \ddot{\theta}_{Ld} - \Lambda \dot{\theta}_L, r = \dot{\theta}_L + \Lambda \dot{\theta}_L, \dot{\theta}_L = \theta_L - \theta_{Ld}, \Lambda, K_B \) are positive gains, and \( \hat{\Theta} \) is an estimated value of \( \Theta \). Also

\[
Y^T(\theta_L, \dot{\theta}_L, \nu, a) = \\
\begin{bmatrix}
a \\
-\sin \frac{\theta_L}{2} a - \frac{1}{2} \sin \frac{\theta_L + 90}{2} \dot{\theta}_L \nu \\
\nu \\
\cos \frac{\theta_L + 90}{2} \nu \\
g \cos \frac{\theta_L + 90}{2} \\
g \sin \frac{\theta_L + 90}{2} \cos \frac{\theta_L + 90}{2}
\end{bmatrix}
\quad (5.18)
\]
\[
\Theta = \begin{bmatrix}
J \\
J_m L Z \\
B_L \\
B_m L Z \\
\frac{1}{2}(m_L L_L + m_C L_L + m_C L_C - m_C L_A) \\
4m_C L Z
\end{bmatrix}
\] (5.19)

Then, the system may be represented by

\[
M(\theta_L) \dot{r} + C(\theta_L, \dot{\theta}_L) r + K_B r = Y \tilde{\Theta}
\] (5.20)

where \( \tilde{\Theta} = \hat{\Theta} - \Theta \). Choose the parameter update law as

\[
\dot{\hat{\Theta}} = -\Gamma^{-1} Y^T (\theta_L, \dot{\theta}_L, a, \nu) r
\] (5.21)

where \(\Gamma\) is a positive constant. Choose the following Lyapunov function [139] as

\[
V = \frac{1}{2} r^T M(\theta) r + \tilde{\Theta}^T \Lambda K_B \tilde{\Theta} + \frac{1}{2} \hat{\Theta}^T \Gamma \hat{\Theta}
\] (5.22)

\[
\dot{V} = -\tilde{\Theta}^T \Lambda K_B \tilde{\Theta} - \tilde{\Theta}^T K_B \dot{\Theta} + \hat{\Theta}^T (\Gamma \dot{\Theta} + Y^T r)
\] (5.23)

where \( \dot{\hat{\Theta}} = \dot{\hat{\Theta}} \).

Substituting (5.21) into (5.23) yields

\[
\dot{V} = -\tilde{\Theta}^T \Lambda K_B \tilde{\Theta} - \tilde{\Theta}^T K_B \dot{\Theta}
\] (5.24)
\[ \dot{V} = -e^T Q e \leq 0 \] \hspace{1cm} (5.25)

where \( e = \begin{bmatrix} \tilde{\theta} \\ \dot{\tilde{\theta}} \end{bmatrix} \) and \( Q = \begin{bmatrix} \Lambda K_B & 0 \\ 0 & K_B \end{bmatrix} \). (5.25) shows that the closed-loop system is stable in the sense of Lyapunov.

By applying Barbalat’s Lemma and assuming \( f : \mathbb{R} \rightarrow \mathbb{R} \) is a square integrable function and that its derivative \( \dot{f} \) is bounded. Then \( f(t) \rightarrow 0 \) as \( t \rightarrow \infty \). A function \( f(x) \) is square integrable if \( \int_{-\infty}^{\infty} |f(x)|^2 < \infty \). This means the tracking error of the closed-loop system (5.20) converges to zero asymptotically, i.e., \( \tilde{\theta} \rightarrow 0 \) as \( t \rightarrow \infty \).

All the previous controllers are implemented and tested for static self-leveling.

### 5.2 Argo J5 Controller Derivation

One of the most simple and widely applicable controllers is the PD controller that can be applied for a MR trajectory tracking. Thus, it is chosen for implementation on the Argo J5. Consider the following PD control law

\[ u_2(t) = K_p \tilde{\theta}_w - K_d \dot{\tilde{\theta}}_w + C_2 \dot{\theta}_w + G_2 \] \hspace{1cm} (5.26)

where \( K_p \) and \( K_d \) are constant gains, \( \tilde{\theta}_w = \theta_{wd} - \theta_w \), and \( \theta_{wd} \) is the desired angle of the wheel.

The above controller achieves zero steady-state error [139] as can be seen by using the Lyapunov function

\[ V = \frac{1}{2} \dot{\theta}_w^T M \dot{\theta}_w + \frac{1}{2} \dot{\tilde{\theta}}_w^T K_p \dot{\tilde{\theta}}_w \] \hspace{1cm} (5.27)
that results in
\[ \dot{V} = -\dot{\theta}_w^T K_d \dot{\theta}_w \leq 0 \] (5.28)

Applying LaSalle’s Theorem, suppose \( \dot{V} \equiv 0 \), then (5.28) implies that \( \dot{\theta}_w \equiv 0 \) and hence \( \ddot{\theta}_w \equiv 0 \), and (4.50) and (5.26) imply \( \ddot{\theta}_w = 0 \), when \( \dot{\theta}_w = 0 \). So, the equilibrium is asymptotically stable. This simple controller guarantees accurate trajectory tracking.

5.3 Argo J5 with the Custom-built Landing Platform

Controller Derivation

Two controls are developed for the combined system to evaluate dynamic self-leveling, these controllers are PBAC and NNBAC, respectively. Both controllers rely on an adaptive controller because the adaptive regulator works when a model mismatch occurs, ensures convergence and boundedness of the state in the closed loop system, and guarantees the robustness. Dynamic NN controller performs on-line identification that provides information to the controller to guarantee convergence of the error to zero. For any undesired performance of the system, the adaptive controller may ensure output boundedness.

