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DESIGNING A HYBRID DRIVE SYSTEM FOR A MEDIUM-SIZED UNMANNED LAND PLATFORM

Abstract. The project was realized as a study preceding the implementation of an innovative hybrid combustion/ electric drive system for an unmanned land platform with a weight of 800 kg. Based on a dynamic model of a hybrid drive system for an unmanned land platform, the target parameters of the drive were specified and its components were sized and selected. A vehicle operating mode was developed and components were reselected with a view to attain the lowest possible weight. A conceptual structural form of an unmanned land vehicle platform was developed.

Keywords: hybrid drive, drive system, wheeled vehicle, drive dynamics.

1. INTRODUCTION

Unmanned land platforms are used by the police and army to carry out reconnaissance, surveillance and engineering tasks. In civilian applications unmanned vehicles are used in disaster response operations or in conducting field research tasks in inaccessible or contaminated areas.

The functioning of these platforms depends heavily on energy sources that enable operation of the installed instruments or equipment and relocation thereof to the target destination. The operating range and time of a vehicle depends on the efficiency of the drive system. It is therefore essential to design drive systems that are capable of meeting all requirements set on vehicles.

The drive system includes a power source and fuel necessary to produce mechanical energy that sets the vehicle into motion. Various types of drives are used nowadays, and selection thereof depends on the application of the vehicle and its mode of operation. When developing a drive system it is necessary to formulate a dynamic model that corresponds to the vehicle type and its operation and movements. One of the purposes of conducting dynamic analysis is to determine the power of engines/motors required to negotiate obstacles under maximum loads and motion resistance and optimization of the drive system. The power required to drive the vehicle defines the type and size of components, which in turn have an effect on the dimensions and shape of the vehicle.

The methodology applied for setting up the drive system involves selection of components in the opposite sequence than the general direction of energy transfer in the drive system. The energy of the system, stored in chemical form in the fuel tank, is converted in the combustion engine into mechanical energy, and then into electric energy in the power generator. The latter, in turn, is stored in batteries, from where it flows to electric motors which convert it into mechanical energy. Designing starts with defining the forces that act on the vehicle and its drive system. The following elements in the kinematic chain are taken into consideration: wheels, reduction gear, up to electric motor and batteries. The last stage is sizing and selection of power generator and combustion engine along with fuel tank.

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2. FORMULATION OF DESIGN REQUIREMENTS

Based on the analysis of the need to put into military service logistic and engineering platforms, initial requirements for the platform were formulated. The requirements and objectives with regard to the drive system for the medium-sized unmanned land platform under design are as follows:

- total weight of vehicle – 800 kg,
- travelling speed - 20 km/h,
- instantaneous travelling speed - 30 km/h,
- travel at 5 km/h for 8 h,
- silent mode travel possible in any terrain type,
- negotiating narrow passages - 1.2 to 1.5 m,
- turning radius - 4 m, capability of turning in place,
- negotiating rubble heaps, high curbs, stairs, marsh and desert areas,

3. DEVELOPING A CONCEPT DESIGN OF THE DRIVE SYSTEM

3.1. Proposed solutions of the drive system

The drive unit must meet the requirements specified above and in addition it must have appropriate performance specifications among the available solutions. In order to determine the optimum drive system to be used in the unmanned land platform, multi-criteria analysis was applied evaluating every possible drive option [4].

The drive systems selected, are those that are in general use in similar designs and meet most of the specified requirements. The drive systems were classified into main categories differing in the manner of converting chemical or electric energy into mechanical energy. These include the following systems: internal combustion, electrical, hydrostatic, parallel hybrid, series hybrid, mixed hybrid and hydrogen fuel cells [2].

3.2. Criteria of selecting a drive system

When sizing and selecting an appropriate drive system, the criteria adopted included those that referred to the fundamental requirements and features of special vehicles, such as: weight ratio of drive system to vehicle, fuel type and consumption rate, vehicle steerability, efficiency of the drive system, optimum utilization of engine/motor performance characteristics, dimensions in relation to output, noise emissions (including silent mode), operation in contaminated area or in low/high temperature regions.

