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Environmental Perception and Intelligent Navigation for Autonomous Delivery Robots in Complex Scenarios

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Abstract. Autonomous delivery robots (ADRs) face perception and navigation challenges in complex scenarios. When operating in real world urban environments, ADRs have trouble negotiating upturned streets, uneven terrain, and moving obstacles. This review covers three key areas: environmental perception, navigation techniques, and mechanical adaptability of delivery vehicles. The reviewed studies show that navigation has evolved beyond avoiding obstacles, to its current state of considering whether the ground can be traversed. ADRs must be able to analyze the ground to navigate. The mechanical structure, suspension systems, and wheel ground contact of mobile robots affect traversability and the stability of onboard sensors. Based on the reviewed studies, perception, planning and control will need to be addressed in an integrated fashion in order to negotiate complex terrain. Future research should focus on a holistic framework of environmental perception, terrain assessment, and control of mechanical systems. Such a framework would help to answer whether a given delivery robot is capable.

Keywords: Autonomous delivery robots, environment perception, terrain-aware navigation, mechanical adaptability

1. Introduction

The last mile of logistics is becoming increasingly challenging with the subsequent growth in e-commerce and the need for fast deliveries. Last mile logistics gets even more complex due to the rapid growth of urbanization and corresponding cost increases for labor [1]. For these reasons, the transport of goods using devices that operate with little to no human involvement have become attractive solutions and have a high potential for development. Autonomous driving technology has been validated for use in the urban environment and also along the sidewalk.

Modern ADR platforms use a combination of sensors for mapping their environment and tracking their own motion in real time. The mainstream ADR uses a combination of Light Detection and Ranging (LiDAR) sensors, Global Navigation Satellite Systems (GNSS), Inertial Measurement Units (IMU), and wheel encoders. These sensors, in combination with other navigation algorithms, offer a capable ADR platform for both road and pedestrian local navigation. An example of an ADR that integrates these sensors is the Ona delivery robot, which uses two 3D LiDARs, three depth cameras, GNSS, IMU and wheel encoders [2].

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Although significant progress has been made, real-world challenges that come with delivery will continue to test the limits of the technology. Urban buildings can attenuate GNSS signals, while dynamic traffic, including both pedestrians and vehicles, creates moving obstacles, and curbs, slopes, and uneven terrain challenges the traditional binary obstacle versus free-space paradigm in mobile robot navigation [3]. In such a scenario, whether a path is traversable depends on how the robot perceives the local terrain, e.g., shape, inclination, and surface. For these reasons, several researchers have proposed mobile robot navigation systems that are aware of the terrain. For example, in their work, Kim et al. presented algorithms to predict modes, which allowed six-wheeled robot platforms to dynamically clear curbs, while Wang et al. introduced multi-axis gimbal stabilization to mitigate shaking of sensors over rough terrains to maintain SLAM accuracy in mobile robots [4, 5].

Despite the best perception algorithms made so far, the physical limitations of the robot's hardware also set perceptible limitations on the robot's navigation performance. The mechanical design of a robot creates fundamental limitations to the performance of navigation. Conventional rigid chassis with small wheels easily slip, tip over, and lose traction when a robot encounters challenging vertical obstacles in an urban environment. Unlike conventional designs, advanced chassis designs are made to improve overall contact with the ground and stability of the vehicle, and such designs incorporate multiple wheels, bogie mechanisms, active suspensions, and wheel-leg mechanisms.

Though there is a great deal of research on sensor fusion algorithms, SLAM, path and chassis design, currently, there are no synthesizing reviews of the different modules. Most of the current reviews cover either perception algorithms or vehicle mechanical design, which has resulted in ignorance of the interaction of different factors, such as the terrain, path planning, vehicle design, and the performance of the sensors.

The rest of this paper is organized as follows: Section 2 explores the progress in ADRS in the context of multi-sensor environmental perception, their gradual integration of positioning, path planning, and assessment of the terrain. Section 3 examines the integration of vehicle structure design along with dynamic performance and autonomous design in planning under complex terrains. Finally, it discusses the practical difficulties these robots face in real urban deployment and integrates all of the above. This gap is addressed by exploring the interaction of the various factors on ADR performance in an urban environment. Lastly, the paper outlines some of the main problems faced by most navigation algorithms in real world environments to better guide the research process of designers and developers.