5.3.1 Passivity-Based Adaptive Controller

The general configuration of the controller is shown in Fig. 5.1. Consider
\[ M(\theta) \ddot{\theta} + C(\theta, \dot{\theta}) \dot{\theta} + G(\theta) = Y(\theta, \dot{\theta}, \ddot{\theta}) \Theta \] (5.29)
where \( Y(\theta, \dot{\theta}, \ddot{\theta}) \) is the regressor, which is a known function of the generalized coordinates [142].

\[
u = \dot{\theta}_d - \Lambda \ddot{\theta}, \quad \nu = (\nu_L, \nu_w), \quad \nu_L = \dot{\theta}_L, \quad \nu_w = \dot{\theta}_w,
\]

\[
a = \ddot{\theta}_d - \Lambda \dot{\theta}, \quad a = (a_L, a_w), \quad a_L = \ddot{\theta}_L, \quad a_w = \ddot{\theta}_w,
\]

\[
r = \dot{\theta} + \Lambda \ddot{\theta},
\]

\[
\tilde{\theta} = \theta - \theta_d, \quad \theta_d \text{ is the desired value of } \theta,
\]

\[
\Lambda, K_B \text{ are positive gains},
\]

\[
\text{and } \hat{\Theta} \text{ is an estimated value of } \Theta.
\]

Also

\[
Y^T_1(\theta_L, \dot{\theta}_L, \nu_L, a_L) = \begin{bmatrix}
a_L \\
-\sin \frac{\theta_L}{2} a_L - \frac{1}{2} \sin \frac{\theta_L + 90}{2} \dot{\theta}_L \nu_L \\
\nu_L \\
\cos \frac{\theta_L + 90}{2} \nu_L \\
g \cos \frac{\theta_L + 90}{2} \\
g \sin \frac{\theta_L + 90}{2} \cos \frac{\theta_L + 90}{2} \\
0 \\
0 \\
0 \\
0
\end{bmatrix}
\] (5.31)
\[ Y_2^T(\theta_L, \nu_w, a_W) = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ a_w \\ \nu_w \\ C_{r_1} + g \sin \theta_G \\ g \sin \theta_G \end{bmatrix} \] (5.32)

\[ Y^T(\theta, \dot{\theta}, \nu, a) = \begin{bmatrix} Y_1^T \\ Y_2^T \end{bmatrix} \] (5.33)

and
Adaptive Controller

Plant (Argo J5 + Landing platform)

Passivity-Based Controller

Adaptive Controller

Figure 5.1: Passivity-based adaptive controller scheme

\[
\Theta = \begin{bmatrix}
J & J_m L_Z \\
J_m L_Z & B \\
B & B_m L_Z \\
\frac{1}{2}(m_L L_L + m_C L_L + m_C L_C - m_C L_A) & 4m_C L_Z \\
J_w + J_w & \frac{J_w}{G_v} + J_w \\
b_w + m r_w^2 C_{r_2} & m r_w \\
m l_p r_w & m l_p r_w \\
\end{bmatrix}
\] (5.34)

Then, the system may be represented by

\[
M(\theta) \ddot{r} + C(\theta, \dot{\theta}) \dot{r} + K_B r = Y \tilde{\Theta}
\] (5.35)

where \( \tilde{\Theta} = \hat{\Theta} - \Theta \). Assume the parameter update law as
\[ \dot{\Theta} = -\Gamma^{-1}Y^T(\theta, \dot{\theta}, a, \nu)r \]  
\[ (5.36) \]

where \( \Gamma \) is a positive constant.

Select the following Lyapunov function [139] candidate as

\[ V = \frac{1}{2}r^T M(\theta)r + \tilde{\theta}^T \Lambda K_B \tilde{\theta} + \frac{1}{2} \tilde{\Theta}^T \Gamma \tilde{\Theta} \]
\[ (5.37) \]

\[ \dot{V} = -\tilde{\theta}^T \Lambda K_B \tilde{\theta} - \tilde{\theta}^T K_B \dot{\theta} + \tilde{\Theta}^T (\Gamma \dot{\Theta} + Y^Tr) \]
\[ (5.38) \]

where \( \dot{\theta} = \dot{\tilde{\theta}} \). Substituting (5.36) into (5.38) yields

\[ \dot{V} = -\tilde{\theta}^T \Lambda K_B \tilde{\theta} - \tilde{\theta}^T K_B \dot{\theta} \]
\[ (5.39) \]

\[ \dot{V} = -e^T Q e \leq 0 \]
\[ (5.40) \]

where \( e = \begin{bmatrix} \tilde{\theta} \\ \dot{\tilde{\theta}} \end{bmatrix} \) and \( Q = \begin{bmatrix} \Lambda K_B & 0 \\ 0 & K_B \end{bmatrix} \). (5.40) shows that the closed-loop system is stable in the sense of Lyapunov.

By applying Barbalat’s Lemma and assuming \( f : R \mapsto R \) is a square integrable function, and that its derivative \( \dot{f} \) is bounded, then, \( f(t) \rightarrow 0 \) as \( t \rightarrow \infty \). A function \( f(x) \) is square integrable if \( \int_{-\infty}^{\infty} |f(x)|^2 < \infty \). This means the tracking error of the closed-loop system (5.35) converges to zero asymptotically, i.e., \( \tilde{\theta} \rightarrow 0 \) as \( t \rightarrow \infty \).
5.3.2 Neural Network-Based Adaptive Controller

The general configuration of the controller is shown in Fig. 5.2. Consider

\[ M(θ)\ddot{θ} + C(θ, \dot{θ})\dot{θ} + G(θ) = u_{NN} \]  \hspace{1cm} (5.41)

where \( u_{NN} \) has the form

\[ u_{NN} = R_{NN} - K_p e \]  \hspace{1cm} (5.42)

where \( e \) is the error, \( K_p \) are a positive gain, and

\[ R_{NN} = \Theta^T Y_{BF} \]  \hspace{1cm} (5.43)

where

\[ \Theta^T = \begin{bmatrix} w_{e11} & \ldots & w_{e1nu} \\ w_{e21} & \ldots & w_{e2nu} \end{bmatrix}, \]

\( we \) is the NN weight, \( nu \) is the number of the Basis Function (BF),

\[ Y_{BF} = \begin{bmatrix} y_{BF1} \\ \vdots \\ y_{BFnu} \end{bmatrix}, \]

\[ y_{BF} = \prod_{i=1}^{ns} y_i(x_i), \]
ns is number of states,

\[ y(x) = e^{-0.5 \left( \frac{x - ce}{ba} \right)^2}, \]

y is the Radial Basis Function (RBF), ce is the RBF center, and ba is the RBF bandwidth.