3.3. Results of multi-criteria analysis

Multi-criteria analysis was applied to make an optimum selection of a drive system from among alternative designs. The results of the multi-criteria analysis are presented in Table 1.

Table 1. Results of multi-criteria analysis regarding drive system selection

	weight	mechanical		elektrical		hydrostatic		series hybrid		parallel hybrid		mixed hybrid		fuel cells		ideal drive	
		rating	product	rating	product	rating	product	rating	product	rating	product	rating	product	rating	product	rating	product
k1	18	5	90	4	72	4	72	3	54	3	54	3	54	5	90	5	90
k2	22	1	22	4	88	2	44	4	88	2	44	3	66	5	110	5	110
k3	2	3	6	5	10	4	8	5	10	5	10	5	10	5	10	5	10
k4	9	4	36	4	36	4	36	4	36	4	36	4	36	4	36	5	45
k5	14	1	14	5	70	4	56	4	56	4	56	4	56	2	28	5	70
k6	14	1	14	4	56	4	56	5	70	5	70	5	70	4	56	5	70
k7	2	3	6	5	10	3	6	4	8	4	8	4	8	1	2	5	10
k8	22	3	66	1	22	3	66	5	110	5	110	5	110	2	44	5	110
k9	2	4	8	3	6	3	6	4	8	4	8	4	8	3	6	5	10
k10	6	4	24	3	18	4	24	3	18	3	18	2	12	3	18	5	30
k11	9	2	18	4	36	3	27	5	45	4	36	5	45	3	27	5	45
k12	14	1	14	5	70	1	14	5	70	1	14	3	42	5	70	5	70
k13	22	5	110	4	88	4	88	3	66	3	66	3	66	2	44	5	110
k14	11	5	55	3	33	5	55	4	44	4	44	4	44	3	33	5	55
		total	483	total	615	total	558	total	683	total	574	total	627	total	574	total	835
		%	57,8	%	73,7	%	66,8	%	81,8	%	68,7	%	75,1	%	68,7	%	100,0

The analysis carried out has shown that a series hybrid drive was the optimum choice among the drives considered. A block diagram of the drive system with all the basic components and direction of power transmission is shown in Fig. 1.

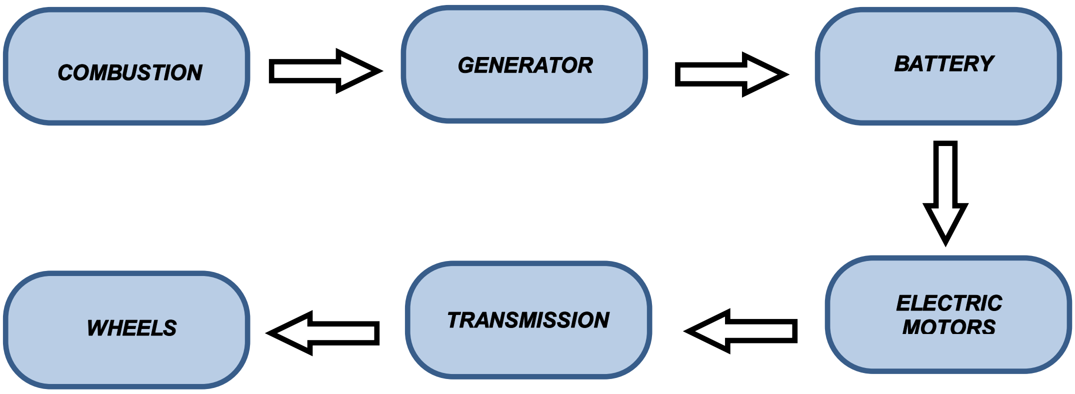

Fig. 1. Block diagram of a series hybrid drive

3.4. Summary of drive system selection

The hybrid drive meets basic environmental requirements, effected by reducing fossil fuel consumption without compromising traction specifications. Fuel consumption reduction is advantageous as it enables extending the travel range of the vehicle or minimizing the size of the fuel tank or of the engine [4], [5], [6], [7].

