International Journal of Engineering Research and Science & Technology
ISSN 2319-5991 www.ijerst.com
© 2026 IJERST. All Rights Reserved
Peer Reviewed, Referred & Indexed Journal

Research Paper

Design and Development of a Reconfigurable Multi-Mode Transformer Robot for Ground and Aerial Operations

J. Prakash Patil
M.Tech, LIMISTE, MIEEI
Assistant Professor
Department of Electronics and Communication Engineering
Vijay Rural Engineering College
Nizamabad, Telangana, India
sangeethaprakash2024@gmail.com

Goutha Swagath
Student
Department of Electronics and Communication Engineering
Vijay Rural Engineering College
Nizamabad, Telangana, India
gouthaswagath@gmail.com

Gattadi Abhinay
Student
Department of Electronics and Communication Engineering
Vijay Rural Engineering College
Nizamabad, Telangana, India
abhinaygattadi2006@gmail.com

Mohd. Faizan
Student
Department of Electronics and Communication Engineering
Vijay Rural Engineering College
Nizamabad, Telangana, India
fmohammedfaizan@gmail.com

Mohd. Arsalan Ali
Student
Department of Electronics and Communication Engineering
Vijay Rural Engineering College
Nizamabad, Telangana, India
mohdarsalanali12@gmail.com

Abstract— The TRANSFORMER-X combines the engineering design of a reconfigurable robotic platform, with the normal ground model, expanded ground model and aerial model. The final system level architecture comprises a set of requirements for mechanical reconfiguration, operator controlled transition between states, ground drive coordination, aerial stabilisation and safety checks based on orientation. It also co-ordinates a common supervisory control mechanism to stop motion, to verify the setup and to switch subsystems on. The design study is conducted based on kinematic, centre of gravity, thrust to weight and energy relations. The operator interface looks like a website, and allows you to choose operating modes, send control commands, check status and see the transformation. The paper describes the known architecture, interface design and requirements for formal verification. The hardware performance of mobility and experimental flight needs to be measured with instrumented prototypes and cannot be derived from the illustration of the interface.

"Index Terms— Reconfigurable robotics, ground–aerial robot, mechanical transformation, multirotor control, state machine, mobility adaptation."

I. INTRODUCTION

There are different capabilities of ground robots and aerial robots. Wheel platforms can be used on accessible surfaces with a relatively low propulsion requirement, but may be restricted on discontinuous surfaces and when obstructions are present. While requiring a continuous supply of thrust and the right operating space for hover flight, multirotor platforms can overcome selected challenges and gain higher observations. These are desirable characteristics of a robotic structure that they are able to achieve in an organized manner, with no harmful interactions between reconfiguration of the structure and active propulsion between the two.

TRANSFORMER-X solves a common platform and the possibilities of this platform are split into two main mobility modes and three functional configurations: compact normal-ground, expanded lateral-ground and airborne. The extended configuration is supposed to change the support geometry, without compromising stability or obstacle crossing capabilities, any improvement will depend on the actual size, load and interaction with the terrain. The airborne variant is only for use when the structure and the operation conditions are appropriate to flight.

A) Problem Definition

Associated needs of the coupling of terrestrial mobility and multirotor propulsion are actuator placement, mass distribution, mechanical retention, sensing, supervisory logic, and power allocation. One of the most critical, is configuration changeover, that is, the controller must make sure that there is no unwanted motion when parts are moving and mechanical readiness must be verified prior to drive or flight command.

B) Research Objectives

From a common structure, an operator controlled transformation and verification sequence, the mathematical representation of ground motion, centre of gravity, flight thrust and energy requirements, as well as repeatable criteria for the evaluation of the reliability of the transformation, ground navigation, stability and aerial endurance, three mobility configurations are determined based on the design of the system.

But the single mode cars have no operational trade-offs that a single platform has. The stability of the air is dependent on the thrust distribution, mass symmetry and rotor dynamics, while the traction on the ground is dependent on the

interaction between the surface and the wheel loading. The equipment that works well for one arrangement of the locomotor may not work for the next. The design approach should then take account of the effect of the structure, battery, actuators and electronic control system on both motion regimes, instead of optimizing them individually.

The supervisory design integrates mechanical motion with propulsion authorisations through operator selection of configurations. In this method, an event is determined as an intervention time when the mechanism fails to get to a certified state. The current design does not analyse the autonomous mode selection.