Assume the parameter update law as

\[ \dot{\hat{\Theta}} = -\Gamma^{-1} Y_{BF} e^T \]  \hspace{1cm} (5.44)

where \( \Gamma \) is a positive constant and \( \hat{\Theta} = \hat{\Theta} - \Theta \).

Figure 5.2: Neural network-based adaptive controller scheme.

Select the following Lyapunov function [139] candidate to be

\[ V = \frac{1}{2} e^T M(\theta)e + \hat{\theta}^T K_p \hat{\theta} + \frac{1}{2} \hat{\Theta}^T \Gamma \hat{\Theta} \]  \hspace{1cm} (5.45)

Differentiation of (5.45) gives

\[ \dot{V} = -\dot{\theta}^T K_p \dot{\theta} - \hat{\theta}^T K_p \hat{\theta} + \hat{\Theta}^T (\Gamma \dot{\Theta} + Y_{BF} e^T) \]  \hspace{1cm} (5.46)
where $\hat{\Theta} = \hat{\Theta}$. Substituting (5.44) into (5.46) yields

$$\dot{V} = -\tilde{\theta}^T K_p \tilde{\theta} - \dot{\tilde{\theta}}^T K_p \dot{\tilde{\theta}}$$  (5.47)

$$\dot{V} = -e^T Q e \leq 0$$  (5.48)

where $e = \begin{bmatrix} \dot{\tilde{\theta}} \\ \tilde{\theta} \end{bmatrix}$ and $Q = \begin{bmatrix} K_p & 0 \\ 0 & K_p \end{bmatrix}$.

Equation (5.48) shows that the closed-loop system is stable in the sense of Lyapunov. By applying Barbalat’s Lemma and assuming $f : R \mapsto R$ is a square integrable function and that its derivative $\dot{f}$ is bounded, then, $f(t) \to 0$ as $t \to \infty$. A function $f(x)$ is square integrable if $\int_{-\infty}^{\infty} |f(x)|^2 < \infty$. This means the tracking error of the closed-loop system (5.41) converges to zero asymptotically, i.e., $\tilde{\theta} \to 0$ as $t \to \infty$. 
Chapter 6

Implementation

This chapter focuses on implementation approaches and scenarios that are introduced to evaluate the dissertation’s study. Section one displays the comparative studies of static self-leveling of the landing platform. Section two presents the performance of Argo J5 on different terrains. Section three shows the dynamic self-leveling of Argo J5 with the custom-built landing platform by using PBAC. Section four demonstrates the dynamic self-leveling of Argo J5 with the custom-built landing platform by using NNBAC. Section five illustrates the tire deflation effect on dynamic self-leveling using NNBAC. The obtained results are mentioned in sequence throughout this chapter.

6.1 Comparative Studies of Static Self-leveling

The results obtained for different types of controllers show the landing platform error angle moving from $5^\circ$, $10^\circ$, $15^\circ$, and $20^\circ$ to $0^\circ$ to keep the platform self-leveled and present the linear velocity of the linear actuator. The controllers are designed
according to (5.1), (5.2), (5.8), (5.14), and (5.30). The physical parameters of the landing platform are shown in Table 6.1.

The desired level angle and velocity for the landing platform are $\theta_d = 0^\circ$ and $\dot{\theta}_d = 0$ m/s. The initial simulation conditions for the landing platform leveling are $\theta(0) = [5 - 20]^\circ$ and $\dot{\theta}(0) = 0$ m/s.

Simulations were done using Matlab Simulink and an m-file with an integral step of $dt = 0.001$ sec. The optimized parameters for the controllers are chosen by the Matlab toolbox. Other design parameters, e.g., $Q$, $R$, $K_B$, and $\Lambda$, are tuned to their best values to illustrate the leveling process accuracy, as shown in Table 6.2. 

The comparative study is presented in Table 6.3. This table clarifies the stability validation, settling time, and the steady-state error of each controller. Figs. 7.1, 7.2, 7.3, and 7.4 present the leveling angle error of the landing platform for the controllers to evaluate the controllers’ performance. Figs. 7.5, 7.6, 7.7, and 7.8 show the linear velocities of the linear actuator that correspond to the controllers during the leveling process. The landing platform’s response to the PID controller has an overshoot, which means this controller requires more time to force the landing platform’s response to follow the desired response, as shown in Figs. 7.1, 7.2, 7.3, and 7.4. This illustrates that the I-component could not compensate for the nonlinearity of the landing platform and forces the response to behave as the desired response. However, the system response to the PD controller does not have the overshoot so this controller is faster than PID, as shown in Figs. 7.1, 7.2, 7.3, and 7.4. The stability of the system for the LQR and feedback linearization is asymptotically stable, which can be proved by applying Lyapunov’s first method, which is applicable for linear systems. The results of feedback linearization show the smoothest performance for the landing platform due to the controller, as shown in Figs. 7.1-7.8.
However, these results needed more time to yield the desired response. The main reason of the slower response is that the controller is designed for a linear system. For the PBAC, Figs. 7.1-7.8, this method shows the faster response that is provided for the leveling process.

Also, to evaluate the controller performance under external disturbances, 100 N.m is added to the landing platform over time intervals of 5 sec, [0,5] sec and [5,10] sec, respectively. Fig. 7.9 shows the leveling error of the landing platform when moving from $5^\circ$ to $0^\circ$ with disturbance effect for the first time interval. Fig. 7.10 shows the leveling error of the landing platform when moving from $5^\circ$ to $0^\circ$ with disturbance effect for the second time interval. This illustrates that the PBA and LQR controllers are suitable for leveling. Fig. 7.11 presents the velocity of the linear actuator under external disturbance for the first time interval. Fig. 7.12 presents the velocity of the linear actuator under external disturbance for the second time interval. Table 6.4 shows the landing platform self-leveling performance under external disturbance values [100,500] N.m.

