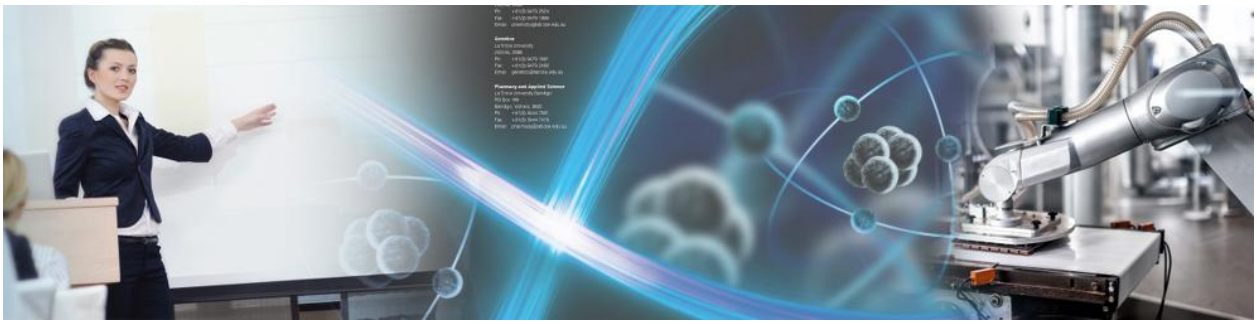
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МАТЕРІАЛИ

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Ярослав Бєлий, Дмитро Гурін

Аналіз принципів нульової довіри для побудови кіберфізичної системи віддаленого моніторингу та керування промисловим обладнанням …… 49

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Sensors and Navigation for Energy-Efficient Mobile Robots

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Annotation: This study examines the role of sensor systems and navigation technologies in improving the energy efficiency of autonomous mobile robots (AMRs). The research considers LiDAR, depth cameras, IMUs, and current sensors as sources of environmental and operational data for energy-aware decision-making. Energy-aware trajectory planning, velocity profile smoothing, adaptive speed control, and dynamic power management of sensors and computing resources are analyzed as key mechanisms for reducing energy consumption during motion. Particular attention is given to the integration of multisensor perception with navigation and motion planning, as well as to the trade-off between computational energy consumption and mechanical energy savings. The study shows that integrating perception, energy-aware path planning, and dynamic power management can support more efficient and sustainable operation of mobile robotic platforms.

***Key words*:** Mobile robots, energy efficiency, navigation systems, sensors, path planning, power optimization, motion control.

I. INTRODUCTION

In today's automated world, autonomous mobile robots (AMRs) and automated guided vehicles (AGVs) have become integral components of modern smart factories, logistics hubs, and precision agriculture [1-10]. Their rapidly expanding range of tasks is accompanied by increasing requirements for operational autonomy, duty cycles, and battery durability. Mobile platforms rely heavily on battery-based energy storage, where energy capacity directly influences operational throughput and system productivity.

The continuous evolution of autonomous operations has significantly reshaped the demands placed on dynamic power control [11-20]. Traditional path planning and motion execution typically focus solely on minimizing total path length or travel time. However, such classical approaches frequently ignore energy losses associated with frequent acceleration, mechanical friction, sharp maneuvers, and variations in surface traction. In this context, developing integrated sensor-driven and navigation-based energy reduction strategies is becoming a critical task.

Ensuring high energy efficiency is closely linked to advanced perception technologies and specialized motion planning methodologies. The use of multi-sensor fusion, energy-efficient spatial mapping, and dynamic trajectory smoothing can reduce motor current spikes and mechanical stress. The integration of these techniques contributes to the creation of field-ready, energy-resilient mobile systems capable of maximizing operating hours per charge cycle and adapting to unpredictable dynamic environments.

Thus, given the persistent demand for extended operational lifespans and lower charging downtime, the relevance of this research is clear. A holistic, energy-conscious framework combining real-time perception with energy-optimal path generation provides new opportunities for enhancing the reliability, efficiency, and sustainability of mobile robotic platforms.

This study aims to analyze the role of sensor systems and navigation technologies in improving the energy efficiency of autonomous mobile robots and to substantiate an integrated approach to reducing energy consumption through multisensor perception, energy-aware trajectory planning, adaptive speed control, and dynamic management of onboard power consumption.

To achieve this aim, the following tasks were addressed:

1. Energy-aware trajectory planning and velocity profile smoothing were examined.
2. Approaches to adaptive speed control and dynamic power management of sensors and computing resources were investigated.
3. The integration of sensor data, motion planning, and power management within a unified energy-aware navigation framework was considered.
4. The trade-off between the energy consumption of computing resources and the energy costs of mobile robot motion was analyzed.