II. RELATED WORK

Feng and You [1] investigated a robot system that is capable of transforming between the land and the air domain in order to share some common mobility capabilities. Mandralis et al. [2] investigated an aerial morphobot that changes shape utilising near-ground aerodynamic effects and model predictive control. Guo and Guo [3] investigated flying, rolling and upright locomotion. Yu et al. [4] developed a quadrotor with variable wheeled-leg configuration. He et al. [5] studied the arm folding and shape adjustable wheels of a land–air robot. These results indicate that the group of ground aerial transformations is a research area and not a new locomotion category.

Research of reconfiguration strategy [6] is a study on the reconfiguration in the field of modular adaptation and planning of structural change. Terrain adaptable transformable-wheel [7] control requires a coupling between physical geometry and motion control. This overall robotic approach is described in the following classical literature on mobile robotics [8] and robot mechanics [9] as well as in robotics planning literature [10] and literature on multirotor control [11]–[16].

The key difference between structural transformation and normal mode switching is that the platform changes its physical dimensions. This makes a verification problem other than switching to a different motor controller. Once the final mechanism has been determined, the position of the moving components has to be deduced via appropriate limit switches, encoders or other feedback. Mechanical retention during vibration and varying load should be accommodated in the flight ready configuration.

A) Research Gap

The engineering contribution is not a prerequisite for the hybrid land–air robots, but the combination of three specific operation configurations in a single operator-supervised architecture. Mechanical converter linkage level of fabrication and detail of parts layout. Lateral support geometry and sequential changes to structure will be evaluated in the same manner as the standard verification process.

There are variations in published land-air designs with respect to platform mass, propulsion architecture, controller bandwidth, ambient situations and measures of successful transformation. The TRANSFORMER-X architecture therefore specifies particular configuration conditions, safety requirements and measurement conditions for the following reproducible comparison. It is mainly known for the coordinated architecture of normal ground, expanded ground and aerial operation.

Various system architecture related methods can be found in the control and robotics literature. The problem of inertial state estimation is solved by applying Kalman filtering and orientation fusion techniques [21] and [22]. Software architectures for robots and simulation tools can serve as implementation precedents [23]–[27]. There are formal explanations of trajectories and obstacle avoidance in the motion-planning literature [28]–[30]. These sources are used to inform the system design and they are not experimental observations to validate TRANSFORMER-X.

III. MATERIALS AND METHODS

A) Mechanical Configurations

The mechanical design comprises a 4-wheel normal ground configuration, a laterally extended ground configuration and an aerial configuration. The ground states facilitate surfaces navigation in different support geometry. Depending on the flying condition, the required secured structure, thrust and attitude-stabilization functions are established. The actual conversion linkage is a fabrication level specification, while the functional configuration is specified at subsystem level.

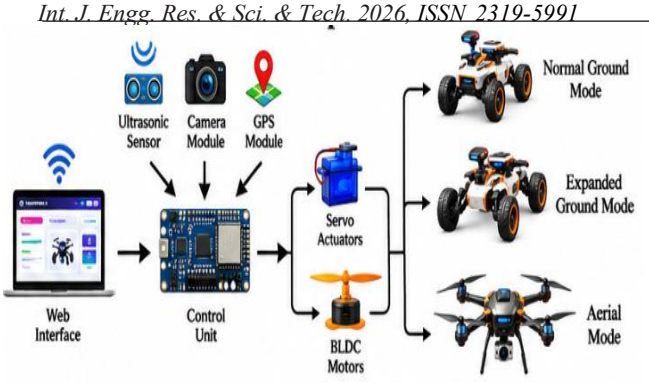
Activation criteria are different for each configuration. The ground movement is permitted with the appropriate ground construction secured. Flight configuration checks for validation and stabilisation of aerial propulsion. The supervisory sequence prevents incompatible motion states from being converted to the structure.

Both normal and enlarged ground configurations are ground mobility, but are viewed as independent mechanically verifiable states. This is significant since the structure may have its centre of gravity or wheel-contact geometry outside the operating condition if it is partially extended. The expansion mechanism must give an accurate signal of full expansion and the supervisor should not rely on only the elapsed time of the actuators for mechanical completion.

Constraints of propeller clearance, thrust, structural retention and mass distribution are imposed by aerial operation. Reconfiguration modifies the positions of moving parts, and can vary pitch and roll inertia. The architecture thus defines mechanical readiness and stabilisation check prior to engine ignition. It is a design of the system. Size at linkage and experimental airworthiness of components.