Another advantage of the series hybrid system is the ability to start driving using only the electric motors, which significantly reduces the platform preparation and launching time. The series hybrid system comprises components connected in series, such as: engine, generator, batteries, electric motors. Modular design of the vehicle enables fast and easy disassembly [4], [5], [6], [7].

The main advantage of this system is moving in silent mode, that is using only the electric motors. Because of the risk of a short circuit in the wiring system, the body has to be tightly sealed to allow deep fording and remaining in water. Prolonged fording requires air to be supplied to the engine which charges the batteries [4], [5], [6], [7].

4. DEVELOPING A CONCEPT DESIGN OF THE TRACTION SYSTEM

4.1. Proposed traction systems

The next stage of the design is the selection and sizing of the traction system which is responsible for vehicle mobility and traction performance. Proper suspension and traction system are the main factors enabling driving in various type of terrain and attaining required speeds. This system should meet the set initial objectives. In an unmanned land platform the traction system must meet the set criteria and must have the highest possible capabilities and properties [1].

There are now a number of traction systems used in vehicles. Bearing in mind the cost and complex design, the systems selected were those that were most common and used in similar vehicles: tracked, wheeled 4x4, wheeled 6x6, semi-tracked, mixed, stepping, screw. Each drive has different properties and capabilities. The advantages and drawbacks of the systems were subjected to multi-criteria analysis.

4.2. Criteria of selecting a traction system

When sizing and selecting an appropriate propeller, the criteria adopted included those that referred to the fundamental requirements and features of special vehicles, such as: ability to negotiate obstacles and upgrades, travelling speed, driving in marsh, sandy, snow-covered land, resistance to damage, failure rate, cost of manufacture, overall dimensions in relation to vehicle weight, agility and response to change in driving direction.

4.3. Results of multi-criteria analysis

When sizing and selecting an appropriate traction system, the criteria adopted included those that referred to the fundamental requirements and features of special vehicles. The results are listed in Table 2.

Table 2. Results of multi-criteria analysis regarding traction system selection

	weigh	tracked		4x4		6x6		semi-tracked		mixed		stepping		screw		ideal	
		rating	product	rating	product	rating	product	rating	product	rating	product	rating	product	rating	product	rating	product
k1	22	4	88	2	44	3	66	3	66	4	88	4	88	3	66	5	110
k2	17	4	68	5	85	5	85	3	51	4	68	1	17	3	51	5	85
k3	22	4	88	2	44	3	66	3	66	4	88	2	44	5	110	5	110
k4	13	3	39	4	52	5	65	2	26	3	39	2	26	4	52	5	65
k5	13	3	39	4	52	4	52	3	39	3	39	3	39	4	52	5	65
k6	5	3	15	5	25	5	25	3	15	3	15	2	10	5	25	5	25
k7	4	3	12	5	20	4	16	2	8	2	8	2	8	5	20	5	20
k8	2	5	10	4	8	4	8	4	8	2	4	2	4	4	8	5	10
k9	1	3	3	5	5	5	5	3	3	2	2	3	3	3	3	5	5
k10	17	5	85	4	68	4	68	5	85	4	68	1	17	3	51	5	85
k11	22	4	88	5	110	5	110	4	88	5	110	5	110	1	22	5	110
k12	10	5	50	4	40	4	40	2	20	5	50	5	50	5	50	5	50
		total	585	total	553	total	606	total	475	total	579	total	416	total	510	total	740
		%	79,1	%	74,7	%	81,9	%	64,2	%	78,2	%	56,2	%	68,9	%	100,0

4.4. Summary of traction system selection

The 6x6 wheeled traction system proved to be optimal among those analyzed. It meets all objectives and requirements for unmanned land platforms. The traction systems analyzed

(Table 2) perform well in terms of some of the objectives only, whereas the 6x6 system meets all set requirements at a satisfactory level [2] [6].

Fig. 2. Hoot ATV 6x6 vehicle with 3 rigid axles

Turning in a 6x6 system can be effected in one of two manners: by turning the wheels of two or three axles in accordance with Ackermann geometry or by varying the speed of the left-hand and right-hand wheels [2] [6].

