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ROBOTICS

Energy efficiency profiles for unmanned ground vehicles

Eero Väljaots* and Raivo Sell

Department of Mechanical and Industrial Engineering, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia

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Abstract. The paper investigates energy efficiency validation of unmanned ground vehicles (UGVs). The energy efficiency of the vehicle platform depends on the design elements and the environment as well as navigation algorithms. Verification of all UGV design factors that have measurable influence on energy efficiency involves an integrated measurement system for measuring the dynamic interactions of the vehicle and the environment during the real-condition test mission. Profiles are used for improving and optimizing the UGV design, control system, and comparison with each other. The obtained results are applied for the development, simulation, and testing library used as early-stage product design support.

Key words: unmanned ground vehicle, energy efficiency, driving dynamics measurement, design evaluation.

1. INTRODUCTION

Unmanned Ground Vehicles (UGVs) are gaining rising interest in the consumer market for civil tasks. While automation and robotics technology become available at less expenses, the development complexity is increasing and lead times to market are shrinking. Vehicle mobility relies on limited energy resources, which creates the need for energy efficiency maximization. As the energy consumption translates to cost, energy efficiency is definitely one of the most important parameters in consumer markets.

The analysis and estimation of efficiency parameters are not straightforward, as they are often contradictive and much dependent on the working environment. For dangerous conditions durable design of UGVs is needed. If the vehicle is heavy and its strength reserves are exaggerated, it is more durable in dangerous conditions, but this is achieved due to lower energy efficiency. While planning mission scenarios for UGVs, energy requirement predicting, use of platform and mission measurable parameters, and prior knowledge are very important [1].

The design of UGV moving capabilities is based on the optimization of the track and vehicle interaction for given conditions. Despite the moving method of the platform, successfully overcoming obstacles in autonomous mode is always most challenging. Optimization of rough terrain control for rovers has become an important and challenging research, especially in space programmes where a real-condition failure leads to a tremendous waste of time and money. Therefore, development of a new platform involves performance studies of previous solutions as well as extensive testing [2].

Although standardized performance evaluation is very important for design comparison and for ensuring real-condition mission success, it is uncommon in mobile robotics [3]. Most notable UGV performance evaluation

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[*] Corresponding author, eero.valjaots@gmail.com

programs and researches are task-based and targeted for testing machine intelligence in an artificial indoor test arena [4] or comparison of basic task capabilities in a virtual or real environment [5,6]. In both cases the results are obtained through scoring and judging. While scoring is appropriate in developing efficient autonomous navigation and obstacle avoidance, it is unreliable for dynamic processes, e.g. for maintaining smooth and efficient ride. Although many navigation methods have been studied, their efficiency and suitability for different conditions are largely not compared.

The current research is a part of a general mobile robot development framework incorporating methodologies, tools, and experimental data focusing on the early stage product design support [7]. Decisions in the early development phase are especially important as they define the whole design process and have a high impact on the overall success of a product. Designing an autonomous robot is not a trivial task and the designer has to consider many limits and opposing requirements. The appropriate model library gives a great benefit to the early stage of platform development by providing guidelines and a baseline design [8]. The included design models and simulation algorithms are validated through their real-condition measurements. The proposed method enables to create energy efficiency profiles for particular solutions and select and optimize the design based on it. While design analysis is categorized and simplified through key parameters, another possibility is the use of the proposed method for comparison of UGVs during performance testing as a tool for the development of efficient moving capabilities and adaptive control algorithms. Therefore, at a higher level the testing method is also used to develop autonomous navigation scenarios of robotic platforms [9].

The earlier research involves determining the UGV key parameters: efficiency and performance measures that can be acquired during simple real-condition real-time testing [10,11]. The key-parameter relations and test layout are described by using pre-defined and validated Systems Modelling Language (SysML) models according to the robot’s purpose [12]. The integrated measurement system developed for acquiring the appropriate dynamic parameters of the vehicle is self-contained and universal and involves data fusion of several sensors [13]. The analysis of measurement system uncertainty [14] indicates a satisfactory accuracy for application for testing common medium-class UGV behaviour.

The target of the current research is energy efficiency evaluation of design models based on medium-class UGV platforms. Measurement method requirements connect the key parameters of the platform design to dynamic measures of energy efficiency. Acquisition of the parameters takes place from direct and indirect measures during the real-condition test as well as separate isolated tests. The real-condition mission provides a set of data for analysing the energy efficiency of vehicle design. The key-parameter relations, dependencies, and test layout planning were modelled by using SysML [15,16]. Although platforms are usually designed with more or less universal capabilities, their most efficient operating area is much narrower. Efficiency metrics for universal platforms are established by mapping tasks and missions in the planned range of use taking into account the environment and terrain properties. This enables compiling efficiency profiles to particular platforms that also show energy consumption distribution. Profiles are used for improving and optimizing the UGV design and control system and comparison with each other to find the most suitable one for a given task.