B) System Architecture

This functional architecture is capacitive to link supervisory control, mechanical transformation actuation, ground propulsion, aerial propulsion and stabilisation, and motion detection and safety feedback. The controller receives operator commands, manages configuration changes and grants access to the specific motion subsystem if appropriate. The defined system architecture is shown in figure 1.



"Fig. 1. Icon-based system architecture of TRANSFORMER-X."

Modular design decouples ground drive coordination, airborne control and mechanical transformation. This separation enables independent monitoring of subsystems and controlled interaction between operator requirements, mechanical state feedback and propulsion licenses. Safety conditions are not the optional interface operations, but rather they are built into the supervisory logic.

C) Supervisory State Transitions

The operational states are standby (S0), regular ground (S1), expanded ground (S2), transformation (S3), flight preparation (S4), flight (S5), landing (S6) and safety lock/fault (S7). An operator gives an instruction for changing the configuration. The controller shuts off the running locomotion subsystem, performs the allowed transformation, checks the structure and turns on the appropriate locomotion mode if it is verified.

The transition phase between ground and air involves stopping the wheels, reconfiguration of the structure, checking the configuration and stabilisation, and controlling the aerial propulsion. To perform a reverse transition, landing, propulsion shutdown and verification of stable support, as well as mechanical conversion and ground-drive enabling, are required. If there is any verification failure, then the motion is disabled and enters the safety state.

The state machine also specifies the behavior of the invalid commands. To prevent multiple simultaneous requests from the air canceling each other out, a request received while there is active ground drive should not override the stopping state. Also, a ground-drive request while in flight should be disabled. Likewise, when a signal is required for a transformation and is not received, then a progression to the next operating state should not be made. The above criteria can be met by declaratively provided state transition guards in addition to documented fault circumstances—rather than an unchecked sequence of operators.

Direct actuator enablement is deliberately separated from the operator. The user selected the configuration and the supervisory logic feedbacks determine if the transition is allowed and what actuator commands can be issued. This part allows for the assessment of the behaviour and offers a logical foundation for the subsequent incorporation of sensor-based mode selection. It can also be used to identify a command from a physically verified operating condition.

D) Mathematical Modelling

The first approximation is a mapping of the ground velocity to wheel radius and angular speeds, the differential drive approximation. It is only applicable to certain final drive and steering configuration:

$$\frac{r(\omega R + \omega L)}{2} \quad (1)$$

where: effective wheel radius r and ωR, ωL are angular speeds of right and left side. For the configuration, the centre of gravity will depend on the configuration, and will be written as: component mass and location:

$$\frac{\Sigma(mi\ xi)}{\Sigma mi} \quad (2)$$

xi is the coordinate along the axis considered and mi is the component of the mass along the axis considered. The remaining axes have equivalent phrases. The ratio of the impulse of the air flow to the weight of the rocket is

$$\frac{Ttotal}{m\ g} \quad (3)$$

Ttotal is the total available force and mg is the weight of platform. The total amount of electrical energy used over t with an average power consumption of P is

$$\frac{Ns}{Nt} \quad (4)$$

whereas Ns is the number of successful transformations, and Nt is the number of attempted transformations. The ratio calculated is the rate of successful change over. The average power, P, and the time, t, elapsed are used to calculate the electrical consumption, E = P × t, individually. All correlations are predictive, not reported test scores.

The ground equations are simplified for the final chassis that may be differential steering, skid steering, or other actuation architecture. If the geometric layout is modified, the kinematic model has to be revised to take into account the real wheel radius, track width and contact circumstances. Similarly, data showing the mass of each component and its centre of gravity must be used to calculate the centre of gravity for each state. These calculations are very important to determine whether there is any gain or loss in the support polygon due to structural expansion.

The thrust model is not a demonstration of flight readiness, it is a feasibility relation. The actual available thrust can vary according to the particular motor, propeller, supply voltage and the aerodynamic interaction between the motor and the surrounding system. Such effects must be demonstrated by bench measurements and controlled flight tests performed during mechanical deployment. The success ratio of the transition should be reported in conjunction with the number of attempts, testing conditions and definition of completion of the transition.