The previous results show that PBAC is applicable for the fast settling time to the landing platform self-level and suitable for the external disturbances; therefore, PBAC is applied for static self-level in the two dimensions (along x and y directions). Figs. 7.13-7.16 present the leveling error of the landing platform along the x and y-axes under external disturbance 100 N.m over a time interval of 5 sec [0,5] sec for different initial conditions.

<table>
<thead>
<tr>
<th>$L_Z$ (m)</th>
<th>$L_C$ (m)</th>
<th>$L_a$ (m)</th>
<th>$L_L$ (m)</th>
<th>$m_L$ (kg)</th>
<th>$m_C$ (kg)</th>
<th>$m_m$ (kg)</th>
<th>$B$ (-)</th>
<th>$B_m$ (-)</th>
<th>$v_L$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.65</td>
<td>0.175</td>
<td>0.71</td>
<td>0.35</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>0.03</td>
<td>0.0105</td>
<td>0.022</td>
</tr>
</tbody>
</table>

Table 6.1: Physical parameters of the landing platform.
Table 6.2: Controllers parameters values.

<table>
<thead>
<tr>
<th>Controllers types</th>
<th>PD</th>
<th>PID</th>
<th>LQR</th>
<th>Feedback linearization</th>
<th>PBA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters values</td>
<td>$K_p = 300$, $K_d = 100$</td>
<td>$K_p = 400$, $K_i = 200$, $K_d = 100$</td>
<td>$Q=1$, $R=0.001$</td>
<td>$Q=10$, $R=0.1$</td>
<td>$T = 0.08$, $K_g = 1000$, $A = 20$</td>
</tr>
</tbody>
</table>

Table 6.3: Comparative and analytical study: the controller results that are obtained during the process of leveling.

<table>
<thead>
<tr>
<th>Control Method</th>
<th>Stability</th>
<th>Settling Time (sec)</th>
<th>Steady-State Error (deg)</th>
<th>Leveling Angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PD</td>
<td>Valid</td>
<td>2.5</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Optimized PID</td>
<td>Valid</td>
<td>13</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>LQR</td>
<td>Valid</td>
<td>2.8</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Feedback Linearization</td>
<td>Valid</td>
<td>7</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>PBA Controller</td>
<td>Valid</td>
<td>2</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>PD</td>
<td>Valid</td>
<td>3.65</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Optimized PID</td>
<td>Valid</td>
<td>16</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>LQR</td>
<td>Valid</td>
<td>3.7</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Feedback Linearization</td>
<td>Valid</td>
<td>16</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>PBA Controller</td>
<td>Valid</td>
<td>3.5</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>PD</td>
<td>Valid</td>
<td>5.8</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>Optimized PID</td>
<td>Valid</td>
<td>20</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>LQR</td>
<td>Valid</td>
<td>6</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>Feedback Linearization</td>
<td>Valid</td>
<td>20</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>PBA Controller</td>
<td>Valid</td>
<td>5</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>PD</td>
<td>Valid</td>
<td>7.3</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>Optimized PID</td>
<td>Valid</td>
<td>20</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>LQR</td>
<td>Valid</td>
<td>7.5</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>Feedback Linearization</td>
<td>Valid</td>
<td>28</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>PBA Controller</td>
<td>Valid</td>
<td>6.5</td>
<td>0</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 6.4: Comparative and analytical study: the controller results that are obtained during the process of leveling with disturbance.

<table>
<thead>
<tr>
<th>Control Method</th>
<th>PD</th>
<th>Optimized PID</th>
<th>LQR</th>
<th>Feedback Linearization</th>
<th>PBA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leveling Process</td>
<td>Not Valid</td>
<td>Not Valid</td>
<td>Valid</td>
<td>Not Valid</td>
<td>Valid</td>
</tr>
</tbody>
</table>
6.2 Argo J5 Performance

Implementation and simulation are obtained in a Matlab environment in three steps. The first step is trajectory tracking of the UGV Argo J5 using a PD controller. $K_p$ and $K_d$ are tuned manually. This step provides the velocity of Argo J5 that considers the initial values of the numerical algorithm [19], see Fig. 6.1, that will couple the Argo J5 model with the wheel-terrain interaction model. The second step is the numerical calculation to find $\theta_{1i}$. Finally, in the third step the dynamic model of the wheel-terrain interaction is combined with the vehicle’s model of Argo J5. The terrain parameters are provided by [71], as shown in Table 6.5. The UGV Argo J5’s physical parameters are shown in Table 6.6. The scenario that is used to obtain the simulation results entails that Argo J5 moves forward then, after 3 sec, turns right, which is the first scenario. Fig. 7.17 shows Argo J5’s left and right wheel speeds when Argo J5 follows the desired trajectory. Fig. 7.18 presents the velocities of the COM of Argo J5 as it moves on different terrain. Also, Figs. 7.19 and 7.20 illustrate the rolling resistance (4.70) and the turning moment resistance (4.74) of the wheel of Argo J5. Fig. 7.21 demonstrates the relationship of the shear stress (4.62) and the contact angle for different kinds of terrain. The second scenario is that Argo J5 moves forward then, after 3 sec, turns right then, after 4.5 sec, returns. The obtained results are as shown in Figs. 7.22-7.25.

Table 6.5: Different terrain’s parameters.