2. Environment perception-based autonomous navigation control system

2.1. Multi-sensor environment perception and vehicle state acquisition

Reliable detection of surroundings and accurate motion estimation are necessary for ADR navigation. The use of single sensors is generally insufficient for the unpredictability of urban environments, therefore, most of the recent research pertains to multi-sensor systems. Such systems may be described in terms of sensor fusion, adaptive localization, and learning-based navigation.

Mwitta and Rains developed a GPS-visual navigation system for an Ackermann-steering agricultural robot used in a cotton field [6]. The system integrated an RTK GNSS receiver, a Zed2 stereo camera, two IMUs, and wheel encoders using an Extended Kalman Filter (EKF). Using GPS-only Pure Pursuit control, the robot exhibited an average lateral deviation of 8.3 cm. The vision-only system using a U-net based FCN and DWA resulted in a deviation of 4.8 cm, while the integrated

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GPS vision system resulted in a row-following error of 9.5 cm. Although the integrated system did not result in the lowest lateral deviation, it performed global mapping and end-of-row turning and provided redundancy of sensors. Thus, multi-sensor fusion may improve the robustness and flexibility of outdoor robotic navigation.

Lee et al. built an outdoor delivery robot with LiDAR, IMU, and GNSS [7]. A GNSS uncertainty map represented regional positioning reliability and allowed the system to switch between GNSS constraints and NDT map matching. During a 4.38 km autonomous navigation task, the system achieved a mean translation error of 0.25 m and a mean absolute yaw error of 0.3°. Localization systems reveal the necessity for a combination of sensors as well as the ability to assess which sensors are reliable in various scenarios.

Lee and others built a wheeled legged quadruped delivery robot controlled by a hierarchical reinforcement learning (HRL) framework [8]. The low-level controller was based on raw IMU and joint data, while the high-level controller learned terrain and elevation using LiDAR data. During testing, the robot was able to travel 8.3 km at an average speed of 1.68 m/s, with a tracking error of 0.24 m/s and no collisions, whereas the traditional baseline had a 100% collision rate. The robot also learned to switch between driving and stepping gaits without manually programmed rules. This work illustrates a closer relationship between sensing and control.

With these studies, it is clear that single sensor systems are giving way to multi sensor fusion, context aware localization, and learning based navigation. The dominant theme is that reliable ADR navigation requires not only multiple sensors, but also contextually assessing the reliability of sensor data.

Table 1 presents a comparative analysis of the three representative systems, detailing their platforms, main approach, and key findings.

Table 1. Comparison of multi-sensor approaches for ADR perception and state assessment

Work	Platform	Sensor	Key Feature
Mwitta and Rains [6]	Ackermann rover	GNSS + VISION + EKF	Improved robustness
Lee et al. [7]	ODS-Bot	LiDAR/GNSS+ uncertainty map	Adaptive localization and traversability
Lee et al. [8]	Wheeled-legged robot	HRL + LiDAR	Integrated sensing and locomotion

2.2. From geometric obstacle avoidance to determining passability on the ground

After obtaining environmental information and position, an ADR needs to determine where it can move safely. Traditional navigation often uses binary maps that divide areas into obstacles and free space. However, curbs, slopes, speed bumps, and uneven roads are not always complete obstacles. Whether they can be crossed depends on the robot's mechanical design, kinematic limits, and current condition. Therefore, navigation research has shifted from only avoiding obstacles to also judging whether different types of ground can be crossed.

One study of this shift is the ODS-Bot navigation system of Lee et al. [7]. Steps higher than 10 cm and slopes steeper than 18° were considered non-traversable. A three-hidden-layer MLP was trained using weakly labeled elevation-map data, together with pseudo-labeling and recursive Bayesian updating. The system generated dense traversability maps from sparse LiDAR data at a

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resolution of 0.1 m. In a 0.6 m-wide corridor, the system avoided collisions with a localization error of 0.70 m. Dynamic obstacle frequency maps also reduced near-miss incidents from 17 to 3. These results show that terrain assessment and dynamic obstacle information can both support safer navigation.

Shaklab et al. built upon traversability assessments by incorporating real-time vibration monitoring [9]. Their Vibration Monitoring Module (VMM) utilized RANSAC-based plane fitting on 3D LiDAR data to more systematically evaluate surface roughness as smooth, moderate, or rough and to adapt driving speeds. On rough terrain, the robot slows by up to 50%, which lowers vibration by about 40% as compared to constant speed movement, though it does take 12 seconds to traverse a 50 m section of terrain. The VMM requires no GPS, thus ensuring operation in areas of poor or no GNSS connectivity. The important feature of the component is that the robot can evaluate many aspects of the terrain and adjust speed accordingly.