E) Experimental Verification Method

Verification is carried out by ground-motion testing, structural-transformation experiments and controlled aerial assessment. These defined measures are: speed, turning behaviour, configuration change time, mechanical alignment, successful transition frequency, take-off readiness, hover behaviour and energy use. These combine

to make up the test methodology; numerical results are only given when supported by instrumented testing.

There are different failure modes for each mode. Therefore, a development sequence is necessary. Without a ground chassis the flight propulsion can be studied first. The expansion system can be used repeatedly with a limited fixture and motion symmetry and lock measurements can be made. The aerial assembly should be verified after structure verification. This ordering enables the distinction of mechanical fault from human error in flight control, and enables systematic repair of the sub-system fault.

If any of the above problem states occurs, completion signal, elapsed transformation time, commanded configuration and initial configuration should be recorded in a consistent experimental log to allow for successful recovery by operator action for a successful transition. Surface and load should be determined by ground tests. The condition of the battery, total mass, surroundings and the set up for stabilisation must be given in aerial tests. These details might otherwise make it confusing to interpret and repeat measurements from different experiments.

IV. EXPERIMENTAL RESULTS

A) Web-Based Operator Interface Design

The frontend design features a home dashboard, a robot control panel, a screen to select operating modes and a visualisation of the transformation. Navigation and information hierarchy separates operator commands, current configuration, monitored parameters and transition states. The user interface of the website is shown in Figure 2. The images shown are the finished interface design requirements and are not hardware telemetry in and of themselves.



"Fig. 2. TRANSFORMER-X website-style operator interface design: home, controls, mode selection, and transformation visualization."

The mode selection screen offers standard ground, large ground and aerial modes. The fields for the equipment status are controlled by the control panel, which controls the directional controls. Changes in state are visualised in the transformation panel. The visual design elements are graphical representations of the state values of the interface, not data that are measured by the robot. All indications of an active state prior to use in operation shall be based on the controller's feedback as specified by the integration standard.

B) Functional Verification Framework

Architecture represents the tested acceptance criteria for the mode selection, configuration confirmation, locomotion enable signals and failure management. The needed verification tests are summarised in Table I. These criteria assess command handling and safety-state logic, and do not substitute for physical mobility tests.

"TABLE I. SYSTEM FUNCTIONAL VERIFICATION CRITERIA"

Function	Required verification
Mode selection	Selected state is registered by the controller
Transformation	Motion disabled until configuration is secured
Ground drive	Drive enabled only in verified ground state
Flight readiness	Stability and structural checks precede thrust
Fault response	Unsafe actuation inhibited upon failed check

If a fault check fails, the system will not move to a safe state.If a fault check fails, the system will not attempt to move to a safe state.

The verification protocol logs the commanded state, detected mechanical configuration, transition time elapsed and fault events. These data give a traceable basis for the analysis of system transformations. A visual status indication means nothing by itself, it does not prove mechanical lock, or flight readiness; a written verification using the proper sensors or physical checks must be used.

The design of the interface distinguishes between a selected mode, a confirmed active mode and a transition status. State changes are controlled by the supervisory controller: the status panel is set to show confirmed state feedback. Authorisation of a flight is not the same as the choice of a flight, and is dependent upon structural and stabilisation restrictions.

The interface definition contains fault reporting for partial movement of actuators and inconsistent feedback of state. The desired reaction is to correlate fault indication with controller safety interlocks and event logging. At the implementation level testing must show quantified interface delay, physical actuator responsiveness and communication dependability.

C) Performance Evaluation Criteria

The evaluation framework identifies: ground speed, steering response, obstacle traversal, lateral stability, transformation time, successful transition rate, flight duration, and hover variability and electrical energy requirement. The measuring basis for the related is shown in Table II. These features allow for controlled comparisons to be made while instrumented operating data are collected. No numerical performance improvement is made through the current architectural and interface.

"TABLE II. PERFORMANCE EVALUATION PARAMETERS"

Parameter	Measurement basis
Ground mobility	Distance, elapsed time, turning response
Stability	Tilt angle and support geometry
Transition reliability	Successful cycles / attempted cycles
Aerial endurance	Flight duration under defined load
Energy	Measured voltage, current and duration

The completed design consists of the operator-interface layout, mode-management logic, safety-state definitions, mathematical models and assessment criteria. The frontend illustrations are not any numerical ground or flying performance observations. So until measured test data support the performance claims, comparison plots and performance claims are not included.