The advantages of this system include simple design and resistance to damage, as the vehicle can move after losing one wheel. Low failure rate and ability to negotiate any obstacle warrants superiority over other solutions [2] [6].

5. CALCULATIONS

5.1. Dynamic parameters

The input data for dynamic analysis includes forces and dynamic parameters of the vehicle. Forces include resisting forces which counteract the motion of the vehicle, and driving forces, which set the vehicle in motion [2] [3].

The basic problem in vehicle dynamics is the comparison between the values of the resisting forces and of the driving forces. In order to set a vehicle in motion the driving force must be higher than the total resisting force, otherwise the vehicle will not be able to start moving or, if it was already set in motion, it will decelerate. A mathematical model was formulated on the basis of the following relationships [2] [3]:

$$F_n = F_t + F_p + F_w + F_b + F_s, \qquad [N] \tag{1}$$

$\mathbf{F_t}$ - rolling resistance;
$\mathbf{F_s}$ - turning resistance;
$\mathbf{F_p}$ - air resistance;
$\mathbf{F_b}$ - resistance of inertia;
$\mathbf{F_w}$- grade resistance.

Similarly, in the case of vehicle turning, resistance to motion is transformed into moments of force about the centre of rotation of the vehicle. The sum of the moments of forces of resistance to motion is equal to the moment of the driving force $\boldsymbol{M_n}$ about the vehicle rotation axis, which is reflected in the relationship:

$$M_n = M_t + M_p + M_w + M_b + M_g, \qquad [Nm] \tag{2}$$

where:
M_t – moment of rolling resistance forces about the vehicle rotation axis;
M_p – moment of air resistance forces about the vehicle rotation axis;
M_w – moment of grade resistance forces about the vehicle rotation axis;
M_b – moment of inertial resistance forces about the vehicle rotation axis;
M_g – moment of turning resistance forces about the vehicle rotation axis.

Resisting forces and driving forces depend on many factors, such as turning resistance, friction, driving uphill, type of ground surface, vehicle speed, air resistance, engine characteristics, transmission ratio, condition of system components [2] [3].

5.3. Analytical calculations

Calculations were done for four different situations: vehicle accelerates travelling straight, travelling uphill and when making a zero turn and a turn with the inside wheels halted. Analytical calculations were input into Matlab software in the form of a script containing the above data and formulas. Each variable was assigned a specific value and, based on that, an analytical model was constructed according to the requirements. Script based on the particular analytical model provides the specific value sought.

5.4. Numerical calculations

A fully parametric model of the drive system of the unmanned land platform was created in the Matlab Simulink environment for both straight line driving and turning. Dynamic Simulink environment enables making numerical simulations of a drive system.

5.5. Summary

Results of analytical and numerical calculations for the four situations are compared in Tables 3, 4, 5 and 6. Each of the tables is divided into two segments, where the first shows resisting forces acting on the vehicle, and the second shows basic dynamic parameters determined for the individual components of the drive system. The adopted drive system comprises an electric motor placed in the wheel and a planetary gear.

Table 3. Results of analytical and numerical calculations for case 1 (vehicle acceleration driving in straight line)

	RESULTS OF ANALYTICAL CALCULATIONS		RESULTS OF NUMERICAL CALCULATIONS		
Surface	asphalt	sand	asphalt	sand	
Rolling resistance	110	1767	110	1766	N
Resistance of inertia	2240	2240	2280	2272	N
Air resistance	40	40	41	31	N
Turning resistance	0	0	0	0	N
Grade resistance	0	0	0	0	N
Total resistance force	2390	4047	2431	4069	N
Moment on wheel	120	202	126	214	Nm
Rpm of wheel	265	265	282	278	min^{-1}
Output on wheel	3.3	5.6	3.3	5.5	kW
Transmission ratio	35	35	35	35	
Moment on motor	4	6	4	6	Nm
Rpm of motor	9252	9252	9880	9740	min^{-1}
Motor output	3.5	5.9	3.5	5.8	kW