Jiang et al. studied the stability of the terrain by employing the Zero Moment Point (ZMP) theory, while incorporating suspension deformation within their calculations [10]. Their six-wheeled, food delivery robot, demonstrated that the overturning limit was a function of spring stiffness; 40 N/m resulted in the robot overturning at 26.79°, while at 400 N/m the limit was increased to 29.03°. The above results show that traversability is a function of not only terrain and its shape, but also the characteristics and design of the robot's suspension system.

Traversability is related to people and social situations. Karnan et al. created the Socially Compliant Navigation Dataset (SCAND), containing 8.7 hours and 138 trajectories from human-controlled navigation with two different robots [11]. They trained a global-local planner with behavior cloning and bird's-eye-view LiDAR data. In a study involving 14 evaluators, the learned policy received higher scores for social compliance (4.39 compared to 2.86) and safety (4.71 compared to 2.89) than the standard move_base planner. This shows that delivery robots must operate within social constraints, such as giving way to pedestrians, maintaining reasonable distances, and operating safely within crowds.

Navigation efficiency is impacted by global path planning and delivery-level routing. Mwitta and Rains used modified Pure Pursuit, cubic spline interpolation, and PID speed control for uneven ground, although the system had limited ability to react to changing obstacles. ODS-Bot used historical dynamic-obstacle information from 3D LiDAR to support global path planning and avoid areas with high pedestrian density. At the routing level, Shaklab et al. modeled delivery scheduling as a Robust Cumulative Capacitated Vehicle Routing Problem with Time Windows (RCCVRPTW) to reduce customer waiting time within uncertain travel time ranges. The combination of local obstacle avoidance, terrain assessment, and global path planning, coupled with delivery routing, is needed for effective ADR navigation.

3. Vehicle adaptation and autonomous motion in complex environments

For ADRs working in complex scenarios, the ability to perceive and navigate is related to physical interaction with the ground. Sensors and SLAM algorithms are the software foundation of autonomous mobility. But how well they can work depends on how well the mechanical structure and control system can turn perceptual information into stable motion on three-dimensional terrain. This section looks at two aspects of this problem.

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3.1. Vehicle–terrain modeling and collaborative planning control

The shift towards terrain passability assessment shows that navigation depends on the robot's mechanical limits. Terrain geometry alone cannot determine whether a path is feasible. Suspension deformation, wheel-ground contact, friction, mass distribution, payload, and vehicle attitude can all affect vehicle motion.

Trojnacki developed a Newton–Euler dynamics model for a six-wheeled skid-steered robot on horizontal, paved surfaces and included wheel slip using a modified Kiencke tire model [12]. The study showed that the instantaneous center of rotation was determined by the dynamic interaction of all wheels with the ground rather than by pure kinematic geometry. It also found that the ratio between wheel track and wheelbase affected motion accuracy and energy efficiency, while pose-level feedback control could reduce trajectory errors caused by wheel slip.

Maintaining stable posture on uneven terrain becomes more difficult when payload changes during delivery. Bouton, Grand, and Benamar proposed Complios, a compliant wheel-on-leg rover in which each wheel was connected to the chassis through a two-joint leg with a series elastic actuator (SEA) [13]. A linear inverted pendulum model controlled the chassis pitch and roll by adjusting the vertical force of each leg. The robot maintained a level platform under a 38 cm height difference between two wheels, helping to keep sensor orientation stable. The design separated posture stabilization from path planning and allowed adaptation to unknown ground terrain without precise terrain mapping or dynamic replanning.

Li and others studied the perception-planning-control framework [14]. They proposed a double-layer nonlinear model predictive control (NMPC) method for a tracked robot with a bio-inspired passive suspension. The upper layer operated at a low frequency for global trajectory tracking, while the lower layer operated at a higher frequency to handle local dynamics, especially slippage during obstacle crossing. The lower layer used track slippage ratios from IMU and encoder data. Compared with single-layer NMPC without slippage compensation, the method reduced peak-to-peak tracking error by 38%–51% and RMS error by 51%–62%.