The verification framework decouples correct safety inhibition from permissible operation. The desired controller behaviour is to not allow activation of propulsion in an unconfirmed mechanical state. This means test cases address errors in mode requests, conflicting sensor readings and aborted configuration changes.

The quantitative reporting should be in terms of number of trials and environmental conditions for each parameter. Comparisons of the ground traversal should be based on a constant payload and surface type between compact and extended variants. Transition time should start at a well defined command event and only end following confirmation of the desired state. Power consumption must be measured at the supply (not based on the nominal power ratings of the components). Multiple measurements would enable checking of variability and operating range.

Repeatability of the transformation is evaluated by the mechanical alignment, joint clearances, and the symmetry and mass distribution of the actuators on repeated cycles. The dependability assessment should include successful and unsuccessful transitions. Results from the obtained values are utilized to check whether the final mechanical assembly meets the specified operation conditions.

The control architecture features manual mode selection and supervisory control of the actuator commands. This results in a bounded operational specification of the three configurations. They are autonomous mode selection vs environmental perception. They require additional sensing and validation of the planning.

In order to have a good comparison, it is important to have the same lateral disturbance in both the normal and expanded geometry configurations. The experiment should note the payload, condition of the floor, initial estimation of the centre of gravity and the point at which the payload dropped off or a set angular limit is reached. This would directly assess the purported stability benefit. Bigger configuration might work well for a particular type of tipping resistance but may not be ideal for narrow routes, turning and mechanism weight. These are conflicting effects that need to be taken into account in interpreting the result.

Each one of the following has to be verified during flight tests: Static thrust, mass distribution, stabilising behaviour. Mechanical conversion system can affect the propeller slipstream or alter the body inertia. The orientation measurements would then be analysed as a function of the test conditions and active geometry. A safe experimental sequence will include checking the propulsion behaviour on a suitable confined fixture, before proceeding to controlled free-flight testing.

They are the controller state logs, timing of transitions, ground mobility measurements, flight evaluations, and electrical-energy records that are the verification deliverables. This document does not specify how physical tests are replaced by graphic status displays, but specifies the criteria for design and collection of these data.

V. CONCLUSION

The TRANSFORMER-X is a complete system level design for normal ground configurations, expanded ground designs and aerial robot designs. The design includes synced-up structural reconfiguration, propulsion control, orientation feedback and supervisory safety criteria. Mathematical description of important kinematic, mass-distribution, thrust and energy relationships. Operator interface like a website for selection and control of mode and visualisation of status. Functional verification standards have been developed for a controlled examination. Still to be validated with instrumentation to prove hardware performance, repeatability and flight qualification .

REFERENCES

[1] Y. Feng and Y. You, “Design and Modeling of a Novel Transformable Land/Air Robot,” International Journal of Aerospace Engineering, vol. 2019, Art. 2064131, 2019. doi:10.1155/2019/2064131.

[2] I. Mandralis, R. Nemovi, A. Ramezani, R. M. Murray, and M. Gharib, “ATMO: An aerially transforming morphobot for dynamic ground-aerial transition,” Communications Engineering, vol. 4, Art. 74, 2025. doi:10.1038/s44172-025-00413-6.

[3] Q. Guo and Z. Guo, “A Multimodal Agile Land-Air Aircraft (AlAA) That Can Fly, Roll, and Stand,” Journal of Field Robotics. doi:10.1002/rob.22491.

[4] S. Yu, B. Dong, K. Bai, and P. Chirarattananon, “A Hybrid Quadrotor With a Passively Reconfigurable Wheeled Leg Capable of Robust Terrestrial Maneuvers,” IEEE Robotics and Automation Letters, vol. 10, no. 4, pp. 3486–3493, 2025. doi:10.1109/LRA.2025.3544078.

[5] Z. He et al., “A Morphing Land–Air Robot with Adaptive Capabilities for Confined Environments,” Drones, vol. 10, no. 1, Art. 45, 2026. doi:10.3390/drones10010045.

[6] Y. Dai et al., “Research on Reconfiguration Strategies for Self-reconfiguring Modular Robots: A Review,” Journal of Intelligent & Robotic Systems, vol. 110, Art. 47, 2024. doi:10.1007/s10846-024-02067-6.