<table>
<thead>
<tr>
<th>Terrain’s Type</th>
<th>$c$ (kPa)</th>
<th>$\phi_f$ (deg)</th>
<th>$k_c$ (kN/m$^{n+1}$)</th>
<th>$k_{\phi}$ (kN/m$^{n+2}$)</th>
<th>n</th>
<th>K (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry sand</td>
<td>1.04</td>
<td>28</td>
<td>0.99</td>
<td>1528.43</td>
<td>1.1</td>
<td>0.01</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>1.72</td>
<td>29</td>
<td>5.27</td>
<td>1515.04</td>
<td>0.7</td>
<td>0.025</td>
</tr>
<tr>
<td>Clayed soil</td>
<td>4.14</td>
<td>13</td>
<td>13.19</td>
<td>692.15</td>
<td>0.5</td>
<td>0.006</td>
</tr>
<tr>
<td>Dry clay</td>
<td>68.95</td>
<td>34</td>
<td>34</td>
<td>1555.95</td>
<td>0.13</td>
<td>0.006</td>
</tr>
</tbody>
</table>
Table 6.6: Argo J5’s physical parameters.

<table>
<thead>
<tr>
<th>$m$ (Kg)</th>
<th>$r$ (m)</th>
<th>$b_{bw}$ (Nms)</th>
<th>$a$ (m)</th>
<th>$B$ (m)</th>
<th>$h$ (m)</th>
<th>$J_w$ (Kgm$^2$)</th>
<th>$J_m$ (Kgm$^2$)</th>
<th>$b$ (m)</th>
<th>$C_{r1}$ (m/s$^2$)</th>
<th>$C_{r2}$ (1/s)</th>
<th>$m_{lp}$ (Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>590</td>
<td>0.3148</td>
<td>0.04</td>
<td>1.194</td>
<td>0.9</td>
<td>0.59</td>
<td>0.34</td>
<td>0.07</td>
<td>0.235</td>
<td>0.1</td>
<td>0.08</td>
<td>36</td>
</tr>
</tbody>
</table>

Figure 6.1: Flow chart for the entry angle
6.3 Dynamic Self-leveling Using PBAC

The UGV Argo J5’s physical parameters are shown in Table 6.7. The physical parameters of the custom-built landing platform are shown in Table 6.8. The first three chosen desired slope angle ranges for the Argo J5 trajectory tracking are

\[ \theta_w(t) = 5 \sin \frac{t}{36} \]  
(6.1)

\[ \theta_w(t) = 10 \sin \frac{t}{36} \]  
(6.2)

and

\[ \theta_w(t) = 15 \sin \frac{t}{36} \]  
(6.3)

which provide different level angles, respectively, between \([-5^\circ, 5^\circ]\), \([-10^\circ, 10^\circ]\), and \([-15^\circ, 15^\circ]\). The controller is designed according to (5.30). The applied scenario requires that the Argo J5 moves forward on three different terrains that have \(-5^\circ\) to \(5^\circ\), \(-10^\circ\) to \(10^\circ\), and \(-15^\circ\) to \(15^\circ\) slope angles. The positions and velocities boundaries/constraints of the landing platform (4.47) and Argo J5 are \([-25, 15]^\circ\), \([-0.022, 0.022]\) m/s, and \([-360, 360]^\circ\), \([-5, 5]\) m/s, respectively. Two separate studies are conducted.

The first study is trajectory tracking of the UGV Argo J5 with different initial level angles for dynamic self-leveling of the landing platform using a PBAC. The initial level angles are \(-20^\circ\), \(-15^\circ\), \(-10^\circ\), \(-5^\circ\), \(0^\circ\), \(5^\circ\), and \(10^\circ\). The obtained results that show the performance of the controller during the leveling process are leveling error of the landing platform, velocity of the landing platform, trajectory tracking error of the Argo J5, and the velocity of the Argo J5. The controller re-
quires 0-35 sec to achieve the desired level depending on the initial level angle value. Basically, as the initial level angle has a larger value, the leveling process of the landing platform needs more time to be achieved and vice versa. The trajectory tracking results are important to ensure that the leveling process is achieved in the same desired ground slope angle. The small error of the trajectory tracking proves this fact. The results of the velocity of the linear actuator demonstrate the actual performance of the linear actuator during the leveling process. Also, the velocity of the Argo J5 is a crucial factor that directly affects the dynamic self-leveling process and stability of the controller; therefore, in the high speed scenario, the leveling process fails due to this physical limitation. Figs. 7.26, 7.27, and 7.28 show the leveling angles error of the landing platform and demonstrate that the self-leveling is achieved by obtaining approximately $0^\circ$ level angle error. Figs. 7.29, 7.30, and 7.31 present the velocity of the linear actuator of the landing platform during dynamic self-leveling and represent the actual value of the linear actuator’s velocity during the leveling process. Figs. 7.32, 7.33, and 7.34 show the trajectory tracking error of Argo J5 while the dynamic leveling process is implemented. The trajectory tracking error value should be around $0^\circ$ to guarantee the success of the dynamic self-leveling process. This means when the trajectory tracking error has a big value, the leveling process fails. Figs. 7.35, 7.36, and 7.37 present the velocity of Argo J5 to evaluate the performance of the Argo J5 during the leveling process. Also, the goal is to find the maximum speed of the Argo J5 that can achieve the dynamic leveling process.

The second study is the trajectory tracking of the Argo J5, with different initial velocities for dynamic self-leveling of the landing platform using a PBAC with $0^\circ$ initial level angle, and its goal is to find the maximum speed of the Argo J5
to achieve the desired level angle. The initial velocities’ values are 1 m/s, 2 m/s, 3 m/s, 4 m/s, and 5 m/s. (6.1) is applied as a trajectory tracking for the Argo J5 to achieve the level in the second study. Fig. 7.38 shows the error leveling angles of the landing platform, which is successfully achieved. Fig. 7.39 presents the velocity of the linear actuator of the landing platform during dynamic self-leveling. Fig. 7.40 shows the trajectory tracking error of Argo J5. Fig. 7.41 presents the velocity of Argo J5 where the first 2 sec and the last 2 sec of this figure are shown in Figs. 7.42 and 7.43, respectively. Also, the simulation is repeated for the same initial velocities of the Argo J5, while keeping the initial values constant during the simulation, as shown in Fig. 7.44. Fig. 7.45 shows the leveling angles error of the landing platform, which fails. Fig. 7.46 presents the velocity of the linear actuator of the landing platform during dynamic self-leveling. Fig. 7.47 shows the trajectory tracking error of Argo J5. The results prove that the dynamic self-leveling will not be applicable for this design with constant velocities of Argo J5 because of the difference between the actuator velocity and the Argo J5 velocity, which is a physical limitation. Thus, the linear actuator needs to be changed to achieve the dynamic self-leveling process.