From these developments, the vehicle is now treated as a 3D multibody system. Suspension articulation, contact forces, mass distribution, and terrain-induced attitude form the real-time configuration, determining which motions are achievable. Planning and control algorithms that account for vehicle–terrain models can generate trajectories that are geometrically optimal and dynamically stable. This forms a basis for reliable delivery operations in real-world last-mile environments with varying elevations.

3.2. Vehicle structure and complex terrain adaptation

Section 2.1 discussed the vehicle–terrain modeling at the algorithmic level. However, the mechanical architecture of the delivery vehicle itself puts equally notable constraints on the system. Traditional rigid chassis with small wheels often have problems with wheel slip, too much tilting, or losing traction when they face vertical urban obstacles. Whether a robot can go over curbs and slopes depends on its kinematic structure. This includes wheel count, suspension type, and how the chassis parts are connected. Too much vibration hurts sensor data quality. Rollover is a major service failure. Getting stuck means the delivery is delayed. The suspension system matters too. It links the perception payload and the ground. The payload includes cameras, LiDAR, and IMUs. If the platform shakes too much while moving, images get blurred, point clouds become noisy, and inertial measurements tend to drift. All such effects can damage the whole navigation stack.

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Among passive suspension architectures, the rocker and rocker-bogie families are the most widely used for rough-terrain and space mission rovers. Ugenti, Mantriota, and Reina proposed a modified elastic rocker suspension in which the two wheels on each side were uncoupled through a spring prismatic joint [15]. Compared with a rigid rocker, this design reduced the driving torque required by 31% and the minimum friction coefficient needed to climb an obstacle by 24%. The innovation also lowered chassis vertical acceleration RMS by 16%–37%. An analytical model was developed and validated against multi-body simulation with an average torque error of less than 2%. This means the rover shakes less, and the frame takes fewer hits when driving.

Jiang et al. designed a six-wheeled food delivery robot with an independent suspension damping structure on all six wheels [10]. From their studies, adjusting the suspension stiffness (40 N/mm, 60 N/mm and 90 N/mm) resulted in deflections of 6.025 mm, 3.86 mm and 2.467 mm respectively. The ZMP analysis indicated that deflection of the suspension joints affected the stability margin of the robot during side slope and furthermore, during the traversal of speed bumps and climbing. This makes this study significant for ADRs. It correlates the effect of suspension design with the real stability of the robot. The delivery robot system can determine the stability margin, in which case the robot can decide if traversing a slope or bumping is safe depending on the load and springs in the current state.

Park, Langari, and Yi designed a double-wishbone suspension module for a six-wheeled robot and optimized the design parameters using NSGA-II to minimize vertical displacement and body acceleration and considered roll center height for the rollover analysis [16]. A rollover index in the range of −1 to 1 was achieved in field tests involving robot driving over a series of bumps. A reduction of 75.7% in the rollover stability factor (RSF) and 9.3% in the shock stability factor (SSF) was observed. The load distribution was uniformly across all six wheels on the outdoors path. For autonomous delivery, having a uniformly distributed load is important. It means that all wheels can contribute equally to traction, preventing the localized slip that would cause odometry drift. It also protects the payload from concentrated shock loads.

By working together, these mechanical designs support stable operation of the perception–planning–control loop on rough terrain, as discussed further in Section 2.1.

4. Conclusion

This paper summarizes the current state of research concerning autonomous delivery robots' (ADRs) environmental sensing, navigation and mechanical adaptation. Current studies suggest that delivery robots are transitioning from obstacle avoidance to terrain-aware navigation. Multi-sensor systems improve robust perception and localization. Assessing the terrain permits a robotic system to comprehend the ground conditions and helps it formulate navigation decisions. ADRs' mechanical design influences their stability as well as their traversability. ADRs' suspension, wheel-ground interaction, and payload influence whether the planned path can be safely executed. Therefore, all components of the system must be integrated to achieve the desired robot behavior. However, ADRs still face several problems when operating in real-world environments due to the constraints of the environment and mechanical limitations.

Perceptual, terrestrial, and mechanical control must be designed as an interrelated system. ADRs should have the ability to analyze the path not only for the presence of obstacles, but also whether stable navigation of the terrain is possible within the constraints of the mechanical system and the payload. Consideration should also be given to the parameters of the real world, such as dynamic obstacles, GNSS uncertainty, and variations in the payload. By integrating mechanical design with autonomous navigation, ADRs should be capable of planning and adapting their motion to the

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variations of the environment and the vehicle's present state. This should provide an enhancement to the safety, stability, and reliability of ADRs in complex operating environments.

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