[7] "Synergistic Terrain-Adaptive Morphing and Trajectory Tracking in a Transformable-Wheeled Robot," IEEE Robotics and Automation Letters, vol. 10, no. 2, pp. 1656–1663, 2025. doi:10.1109/LRA.2024.3524876.
[8] R. Siegwart, I. R. Nourbakhsh, and D. Scaramuzza, Introduction to Autonomous Mobile Robots, 2nd ed. MIT Press, 2011.
[9] P. Corke, Robotics, Vision and Control: Fundamental Algorithms in MATLAB, 2nd ed. Springer, 2017.
[10] S. M. LaValle, Planning Algorithms. Cambridge University Press, 2006.
[11] R. Mahony, V. Kumar, and P. Corke, "Multirotor Aerial Vehicles: Modeling, Estimation, and Control of Quadrotor," IEEE Robotics & Automation Magazine, vol. 19, no. 3, pp. 20–32, 2012.
[12] R. W. Beard and T. W. McLain, Small Unmanned Aircraft: Theory and Practice. Princeton University Press, 2012.
[13] D. Mellinger and V. Kumar, "Minimum Snap Trajectory Generation and Control for Quadrotors," in Proc. IEEE ICRA, 2011, pp. 2520–2525.
[14] S. Bouabdallah and R. Siegwart, "Full control of a quadrotor," in Proc. IEEE/RSJ IROS, 2007, pp. 153–158.
[15] P. Pounds, R. Mahony, and P. Corke, "Modelling and control of a large quadrotor robot," Control Engineering Practice, vol. 18, no. 7, pp. 691–699, 2010.
[16] G. Hoffmann, H. Huang, S. Waslander, and C. Tomlin, "Quadrotor Helicopter Flight Dynamics and Control: Theory and Experiment," in Proc. AIAA Guidance, Navigation and Control Conference, 2007.
[17] B. Siciliano, L. Sciavicco, L. Villani, and G. Oriolo, Robotics: Modelling, Planning and Control. Springer, 2009.
[18] M. W. Spong, S. Hutchinson, and M. Vidyasagar, Robot Modeling and Control. Wiley, 2006.
[19] R. M. Murray, Z. Li, and S. S. Sastry, A Mathematical Introduction to Robotic Manipulation. CRC Press, 1994.
[20] H. Choset et al., Principles of Robot Motion: Theory, Algorithms, and Implementations. MIT Press, 2005.
[21] R. E. Kalman, "A New Approach to Linear Filtering and Prediction Problems," Journal of Basic Engineering, vol. 82, no. 1, pp. 35–45, 1960.
[22] A. M. Sabatini, "Quaternion-based extended Kalman filter for determining orientation by inertial and magnetic sensing," IEEE Transactions on Biomedical Engineering, vol. 53, no. 7, pp. 1346–1356, 2006.
[23] M. Quigley et al., "ROS: an open-source Robot Operating System," in ICRA Workshop on Open Source Software, 2009.
[24] S. Macenski, T. Foote, B. Gerkey, C. Lalancette, and W. Woodall, "Robot Operating System 2: Design, architecture, and uses in the wild," Science Robotics, vol. 7, no. 66, eabm6074, 2022.
[25] N. Koenig and A. Howard, "Design and use paradigms for Gazebo, an open-source multi-robot simulator," in Proc. IEEE/RSJ IROS, 2004, pp. 2149–2154.
[26] F. Furrer, M. Burri, M. Achtelik, and R. Siegwart, "RotorS—A Modular Gazebo MAV Simulator Framework," in Robot Operating System (ROS): The Complete Reference, vol. 1, Springer, 2016.
[27] L. Meier, D. Honegger, and M. Pollefeys, "PX4: A Node-Based Multithreaded Open Source Robotics Framework for Deeply Embedded Platforms," in Proc. IEEE ICRA, 2015, pp. 6235–6240.
[28] S. Karaman and E. Frazzoli, "Sampling-based algorithms for optimal motion planning," International Journal of Robotics Research, vol. 30, no. 7, pp. 846–894, 2011.
[29] S. M. LaValle and J. J. Kuffner, "Randomized Kinodynamic Planning," International Journal of Robotics Research, vol. 20, no. 5, pp. 378–400, 2001.
[30] P. Hart, N. Nilsson, and B. Raphael, "A Formal Basis for the Heuristic Determination of Minimum Cost Paths," IEEE Transactions on Systems Science and Cybernetics, vol. 4, no. 2, pp. 100–107, 1968.