Table 4. Results of analytical and numerical calculations for case 2 (vehicle acceleration driving in straight line uphill)

	RESULTS OF ANALYTICAL CALCULATIONS		RESULTS OF NUMERICAL CALCULATIONS		
Surface	asphalt	sand	asphalt	sand	
Rolling resistance	99	1596	110	1766	N
Resistance of inertia	800	800	840	920	N
Air resistance	39	39	38	41	N
Turning resistance	0	0	0	0	N
Grade resistance	3924	3924	3925	3925	N
Total resistance force	4862	6359	4913	6652	N
Moment on wheel	243	318	255	336	Nm
Rpm of wheel	264	264	257	257	min^{-1}
Output on wheel	6.7	8.8	6	8	kW
Transmission ratio	35	35	35	35	
Moment on motor	7	10	7	10	Nm
Rpm of motor	9251	9251	8980	8980	min^{-1}
Motor output	7	9.3	6.4	8.4	kW

Table 5. Results of analytical and numerical calculations for case 3 (vehicle making a zero turn)

	RESULTS OF ANALYTICAL CALCULATIONS		RESULTS OF NUMERICAL CALCULATIONS		
Surface	asphalt	sand	asphalt	sand	
Rolling resistance	55	883	110	883	N
Resistance of inertia	217	217	307	296	N
Air resistance	0	0	0	0	N
Turning resistance	3140	1295	3150	1295	N
Grade resistance	0	0	0	0	N
Total resistance force	3412	2395	3567	2474	N
Moment on wheel	314	239	339	238	Nm
Rpm of wheel	29	29	24	27	min^{-1}
Output on wheel	1	0.7	0.9	0.8	kW
Transmission ratio	35	35	35	35	
Moment on motor	10	7	10	7	Nm
Rpm of motor	1000	1000	840	950	min^{-1}
Motor output	1.1	0.8	1	0.8	kW

Table 6. Results of analytical and numerical calculations for case 4 (vehicle making a turn with inside wheels halted)

	RESULTS OF ANALYTICAL CALCULATIONS		RESULTS OF NUMERICAL CALCULATIONS		
Surface	asphalt	sand	asphalt	sand	
Rolling resistance	99	1596	99	1596	N
Resistance of inertia	337	336	536	400	N
Air resistance	0	0	0	0	N
Turning resistance	3139	1295	3139	1295	N
Grade resistance	1962	1962	1680	1680	N
Total resistance force	5537	5189	5454	4971	N
Moment on wheel	548	439	548	439	Nm
Rpm of wheel	57	57	49	57	min^{-1}
Output on wheel	3.3	2.6	2.9	2.3	kW
Transmission ratio	35	35	35	35	
Moment on motor	17	13	17	13	Nm
Rpm of motor	2000	2000	1700	1700	min^{-1}
Motor output	3.5	2.8	2.9	2.5	kW

6. SELECTION AND SIZING OF DRIVE SYSTEM COMPONENTS

6.1. Determination of energy consumption rate of vehicle

In the case of hybrid drives, proper selection of components of the drive system is largely dependent on the mode of vehicle operation. Operating mode takes into account the conditions and parameters of the vehicle and terrain configuration. The advantage of hybrid drives is the possibility of storing energy that is used in emergency and rare situations. The main engine (combustion engine) takes advantage of that situation and runs within its optimum operating range.

The target range of the vehicle in silent mode should be about 10 km when driving on an asphalt road and 5 km on grassy surface. Reaction forces that occur when driving are derived from rolling resistance and air resistance of the vehicle. Air resistance strongly depends on speed; for the adopted continuous speed of 20 km/h air resistance is 470 kN. Rolling resistance is independent of vehicle motion parameters and is equal to 110 N when driving on an asphalt road and to 630 N when driving on grassy ground (tall grass). Therefore the total resistance is: 580 N and 1100 N, respectively, while numerical simulation gives the following results: 554 N and 1074 N, respectively. Based on the values presented, the work done by a vehicle (in joules) can be determined from the following relatioship:

$$W = \frac{(F_t + F_p) * S}{\eta_g + \eta} \tag{3}$$

where:

- $\mathbf{F_t}$ - rolling resistance (N);
- $\mathbf{F_p}$ - air resistance (N);
- **S** – total distance covered (m);
- $\boldsymbol{\eta_g}$ - efficiency of the traction system;
- $\boldsymbol{\eta}$- efficiency of the power transmission.