The controller during the second part of the process with the constant velocities is unstable, causing the leveling process to fail, as shown in Figs. 7.46 and 7.47. To further justify the approach, a fourth trajectory is chosen as

$$\theta_w(t) = 0.5 \sin \frac{t}{36}$$  \hspace{1cm} (6.4)

which provides different level angles between $[-0.5^\circ, 0.5^\circ]$ to repeat the second study. Fig. 7.48 shows the leveling error of landing platform. Fig 7.49 presents the
velocity of the linear actuator. Fig 7.50 shows the trajectory tracking error of the Argo J5.

In general, the results prove that the velocity of Argo J5 should be less than the velocity of the linear actuator. However, for any velocity, Argo J5 can achieve the dynamic self-leveling of the landing platform on the ground that has a small slope angle.

Simulations were done using Matlab, an m-file with an integral step of $dt = 0.001$ sec. The design parameters $\Gamma$, $K_B$, and $\Lambda$, are tuned to their best values to illustrate the leveling process accuracy, as shown in Table 6.9.

Table 6.7: Argo J5’s physical parameters.

<table>
<thead>
<tr>
<th>$m$ (Kg)</th>
<th>$r$ (m)</th>
<th>$b_w$ (Nms)</th>
<th>$J_w$ (Kgm$^2$)</th>
<th>$J_m$ (Kgm$^2$)</th>
<th>$b$ (m)</th>
<th>$C_{r1}$ (m/s$^2$)</th>
<th>$C_{r2}$ (1/s)</th>
<th>$m_{lp}$ (Kg)</th>
<th>$G_r$ (.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>590</td>
<td>0.3148</td>
<td>0.04</td>
<td>0.34</td>
<td>0.07</td>
<td>0.235</td>
<td>0.1</td>
<td>0.08</td>
<td>36</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Table 6.8: Physical parameters of the landing platform.

<table>
<thead>
<tr>
<th>$L_Z$ (m)</th>
<th>$L_C$ (m)</th>
<th>$L_a$ (m)</th>
<th>$L_L$ (m)</th>
<th>$m_L$ (kg)</th>
<th>$m_C$ (kg)</th>
<th>$m_m$ (kg)</th>
<th>$B$ (-)</th>
<th>$B_m$ (-)</th>
<th>$v_L$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.65</td>
<td>0.175</td>
<td>0.71</td>
<td>0.35</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>0.03</td>
<td>0.0105</td>
<td>0.022</td>
</tr>
</tbody>
</table>

Table 6.9: Controllers parameters values.

<table>
<thead>
<tr>
<th>$\Gamma$</th>
<th>$K_B$</th>
<th>$\Lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>8000</td>
<td>6</td>
</tr>
</tbody>
</table>
6.4 Dynamic Self-leveling Using NNBAC

The UGV Argo J5’s physical parameters are shown in Table 6.7. The physical parameters of the custom-built landing platform are shown in Table 6.8. The chosen desired ground slope angle range for the Argo J5 trajectory tracking is (6.3) which provides different level angles between $[-15^\circ, 15^\circ]$. The controller is designed according to (5.42). The applied scenario requires that the Argo J5 moves forward on the terrain that has $-15^\circ$ to $15^\circ$ slope angles. The positions and velocities boundaries of the landing platform and Argo J5 are $[-25, 15]^\circ$, $[-0.022, 0.022]m/s$, and $[-360, 360]^\circ$, $[-5, 5]m/s$, respectively. The centers and widths of the basis functions are regularly distributed within the boundaries. For four input variables, 10 basis functions are required to approximate the nonlinear function (5.41) according to the design. Two separate studies are conducted.

The first study is trajectory tracking of the UGV Argo J5 with different initial level angles for the error $0^\circ$ of the landing platform dynamic self-leveling using the NNBAC. The initial level angles are $-20^\circ$, $-15^\circ$, $-10^\circ$, $-5^\circ$, $0^\circ$, $5^\circ$, and $10^\circ$. The obtained results are leveling error of the landing platform, velocity of the landing platform, trajectory tracking error of the Argo J5, and the velocity of the Argo J5 that show performance of the controller during the leveling process. The controller requires 0-36 sec to achieve the desired level depending on the initial level angle value. Fig. 7.51 shows the leveling angles error of the landing platform and demonstrates that the self-leveling is achieved by obtaining approximately $0^\circ$ level angle error. Fig. 7.52 presents the velocity of the linear actuator of the landing platform during dynamic self-leveling and represents the actual value of the linear actuator’s velocity during the leveling process. Fig. 7.53 shows the trajectory tracking error of
the Argo J5 while the dynamic leveling process is implemented. Fig. 7.54 presents the velocity of the Argo J5 to evaluate the performance of the Argo J5 during the leveling process. Also, the goal is to find the maximum speed of the Argo J5 that can achieve the dynamic leveling process.

The second study is obtained by increasing the velocity of the Argo J5 until the leveling error is within $1^\circ$ of the horizon. The initial level angle is $10^\circ$ for the same slope level angle as above. Fig. 7.55 shows the leveling error angles of the landing platform, which is successfully achieved. Fig. 7.56 presents the velocity of the linear actuator of the landing platform during dynamic self-leveling. Fig. 7.57 shows the trajectory tracking error of the Argo J5. Fig. 7.58 presents the velocity of the Argo J5.