2. MATERIALS AND METHODS

The research is targeted to the available medium-size UGVs that can be used to accomplish many missions involving transportation, surveillance, maintenance, service, agriculture, etc. During the current research, we had an opportunity to test and analyse two medium-size UGV platforms. They are similar wheeled platforms with off-road capabilities and a full set of sensors that enable autonomous operation and navigation. The platforms have a different range of use and capabilities, but both operate with relatively low speed (under 30 km/h) and can carry a fair amount of useful load.

One robot was developed in the Department of Mechatronics of Tallinn University of Technology and it is called Uku [17] (Fig. 1). This all-terrain-vehicle (ATV) size UGV weighs 250 kg and is an open platform for testing several unmanned technology subsystems. Its power transmission layout is simple, consisting of planetary gearing in the brushed DC motor output and straight bevel gearing without a differential on the rear axle.

The drawback of the design is that as Uku uses only rear wheel drive (RWD) and has a light mass on the rear axle, it generates wheel slip easily when driven on loose ground. Fully electric Uku navigates with the aid of an Xsens 3D motion tracker (GPS + INS), a SICK 3D laser scanner and a stereo vision camera, and rear axle and steering wheel encoders. Its electric energy consumption is measured by a non-contact current sensor on a battery output cable and battery voltage measurement sensor. The Xsens motion tracker provides global position system (GPS) coordinates, driving velocity, accelerations, and track slopes.

Fig. 1. Electric UGV Uku.

Fig. 2. Electric UGV Tracdrone with articulated steering and hydraulic drive.

The other robot platform, called Tracdrone (Fig. 2), was developed by Hecada OÜ in cooperation with the Estonian University of Life Sciences. This vehicle is heavier (470 kg) and is planned to have a field of applications in agricultural activities such as automated sampling in cultivated land, unmanned miniloader function, and non-chemical pest control. The UGV layout is modular, consisting of identical modules that are connected with each other through steering linkage. All wheel drive (AWD) is achieved by routing hydraulics lines to every wheel and body module. This enables to connect two or more modules with dedicated functions or working tools. The platform is front frame articulated with differential axles. The power unit is brushless direct current (BLDC) electric motor.

The platform navigates with the aid of custom-built GPS + INS, each wheel, and steering linkage encoders. Its higher level obstacle detection uses LeddarTech's inexpensive 3D LiDARs in the front and back of the body, complemented with ZED stereo cameras, which provide range imaging. Manoeuvring and emergency system backup is provided by ultrasonic distance sensors. The internal electronic modules of the platform use a controller area network (CAN) for data exchange. The powerful Nvidia Jetson TX1 main computing unit provides 20 Hz constant data output combined from data acquired from CAN modules. Data transmission with an operator is possible over WiFi or a 4G network. Electric power consumption is measured by a non-contact current sensor on a battery output cable and a battery voltage measurement sensor.

Evaluation of the energy efficiency of the mobile robotic platform requires investigation of the distribution of energy consumption inside and outside the platform. For this purpose, a digital measurement system is used for acquiring direct dynamic parameters and also statistics from use cases [18]. Building upon the energy consumption model, the platform design is evaluated, compared, and developed based on testing results.

In the case of fully electric UGVs (e.g. Uku or Tracdrone), the total current consumption of the platform consists of a passive and an active part. Passive consumption in the idle mode keeps the UGV actuators alive and responsible. Active consumption is present when the UGV accomplishes useful tasks like driving from one point to another. The basic energy conversion efficiency inside the vehicle is the ratio of the output (useful energy) to the input (all consumed energy):

$$\eta = \frac{E_{out}}{E_{in}} . \tag{1}$$

Energy consumption is the sum of resistive forces against vehicle movement. As both platforms are fully electric, instantaneous energy consumption E is calculated from consumed current ΔI and battery voltage ΔU during the time t in relation to the driven distance s (described using SysML parametric diagram in Fig. 3):

$$E = \frac{\Delta I \Delta U t}{s} . \tag{2}$$

The full resistive forces to the vehicle movement can be measured using coast-down testing [19]. However, it is quite difficult to allocate single elements and estimate their contribution to the full resistance. By using a digital road slope measuring device [20], it is possible to measure the test track gradient manually and calculate the corresponding resistive force F from the vehicle weight m, gravity acceleration g, and track gradient angle α:

$$F_g = mg \sin\alpha . \tag{3}$$

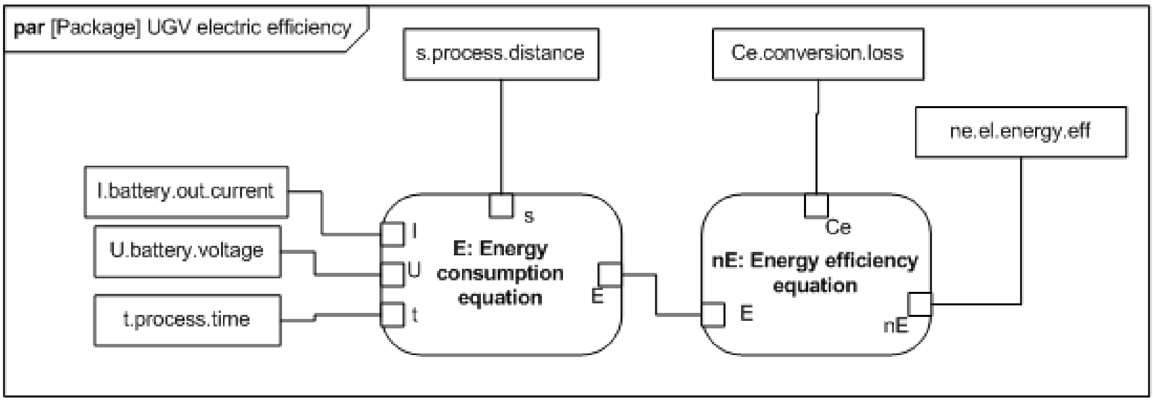

Fig. 3. Parametric diagram of the UGV electric energy efficiency.

The aerodynamic drag resistive force of the vehicle bodywork F_d is calculated from the cross-sectional area of the vehicle body A_b, coefficient of drag C_d, air density ρ_a, and relative velocity of the air v_a (wind):

$$F_d = A_b C_d \frac{v_a^2 \rho_a}{2} . \tag{4}$$

In the case of a slow offroad UGV, the vehicle bodywork has a small impact on performance. However, moderate wind might have a considerable influence on resistance. As the aerodynamic resistance of the bodywork is constant, the resistance of air can be measured through speed using a vane style anemometer mounted on the vehicle.

In most cases, the interaction of the track and the vehicle wheel has the greatest impact on energy efficiency. The rolling resistance coefficient is difficult to estimate theoretically, but it can be measured separately for a given torque transfer element [21]. Tire rolling resistance force F_r has a constant value based on resistance coefficient C_r, vehicle weight m, acceleration due to gravity g, and track gradient angle α:

$$F_r = C_r mg \sin\alpha . \tag{5}$$

Decelerating or braking is the opposite of accelerating. Its resistance can be calculated using inertial sensor measurements. As a UGV is usually doing useful work, the resistance force from the working operation is also observed, e.g. the UGV is pushing/pulling something. It is possible to measure working operation resistance F_n using the load cell between the vehicle and the tool (e.g. snow plough) and compare it with vehicle accelerating force F_a. The amount of the useful horizontal force available for the working operation, pushing or pulling a load, is drawbar pull force F_p:

$$F_p = F_a - F_n . \tag{6}$$

When a UGV is designed for a certain task, positive drawbar force ($F_a > F_n$) is desired. An excessively high drawbar force capacity leads to poor energy efficiency due to increased power (high fuel/current consumption), rolling resistance, or platform weight. If resistive forces become too high, no useful output remains available and the drawbar pull force becomes zero ($F_a = F_n$); for example, when the vehicle is accelerated to its maximum achievable speed that is not limited by transmission. In case the drawbar pull force is lower than needed ($F_a < F_n$) for accomplishing a task (snow ploughing, obstacle crossing), the traction efficiency η_t decreases the energy efficiency.

In addition to outer resistive forces acting on a vehicle, its internal resistance C_i might cause a great loss of energy. Vehicle internal resistance is the sum of power converting losses. It is easier to measure the voltage drop in power cables than the energy loss in mechanical transmission. These parameters are available but usually given as a range, depending partly on machining quality. Transmission efficiency can be calculated using high-precision thermal camera measurements [22] or a dynamometer device that consists of a drive motor, strain gauge torque sensor, and load motor [23,24]. In our case, it is possible to use a hydraulic pump as the load motor, which offers suitable high resistance. It produces hydraulic pressure that is proportional to the torque applied to its shaft (Fig. 4). Because of the feedback of the high-precision pressure sensor, no strain gauge torque sensor is necessary. The base pressure condition P_1 is measured while the motor is directly driving the pump. The lower pressure P_2 is produced by the ratio inefficiency occurring in the drive or the gearbox; therefore, the mechanical efficiency can be calculated using pressure measures:

$$\eta = \frac{T_{out}}{T_{in}} = \frac{P_2}{P_1} . \tag{7}$$

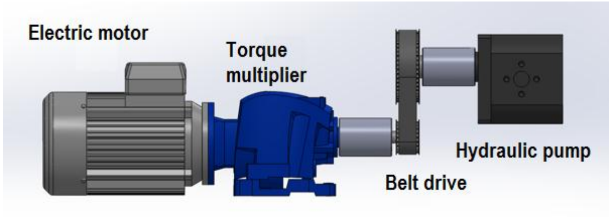

Fig. 4. Setup of the measurement of internal resistance of the drive.