II. THE ROLE OF SENSOR SYSTEMS IN ENERGY OPTIMIZATION

In modern robotic applications, where autonomous units operate continuously across diverse terrain, energy management mechanisms play a decisive role. Advanced hardware and algorithmic strategies not only streamline power distribution across internal components but also can adapt movement characteristics in real time and thereby reduce cumulative energy consumption. Among these strategies, computer vision and other exteroceptive sensing technologies – including depth cameras and LiDAR – provide the environmental interpretation layer that downstream planning algorithms rely on for energy-aware decision-making. Table 1 provides an overview of how key sensory and navigational components directly contribute to reducing power draw in mobile platforms.

Analysis of the presented sensory and navigational components demonstrates a multi-layered approach to optimizing energy efficiency in mobile robots. Exteroceptive sensors form the foundational perception layer, identifying environmental obstacles and surface characteristics to prevent redundant dynamic maneuvers and high-resistance path traversals. Interoceptive sensors create a secondary monitoring layer, tracking wheel slip, motor current spikes, and spatial orientation to optimize dynamic power distribution in real time.

Table 1. Role of sensor and navigation components in energy optimization

Sensing/Control Component	Role in reducing mobile robot energy consumption
Exteroceptive Sensors (LiDAR, Depth Cameras, Ultrasonic Sensors)	Early obstacle detection to avoid emergency braking.
	Terrain mapping to bypass high-resistance paths.
	Adaptive sensor power-cycling in static zones.
Interoceptive Sensors (IMU, Wheel Encoders, Current Sensors)	Estimation of wheel slip and monitoring of motor current and power.
Sensing/Control Component	Role in reducing mobile robot energy consumption
Interoceptive Sensors (IMU, Wheel Encoders, Current Sensors)	Accurate odometry to reduce localization drift.
	Motor-current feedback for load and torque regulation on inclines and rough surfaces.
Energy-Aware Navigation & Path Planning	Energy-optimal global path planning.
	Velocity profile smoothing to reduce dynamic torque spikes.
	Dynamic re-planning in SLAM to avoid redundant loops.

Energy-aware navigation systems and path-planning algorithms implement proactive optimization at the control level, generating smoothed velocity profiles and energy-optimal trajectories to minimize acceleration losses.

The integration of these sensing, planning, and control mechanisms is important for constructing a comprehensive energy management framework. Each layer of hardware and algorithmic control compensates for the physical power losses of others, forming an effective multi-tiered efficiency architecture. The absence or insufficient integration of any of these components leads to excessive power dissipation, drastically reducing operational autonomy and battery life.

III. MAIN ENERGY EFFICIENCY MECHANISMS AND COUNTERMEASURES

The optimization of power consumption is a top priority in ensuring mobile robot autonomy, as energy exhaustion can lead to serious operational failures – from mission interruption to complete system power drain. Modern autonomous platforms face a wide range of energy dissipation sources, requiring a comprehensive optimization approach. The most common methods include energy-optimal path planning – which incorporates velocity profile smoothing as an integral stage – sensor-driven dynamic power management, and multimodal energy-aware navigation that fuses both approaches into a unified control strategy.

Energy-optimal path planning is one of the key strategies for reducing energy consumption. This process allows the navigation stack to calculate trajectories based on dynamic physical parameters rather than purely geometric distance.

The energy-aware path-planning process can be represented as a continuous kinematic data-processing pipeline. At the initial stage, the mobile robot receives a spatial environmental map from its perception system, which provides the primary information for navigation and terrain assessment. This information can then be processed by an energy-aware motion planner that considers terrain characteristics, friction conditions, incline angles, rotational constraints, and required torque levels. Based on these parameters, the planner can generate candidate trajectories and assign an energy cost to individual path segments, taking into account motor electrical losses, changes in kinetic energy, and battery energy consumption. Trajectory smoothing and the reduction of sharp turns can additionally be applied to decrease unnecessary acceleration and deceleration. The generated trajectories can then be evaluated with respect to the mechanical capabilities of the specific drive system, allowing the navigation system to select a trajectory that provides a suitable balance between travel distance, motion smoothness, and estimated energy consumption. Finally, the selected trajectory can be converted into motion commands for the robot's motor control system. At the kinematic parameter evaluation stage, possible movement options can be analyzed in terms of acceleration rates and steering angles. Dynamic cost models and smooth spline-based trajectories can be used to reduce abrupt changes in velocity and associated current spikes. At the profile generation stage, the selected trajectory can be converted into a velocity profile, providing the basis for adaptive speed control. Each trajectory segment can be assigned an appropriate velocity and estimated torque requirement according to terrain characteristics and expected load conditions.

Dynamic power management uses sensor feedback to optimize component energy draw. A key feature of this method is that it relies on real-time operational demands, adjusting sensor sampling frequencies and processor clock speeds dynamically.