For initial condition $0^\circ$ level angle, Fig. 7.59 shows the leveling error angles of the landing platform, which is achieved within $1^\circ$ of the horizon. Fig. 7.60 presents the velocity of the linear actuator of the landing platform during dynamic self-leveling, which is still $0.022$ m/s. Fig. 7.61 shows the trajectory tracking error of the Argo J5. Fig. 7.62 presents the maximum velocity of the Argo J5 that can achieve the dynamic self-leveling, which is $0.5$ m/s.

Table 6.10 demonstrates the required velocity of the linear actuator that can be accompanied with the assumed velocity of the Argo J5 to verify the dynamic self-leveling.

In general, the results confirm the same conclusion in the previous section that is obtained by the PBAC.

Simulations were done using Matlab, an m-file with an integral step of $dt = 0.001$ sec. The design parameters $\Gamma$ and $K_p$ are tuned to their best values to illustrate the leveling process accuracy, as shown in Table 6.11.

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Table 6.10: Linear actuator velocities for different Argo J5 velocities.

<table>
<thead>
<tr>
<th>Argo J5 velocity (m/s)</th>
<th>Linear actuator velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.225</td>
</tr>
<tr>
<td>2</td>
<td>1.6</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>2.39</td>
</tr>
<tr>
<td>5</td>
<td>3.162</td>
</tr>
</tbody>
</table>

Table 6.11: Controllers parameters values.

<table>
<thead>
<tr>
<th>$\Gamma$</th>
<th>$K_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>350</td>
</tr>
</tbody>
</table>

Table 6.12 summarizes the controller types that are used for different applications and implementations of the Argo J5.

Table 6.12: Controllers applications.

<table>
<thead>
<tr>
<th>Controller</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>PD, PID, LQR, feedback linearization, and PBAC</td>
<td>Static self-leveling with and without external disturbances</td>
</tr>
<tr>
<td>PD</td>
<td>Argo J5 trajectory tracking</td>
</tr>
<tr>
<td>PBAC and NNBAC</td>
<td>Dynamic self-leveling</td>
</tr>
</tbody>
</table>
6.5 Tire Deflation Effect on Dynamic Self-leveling Using NNBAC

The UGV Argo J5’s physical parameters and the physical parameters of the custom-built landing platform are shown in Table 6.8 and Table 6.7, respectively. The chosen desired ground slope angle range for the Argo J5 trajectory tracking is (6.3) and the controller derives according to (5.42). The applied scenario requires that the Argo J5 moves forward on the terrain that has $-15^\circ$ to $15^\circ$ slope angles with each tire having an identical hole. The positions and velocities boundaries of the landing platform and Argo J5 were shown previously. The obtained results are Fig. 7.63-Fig. 7.66. The conclusion is the tire deflation and the temperature of the surroundings do not affect the dynamic self-leveling process along the x and y directions because of the suspension system that the Argo J5 has. The suspension system can compensate for slope level angles of the terrain more than the provided level angle of the landing platform as expected. Therefore, the tire deflation and the temperature of the surroundings mainly affect the performance of the Argo J5 only. Table 6.13 shows the air parameters values that are used in the simulation.

Table 6.13: Air parameters values [138].

<table>
<thead>
<tr>
<th>R</th>
<th>T</th>
<th>$M_a$</th>
<th>$A_h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$8.31 \ J/mol.K$</td>
<td>$10^\circ C$</td>
<td>0.02896 $kg/mol$</td>
<td>1 $mm^2$</td>
</tr>
</tbody>
</table>
Chapter 7

Results

In this chapter, the preliminary results that are obtained through the simulation are shown. The first section shows the results for static self-leveling of the landing platform. The second section displays results of the Argo J5 performance. The third section presents the results of dynamic self-leveling of the whole robot by using PBAC. The fourth section demonstrates the results of dynamic self-leveling of the whole robot by using NNBAC. The fifth section illustrates the results of tire deflation on dynamic self-leveling using NNBAC. All results, all controller gain values, scenarios, and physical parameters are explained in detail in the previous chapter.

7.1 Static Self-leveling

The results of static self-leveling of the landing platform, as mentioned in the previous chapter, are shown in Figs. 7.1-7.16.
Figure 7.1: Leveling error of the landing platform when moving from $5^\circ$ to $0^\circ$.

Figure 7.2: Leveling error of the landing platform when moving from $10^\circ$ to $0^\circ$.
Figure 7.3: Leveling error of the landing platform when moving from $15^\circ$ to $0^\circ$.

Figure 7.4: Leveling error of the landing platform when moving from $20^\circ$ to $0^\circ$. 

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Figure 7.5: Linear actuator velocity when starting at 5°.

Figure 7.6: Linear actuator velocity when starting at 10°.
Figure 7.7: Linear actuator velocity when starting at 15°.

Figure 7.8: Linear actuator velocity when starting at 20°.
Figure 7.9: Leveling error of the landing platform when moving from 5° to 0° with disturbance.

Figure 7.10: Leveling error of the landing platform when moving from 5° to 0° with disturbance.
Figure 7.11: Linear actuator velocity when starting at 5° with disturbance.

Figure 7.12: Linear actuator velocity when starting at 5° with disturbance.
Figure 7.13: Two-dimension leveling error under the external disturbance.

Figure 7.14: Two-dimension leveling error under the external disturbance.
Figure 7.15: Two-dimension leveling error under the external disturbance.

Figure 7.16: Two-dimension leveling error under the external disturbance.
7.2 Argo J5 Performance

The results of Argo J5 for a trajectory tracking in different terrains, as mentioned in the previous chapter, are shown in Figs. 7.17-7.25.

![Figure 7.17: Argo J5’s wheel velocities.](image)

Figure 7.17: Argo J5’s wheel velocities.
Figure 7.18: Argo J5’s velocities on different terrains.

Figure 7.19: Argo J5’s wheel rolling resistance.
Figure 7.20: Argo J5’s wheel turning moment resistance.

Figure 7.21: Shear stress with contact angle of Argo J5’s first wheel.
Figure 7.22: Argo J5’s wheel velocities.