In a similar way, hydraulics transmission efficiencies can be found using pressure measurements in different points of oil lines. However, the measurement of hydraulic motor efficiency requires testing the whole system in a test bench or using a strain gauge torque sensor on the output. Figures 5 and 6 present the measured or estimated energy conversion losses inside the test vehicles.

Using a typical vehicle longitudinal dynamics model [25] and adapting it for UGVs, the resistive forces can be combined into a model of vehicle power consumption:

$$\begin{aligned}P(t) = \sum Fv(t) = (F_a + F_r + F_g + F_d + F_p + C_i)v(t) \\ + P_e(t) + \varepsilon(t),\end{aligned} \tag{8}$$

where v is speed, F_a accelerating force, F_r rolling resistance, F_g resistance caused by the track gradient, F_d aerodynamic drag, F_p working operation resistance, C_i vehicle internal resistance, P_e power consumption by the electronic equipment, and $\varepsilon(t)$ is model error. Key factor assessment requires composition of profiles for the vehicle: driving style profile, track surface roughness profile, track gradient profile, etc., which can be composed based on the results of real-condition testing measurements.

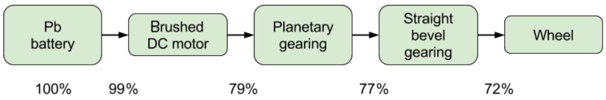

Fig. 5. Uku’s internal losses of power transmission.

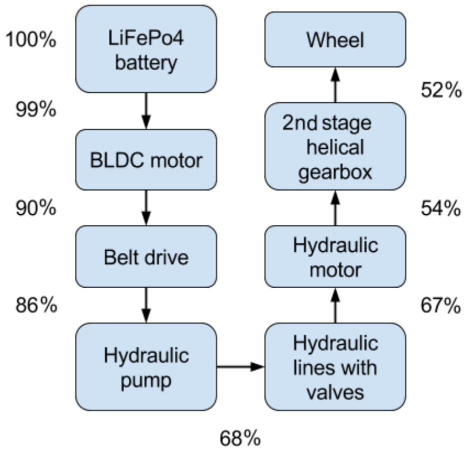

Fig. 6. Tracdrone’s internal losses of power transmission.

The model error *ε(t)* includes non-compliances between simulation and real-condition measurement results. As the measurement system is self-contained, resistive forces are measured indirectly. Acceleration measurements are provided by the platform’s inertial measurement unit (IMU). Therefore, the model error includes several components that affect the acceleration measurements. The measurement model for the inertial MEMS sensor is expressed with random and systematic effect corrections δ_i added to output y:

$$y = \bar{a}_t^{sc} + \sum_{i=1}^{n} \delta x_{sens}^i + \delta x_{res} + \delta x_{wn} + \delta x_g + \delta x_{tmp}\,, \tag{9}$$

where

$$\sum_{i=1}^{n} \delta x_{sens}^i = \sum_{i=1}^{n} (\delta x_b^i + \delta x_{sc}^i + \delta x_{nl}^i)\,, \tag{10}$$

where δx_{sens} is sensor correction, δx_{res} is the analogue to digital converter (ADC) resolution correction, δx_{wn} is white noise correction, δx_g is natural acceleration change correction, δx_{temp} is environment temperature correction, δx_b is axis bias correction, δx_{sc} is axis scale factor correction, and δx_{nl} is axis nonlinearity correction. Thus, combined standard deviation u for sensor output can be expressed by

$$u(y) = \sqrt{u^2(\bar{a}_t^{sc}) + \sum_{i=1}^{n} u^2(\delta x_i)}. \tag{11}$$

The efficiency of a UGV’s energy conversion can be evaluated on different levels:

- Input energy transformation into useful output. For example, electric energy produced by the battery is converted into wheel torque with minimal losses, yielding high energy efficiency.
- Output transformation into useful work. For example, torque is applied to wheels only when they have enough grip to move the vehicle, which means high traction efficiency.
- Work planning and processing for successfully completing a mission. For example, the vehicle is driven around obstacles along the shortest track with minimal energy consumption, which means high navigational efficiency.