The sensor power optimization process begins with the acquisition of status data from onboard diagnostic tools and localization algorithms, which monitor the surrounding dynamic complexity. This initial status data undergoes an assessment stage to determine current environmental requirements, ensuring an accurate evaluation of required perception density. Following this, the system adjusts the active state of exteroceptive sensors to match the operational context, placing redundant vision modules or high-power LiDARs into low-power standby modes during straightforward movements. Subsequently, processor workload is managed to evaluate compute power efficiency, scaling down complex mapping algorithms when operating in fully mapped or static environments. Based on these combined sensory metrics, the system makes a final decision regarding dynamic power distribution, determining whether the current operational state allows for temporary hardware deactivation without compromising safety.

To maximize energy efficiency, multimodal energy-aware navigation combines the strengths of both kinematic planning and hardware management approaches. This process integrates a power-optimized trajectory plan derived from terrain mapping with a dynamic hardware control profile obtained from system diagnostics. The

combined data undergoes operational fusion at the motion controller level, enabling an intelligent power management unit to comprehensively analyze both the external route demands and internal electrical loads, which supports energy-efficient movement execution. This integration is typically implemented using two primary strategies. In the early fusion approach, data is combined at the initial stage to form a unified energy profile, allowing the control system to simultaneously balance mechanical drive power and computing draw from the ground up. Alternatively, the late fusion approach processes motion planning and hardware management through separate branches of the embedded computing system, merging the independently analyzed control parameters only at the final motor command stage to support a balanced, energy-efficient movement sequence.

IV. COMPUTATIONAL OVERHEAD AND NAVIGATION METRICS

Implementing high-level perception systems and advanced energy-aware navigation logic introduces a fundamental trade-off, as onboard compute units consume electrical energy that must be balanced against kinetic motion savings. Complex real-time processing pipelines, such as continuous dense 3D mapping, multi-sensor Kalman filtering, and deep neural network inference, impose a substantial computational load on embedded CPUs and GPUs. If the electrical power required to compute an optimal route exceeds the mechanical power saved by executing that route, the overall system efficiency declines. To maintain a positive energy balance, algorithms must be optimized for execution on low-power edge hardware, utilizing optimized matrix operations and dynamic downsampling.

Sensor suite power draw represents another critical factor in total system energy expenditure. High-resolution multi-beam LiDARs, active stereo depth sensors, and high-frequency inertial hardware can draw significant continuous wattage directly from the primary power bus. Managing these devices dynamically – by adjusting scan frequencies or placing redundant sensors into low-power states during low-risk maneuvers – ensures sufficient spatial awareness without prematurely draining the main battery. The overall efficiency gain depends directly on aligning the computational complexity with the physical scale, velocity, and environmental constraints of the mobile platform.

The practical advantages of integrating sensor-driven energy management extend beyond immediate power savings. Systematic trajectory smoothing and dynamic velocity regulation reduce peak motor currents, which significantly mitigates thermal dissipation in drive electronics and reduces mechanical wear on gearboxes and actuators. Furthermore, reducing high current peaks during heavy acceleration can help extend the operating lifetime of electrochemical battery cells. Ultimately, this balanced approach can increase operational autonomy per charge cycle while enhancing the overall mechanical and electrical reliability of the platform.

V. CONCLUSIONS

This research has conducted a comprehensive investigation into the role of sensor suites and navigation systems in optimizing the energy efficiency of autonomous mobile robots. The primary sources of dynamic power dissipation – including high-torque acceleration surges, wheel slippage, unoptimized path selection, and dynamic sensor draw – were evaluated alongside modern hardware and algorithmic countermeasures. The analysis suggests that energy savings can be achieved when spatial perception and motion planning are directly linked to the physical power characteristics of the mobile platform.

The analysis indicates that maximizing battery longevity requires more than hardware selection or trajectory planning in isolation and benefits from a multi-layered control approach. Combining low-power exteroceptive sensing, real-time interoceptive motor feedback, and energy-aware path generation can help reduce unnecessary stopping and re-acceleration cycles. By smoothing velocity profiles and adapting hardware clock speeds based on environmental complexity, the framework can balance onboard computational draw with dynamic motion savings.

The presented concepts and control strategies provide a basis for designing energy-resilient mobile platforms in modern industrial, agricultural, and logistical applications. The implementation of such integrated strategies can help robotics engineers to maximize mission runtime, reduce fleet charging downtime, and lower long-term maintenance costs. Future research should focus on implementing adaptive reinforcement learning algorithms for dynamic real-time energy modeling under unpredictable terrain conditions and evaluating wireless energy-harvesting technologies during autonomous operation.

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