Figure 7.23: Argo J5’s velocities on different terrains.
Figure 7.24: Argo J5’s wheel rolling resistance.

Figure 7.25: Argo J5’s wheel turning moment resistance.
7.3 Dynamic Self-leveling Using PBAC

The results of dynamic self-leveling of Argo J5 with the custom-built landing platform using PBAC, as mentioned in the previous chapter, are shown in Figs. 7.26-7.50.

Figure 7.26: Leveling error of the landing platform of the first trajectory for different initial angles.
Figure 7.27: Leveling error of the landing platform of the second trajectory for different initial angles.

Figure 7.28: Leveling error of the landing platform of the third trajectory for different initial angles.
Figure 7.29: Linear actuator velocity of the first trajectory for different initial angles.

Figure 7.30: Linear actuator velocity of the second trajectory for different initial angles.
Figure 7.31: Linear actuator velocity of the third trajectory for different initial angles.

Figure 7.32: Trajectory tracking error of the Argo J5 of the first trajectory for different initial angles.
Figure 7.33: Trajectory tracking error of the Argo J5 of the second trajectory for different initial angles.

Figure 7.34: Trajectory tracking error of the Argo J5 of the third trajectory for different initial angles.
Figure 7.35: Argo J5 velocity of the first trajectory for different initial angles.

Figure 7.36: Argo J5 velocity of the second trajectory for different initial angles.
Figure 7.37: Argo J5 velocity of the third trajectory for different initial angles.

Figure 7.38: Leveling error of the landing platform for different initial velocities of the Argo J5.
Figure 7.39: Linear actuator velocity of the landing platform for different initial velocities of the Argo J5.

Figure 7.40: Trajectory tracking error for different initial velocities of the Argo J5.
Figure 7.41: Argo J5 initial velocities.

Figure 7.42: Argo J5 initial velocities for the first 2 sec.
Figure 7.43: Argo J5 initial velocities for the last 2 sec.

Figure 7.44: Argo J5 velocity.
Figure 7.45: Leveling error of the landing platform for different velocities of the Argo J5.

Figure 7.46: Linear actuator velocity of the landing platform for different velocities of the Argo J5.
Figure 7.47: Trajectory tracking error for different velocities of the Argo J5.

Figure 7.48: Leveling error of the landing platform for different velocities of the Argo J5.
Figure 7.49: Linear actuator velocity of the landing platform for different velocities of the Argo J5.

Figure 7.50: Trajectory tracking error for different velocities of the Argo J5.
7.4 Dynamic Self-leveling Using NNBAC

The results of dynamic self-leveling of Argo J5 with the custom-built landing platform using NNBAC, as mentioned in the previous chapter, are shown in Figs. 7.51-7.62.

Figure 7.51: Leveling error of the landing platform for different initial angles.
Figure 7.52: Linear actuator velocity for different initial angles.

Figure 7.53: Trajectory tracking error of the Argo J5 for different initial angles.
Figure 7.54: Argo J5 velocity for different initial angles.

Figure 7.55: Leveling error of the landing platform.
Figure 7.56: Linear actuator velocity.

Figure 7.57: Trajectory tracking error of the Argo J5.
Figure 7.58: Argo J5 velocity.

Figure 7.59: Leveling error of the landing platform.
Figure 7.60: Linear actuator velocity.

Figure 7.61: Trajectory tracking error of the Argo J5.
The results of tire deflation effect on dynamic self-leveling using NNBAC, as mentioned in the previous chapter, are shown in Figs. 7.63-7.66.
Figure 7.63: Leveling error of the landing platform.

Figure 7.64: Linear actuator velocity.
Figure 7.65: Trajectory tracking error of the Argo J5.

Figure 7.66: Argo J5 velocity.
Chapter 8

Conclusions & Future Works

In this chapter, the conclusions of the dissertation are summarized in the first section. Then, the future works of the dissertation are presented in the next section.

8.1 Conclusions

In this research work, several issues have primarily addressed:

1. Analytical dynamic model of Argo J5 and the landing platform are derived in detail to achieve motion control behavior on uncertain terrain with dynamic self-leveling to be a safe spot for launching and recovering a small drone, respectively. First of all, the dynamic model of the landing platform is derived. The second step is a dynamic model of Argo J5 that is derived by using Euler-Lagrange formulation. Then, the driveline components and vehicle-terrain interaction are modeled together to compose the development model of Argo J5. Terramechanics theory is applied to identify the wheel model of Argo J5,
find the relationships of the shear stress, shear displacement, vertical wheels load, normal stress, reaction forces, and Argo J5 kinetics.

2. Navigation control for Argo J5 trajectory tracking tasks and leveling control, which are the basics in the application for the landing platform, should be parallel to the axis in 1 and 2 dimensions of the world frame. Different controller techniques are applied to find the fast self-leveling process and to deal with external disturbances on the landing platform.

3. Leveling of the landing platform is one of the applications that this dissertation tackles. Leveling relationships are derived by trigonometric functions that can make a relationship between terrain slope angle and the length of the linear actuator of the landing platform for the x and y axes.

4. Landing platform static and dynamic leveling preliminary results are added to verify the performance of the landing platform. The results emphasize that the landing platform design will not be able to perform the dynamic self-leveling with high speed of the mobile robot. The highest velocity of the Argo J5 that can implement the dynamic self-leveling with 1° of the horizon is 0.5 m/s.

5. Argo J5 preliminary results are added to evaluate the performance of Argo J5 on the different terrains.

6. Tire deflation model of the Argo J5 is derived to justify the deflation effect on the dynamic self-leveling. The preliminary results affirm that the tire deflation affects on the Argo J5 performance without any defect on the landing platform performance because of the suspension system.
8.2 Future Works

There are several steps to be executed throughout this paper research, which are

1. Implement the dynamic self-leveling with 0.5 m/s of the Argo J5 velocity.

2. Change the design of the landing platform with linear actuator that has a higher velocity as in Table 6.10.

3. Replace the landing platform by a machine gun and test it for military applications.
Bibliography