Besides internal energy transformation losses and resistances to movement, there are higher level factors that describe efficient platform operation. There is a notable power loss in the tire and track surface contact, which can be calculated. Traction efficiency is the ratio of the distance covered without slipping s_i and the distance covered by a driving element s_e [26]:

$$\eta_t = \frac{s_i}{s_e}\,. \tag{12}$$

While s_e is measured by the wheel encoder, s_i is more complicated to measure. For this, GPS and gyroscope are used to find the distance the platform has moved on landscape. The ideal trajectory s_r and the distance covered without slipping s_i can be used to calculate navigation efficiency:

$$\eta_n = \frac{s_r}{s_i}\,. \tag{13}$$

It is even more complicated to find the ideal trajectory that the platform should follow instead of moving on the actual route. This can be done by planning the optimal route on a map with considering the real conditions measured during the testing.

Although operational efficiency is not directly related to the energy consumption measure, efficient operation always translates into energy efficiency improvements.

Autonomy ratio η_a is the measure of the time the operator spent to achieve robot operation time t_r:

$$\eta_a = \frac{t_r - t_o}{t_r}\,. \tag{14}$$

As failures decrease the UGV's operational efficiency, their occurrence and effect are statistically obtained. Reliability ratio is full performance measured by time t_{fp} compared to reduced performance measured by time t_{rp}:

$$\eta_r = \frac{t_{rp}}{t_{fp}}\,. \tag{15}$$

As each ratio represents one section of energy transformation into useful work during the task, they are interrelated. The platform's total energy efficiency ratio η_Σ is a function of all efficiency ratios:

$$\eta_\Sigma = f\left(\eta_e \eta_t \eta_n\right). \tag{16}$$

Design models of the UGVs are validated based on real-condition testing, during which data acquisition takes place simultaneously. Several test missions were created that allow testing the performance and efficiency of available universal UGV platforms. For measuring dynamic performance efficiency, the missions can be split into three parts:

1. covering a distance or area, for example territory surveillance;
2. performing a task, for example loading on/off cargo;
3. support functions, for example measurement system itself, communication.

The requirements for appropriate testing scenarios for a mission model are

1. feasibility to complete by a medium-size wheeled UGV during reasonable time (executable),
2. easy repeatability (steady environment condition),
3. capability to measure all key parameters (not isolated).

Territory surveillance mission is described here as a mission suitable to be accomplished by both test platforms for comparison purposes (SysML action diagram in Fig. 7). The mission involves covering a distance between GPS waypoints, while the driving route between them is unspecified: the UGV navigation system can choose the path that suits it and is easier to pass through. The patrol route is closed, the UGV returns to the control point. The terrain is diverse, including gravel, loose sand, and grass. Obstacles are mostly trees, stones, fallen tree branches, trenches, etc. The testing platforms carry no payload, only scan the surrounding environment while driving autonomously. The defined scenario requires that action be taken when movement is detected, that is the UGV has to find the approaching intruders and send photos of the intruders to the control centre while staying at a distance itself. Its intruder detecting capability means the UGV detects moving objects (humans, animals, other vehicles) using stereo camera image processing.

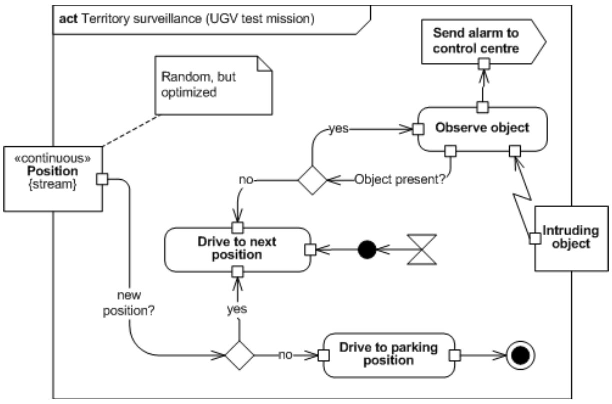

Fig. 7. Diagram of territory surveillance action.

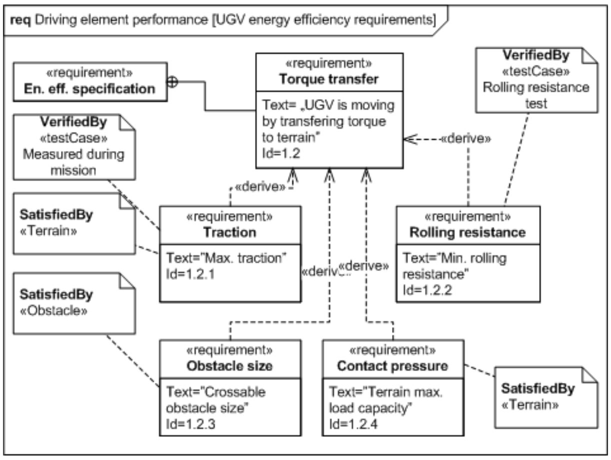

Fig. 8. Diagram of requirements for the wheel.

During the mission, the platform control system solves several automated tasks:

- tracks its position and energy amount,
- detects moving intruders and takes action,
- avoids obstacles while driving around,
- prevents the UGV from being stuck,
- calculates the optimal (shortest) course length to be travelled between waypoints,
- adjusts the route based on the vehicle and the environment.

As the mobile platforms and their tasks are complex, the efficiency of a platform cannot be described with one parameter, rather a set of key parameters and parameter relations corresponding to the task is needed. Tasks and missions in the field of a particular UGV application determine the requirements for its design. The task requirements define the requirements for design elements. An example SysML requirement diagram with identification symbols is shown in Fig. 8. Usually UGV missions include several different tasks, for example drive to the location, operate the tool, send information, etc. A requirement list can be composed for every task.

Further merging of the requirements of tasks gives a requirement list for the mission. Depending on the mission goals, some tasks are more important and more often performed. Therefore, priorities have to be assigned. For example, transportation capacity is the most important factor in case of a vehicle used for carrying gravel to building sites. Moreover, many tasks that contribute to key parameters are opposing each other, which makes assigning priorities and their comparison a comprehensive task. For example, vehicle weight is a very important factor for energy efficiency; however, decreasing the weight reduces also the payload carrying capability. Similarly, tire rolling resistance is controversial to traction in an offroad track and a powerful motor shortens travelling times but consumes more energy. To solve these problems, priorities are assigned by scaling the parameters in comparison to each other. This will increase or decrease the importance of parameter properties for the UGV efficiency profile.

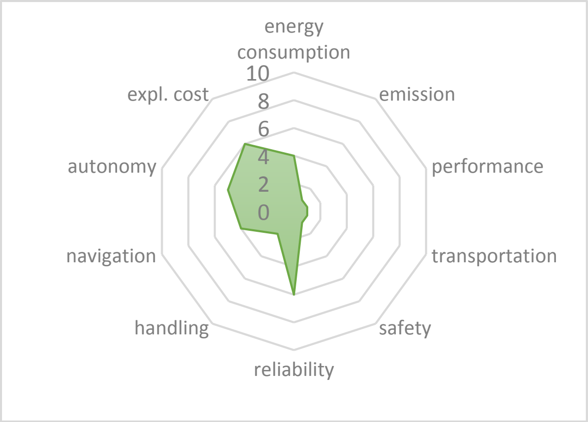

Fig. 9. Requirement map for a territory surveillance mission.

By using efficiency operation ratios, the requirement map can be compiled for a mission (Fig. 9). The map corresponds to the efficiency distribution of any UGV to qualify for this mission. The map is organized from lower to higher level and from energy conversion to versatile operation, which translates into platform exploitation cost.

In order to compile the requirement map, limits must be assigned to platform properties. The maximum limit, 100%, means that the UGV achieves the best possible result during the test mission: zero emission (fully electric platform), no incidents (absolute safety, reliability), no exploitation costs (for example, regenerates all consumed energy with solar panels), no need for operator intervention (fully autonomous), energy conversion without losses, and transportation capabilities for delivering cargo within a single load.

3. RESULTS

Efficiency profile manages and connects cross-relations of the platform design elements and control system specifications with their effects on the performance and energy consumption. The meta-level layout (Fig. 10) includes:

- Design models or a sufficiently detailed design specification. For example, the platform has a specific agricultural tire fitted to the wheel.
- Corresponding behaviour parameters. For example, this tire generates high rolling resistance, yet prevents slip up to some level.

- Effect on energy and operation efficiency. For example, traction is good but energy consumption is too high.

Extensible markup language (XML) based models can be used to make automatic cross-linking between elements inside the profiles. The energy consumption of the platform can be visualized with a pie chart with the whole consumption divided into parts as losses. Energy efficiency is plotted on a radar chart to illustrate the strengths and weaknesses, while efficiency ratios of different properties are given on several axes, and the calculated ratios are presented from worst to best in percentages. Based on results, improvements can be made to the platform design or the entire platform can be replaced, and a new cycle of testing would follow.

Platform efficiency profile is designed to coincide with the task and mission requirement profiles. The overlapping of the task/mission profile with the platform profile indicates the ability of the UGV design to complete the task and its suitability into the given field of application. If the ratio is 0%, the UGV cannot complete the task as its power source is too weak, grip too low, etc. The 100% ratio means full compatibility with the mission requirements. For example, durability indicator is a platform design property. Durable construction is often heavy, simultaneously decreasing economy. If lightweight durable materials (e.g. titanium, carbon fibre) are used, the cost will be much higher, which is often unwanted in case of consumer products.

Real-condition testing generates large sets of data that are used for analysing the platform design properties. The recorded test data enable to calculate several specific parameters for the efficiency profile as observed in efficiency metrics analysis. By using efficiency profile visualization, better feedback on the studied platform design and operational suitability can be given. A platform efficiency map in the form of a radar chart is presented in Fig. 11, which can be compared with the previous mission map (*see* Fig. 9). The map plots the summary efficiency ratio of platforms and distinguishes the energy losses by type. Although all platforms are universal, their properties and capabilities are different. Similarly, mission layouts and requirements need particular UGV properties for processing with maximum efficiency. If the mission profile area fits into the platform profile area, the platform can meet all mission requirements. However, a considerably larger platform capability margin indicates poor energy efficiency as its strength reserves are exaggerated.

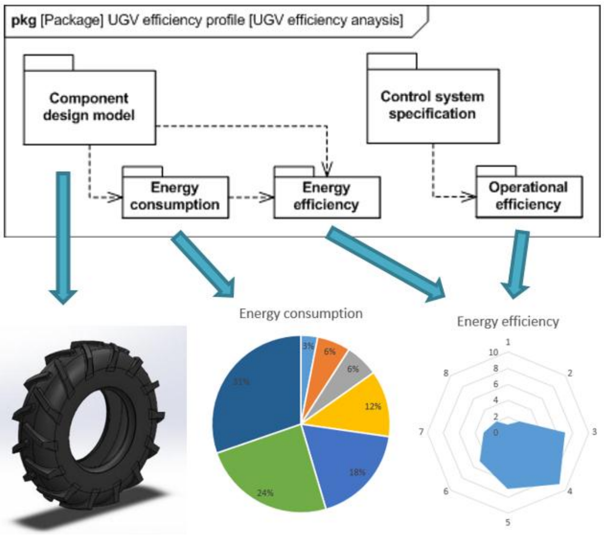

Fig. 10. Profile layout with examples of elements.

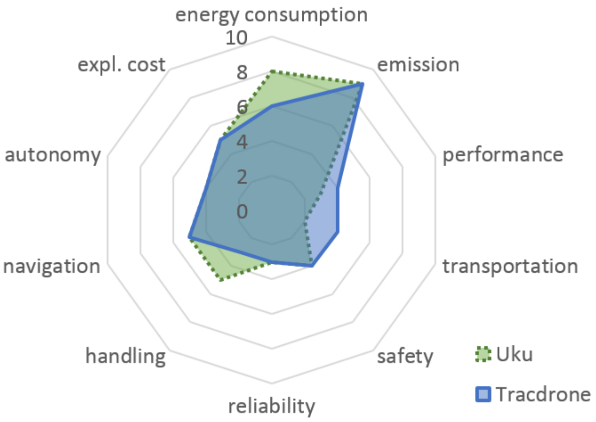

Fig. 11. Calculated efficiency ratios for test platforms.

The recorded route of a territory surveillance mission around a defined guarded area accomplished by Tracdrone is shown in Fig. 12.

Fig. 12. Route around a defined guarded area of a territory surveillance test with Tracdrone recorded by GPS (1 – start, 2 – stop, 3 – pause).

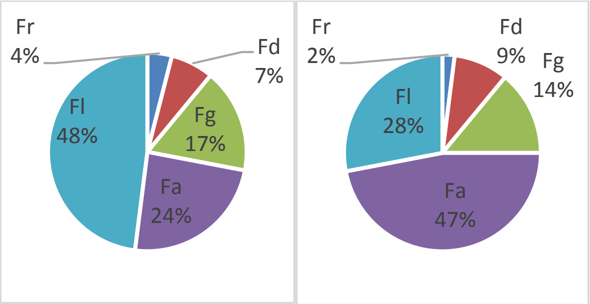

Fig. 13. Distribution of resistive forces during Tracdrone (left) and Uku (right) tests obtained by Eq. (8).

Due to separate coast-down testing, it is possible to calculate resistive forces using Eq. (8) from the energy consumption of both platforms (Fig. 13). As seen, a great efficiency increase can be obtained by improving power transmission. All available output energy is consumed mainly by accelerating the platform and overcoming slopes. Uku was driven under different road conditions. Its offroad movement required more power to accelerate the vehicle due to frequent slopes and high terrain roughness. The aerodynamic drag effect was negligible in case of both UGVs as expected because the platforms were operated at low speed only.

By using the proposed profiles, the energy efficiency of different design candidates can be better estimated and the result is a good input also for a more complex path and mission planning. For example, an agricultural mission like free-flowing pile pushing in farms [27] or soil sampling can be utilized by an optimized mobile robot platform.

4. DISCUSSION

Although the practical exploitation of universal UGV platforms is gaining ever more interest and new development projects are often introduced, evaluation of the performance and energy efficiency is not common. Consumers clearly benefit from getting objective benchmarks through standardized testing. Energy efficiency and versatility of platform design must become commonplace. As robot platforms are often designed as universal, design requirements consider multiple aspects, which makes optimizing energy efficiency and meeting requirements complex.

Validated and accurate energy efficiency information and design guidelines based on it further great improvements for optimizing UGV platforms. Several improvements to platforms can be suggested by the compiled efficiency profiles. All platforms should be fitted with tires of lower rolling resistance as the terrain is fairly even. Uku could benefit from powertrain development, shifted centre of gravity, and differential transmission. Tracdrone's articulated steering and hydraulic powertrain are not designed for smooth handling and long driving being too sensitive and inefficient. A database of the testing results for several mobile platforms can be used for predicting the results when similar solutions are under development. Although simulation and estimation methods are available for early design support, a comparative database would greatly enhance energy efficiency forecasting. More precise input to simulations yields better output.

All obtained profiles should be saved to an open database for future use. Currently there are no freely available databases for example of rolling resistances of different sufficiently described tyres. XML-based design models enable to make automatic cross-linking between different profiles. When new information is uploaded, the system would benefit from self-training algorithms. The solution could become a valuable part of an online knowledge base that combines information and great tools to aid the design process of mobile robotics. The already configured and validated components would be freely available. In addition, a common knowledge sharing environment would activate cooperation between small and medium-sized enterprises and research institutes.

5. CONCLUSIONS

Today medium-sized UGVs are entering into civilian market and, together with the growing demand, this creates a stronger need for handling the complex design process. As energy efficiency is always one of the most important factors in consumer products, it is especially important to consider it in the design process at an early stage. Validated and accurate energy efficiency information and design guidelines could greatly enhance UGV platform optimization. The current research concentrates on a direct numerical performance and energy efficiency measurement method of UGV platforms in contrast to other, scoring and judging based methods. The key parameters of energy efficiency are examined based on two available medium-size UGVs that have different layouts. As robot platforms are often designed as more or less universal, design requirements have to consider multiple aspects, which makes optimizing energy efficiency complex and involving opposing requirements.

Although accelerating and resistive forces can be measured together, it is not enough to know the summary values. Instead, design analysis requires that the applied forces be separated from each other and described individually. Therefore, some UGV design parameters should be measured directly (e.g. weight), during an isolated test (rolling resistance), or calculated (drag area). Others can be calculated from dynamic data recorded with a self-contained measurement system during the real-condition test mission. Based on testing results, energy efficiency profiles can be compiled for the both UGVs to indicate the most suitable UGV design for particular missions for energy efficiency maximization. The purpose of testing the existing designs for various mission parts was to develop a profile library, which can be used for early design simulations by providing validated energy efficiency expectations for certain types of UGV platforms. There is a great need for such an engineering toolkit that allows easy platform design validation, comparison, and efficiency prediction.

The efficiency profile of a platform represents the index of suitability under the desired conditions. Both UGV platforms are in active development; therefore, the measurement results are used constantly to adjust their mobile efficiency maps. While assessing the resistive forces, we can also presume the UGV useful force capability and assign executable missions based on this. As both UGVs are built for universal use, suitable for many missions and tasks, their limits can be tested and therefore the optimal range of use can be recommended. In general, the energy consumption graphs for different designs and the analysed sources of inefficiencies are used for design validation to support especially early-stage platform development and later navigation efficiency improvement.

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Energiaefektiivsuse profiilid mehitamata sõidukitele

Eero Väljaots ja Raivo Sell

On käsitletud mehitamata sõidukite energiaefektiivsuse valideerimist. See sõltub kasutatavatest konstruktsioonielementidest, keskkonnast ja juhtsüsteemist. Kõigi sõiduki platvormi konstruktsiooni mõjurite hindamine nõuab sõidukiga integreeritud mõõtesüsteemi keskkonna vastastikmõjude testimist sõiduki kasutusalal. Mõõdistatud profiile kasutatakse sõidukite konstruktsiooni ja juhtsüsteemi optimeerimiseks ning võrdluseks teiste sõidukitega. Tulemusi kasutatakse andmebaasi loomiseks, mis kiirendab arendust, simulatsiooni ja testimist eelkõige projekteerimise varases faasis.