6.2. Selection and sizing of motors

For the purpose of carrying out concept analysis, the following traction motors were initially selected: brushless direct current motors with an instantaneous output of 12 kW at a voltage of 72V. This type of motors is used, for instance, in cars, motorcycles, boats and powered hang gliders. Specifications of the motors are listed in Table 7.

Table 7. Specifications of the selected electric motors

Voltage	**72 V**
Max. instantenous output	12 kW
Max. continuous output	6 kW
Maximum current consumption	180 A
Current consumption under continuous duty	90 A
Speed under continuous duty	9000 min^{-1}
Max. instantaneous torque	13 Nm
Torque under continuous duty	6 Nm
Weight	2.6 kg
Dimensions (Length x Width x Height)	170 mm x 100 mm x 100 mm

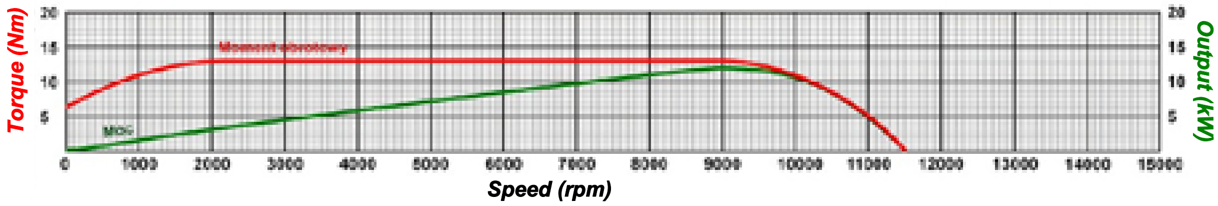

Fig. 3. Characteristics of the selected electric motor (supply voltage 72 V)

6.3. Selection and sizing of batteries

The law of conservation of energy indicates that work done by a vehicle should be equal to the work provided by batteries. This rule enables the determination of the capacity of batteries C (in ampere-hours Ah) using the relationship:

$$C = \frac{W}{U * 3600} \tag{4}$$

where:

C - capacity of batteries (Ah)

W - work done by the vehicle (J)

U - current voltage of batteries (V).

Work done by the vehicle travelling on an asphalt road is 6.4 MJ. The total capacity of batteries, corresponding to the above calculated work, is 37.2 Ah. Work done when travelling over grass is 12.2 MJ, and the corresponding capacity of batteries is 70.5 Ah.

A set of three LiFePO4 72V/20Ah batteries was selected. Specifications thereof are listed in Table 8.

Table 8. Battery specifications

Capacity	**20 Ah**
Voltage	72 V
Weight	17 kg
Dimensions (Length x Width x Height)	560 mm x 150 mm x 160 mm

6.4. Selection of transmission gears, generators and engines

Transmission ratio was sized taking into account maximum speed of the vehicle (30 km/h) and maximum speeds of standard electric motors (ca. 9000 rpm at 70V supply voltage) for similar applications. Reduction of the set speeds generated a high torque on the output shaft of the transmission. The adopted transmission ratio was i=35 and it was taken into ccount in the analyses conducted. The design concept included parallel operation of two power generators of different output, each of them driven by a separate engine. This solution allows adjusting power delivery to the demand of the vehicle. The generators may operate in individual or common mode. The first, "smaller" generator is an electric machine with continuous output of 5 kW and instantaneous output of 8.5 kW, while the other generator has continuous output of 10 kW and instantaneous output of 20 kW. Both machines may operate in motor or generator mode. Table 9 lists specifications of the 5 kW generator, Table 10 that of the 10 kW generator.

Table 9. Specifications of the 5 kW generator

Voltage	**72 V**
Max. instantaneous output	8.5 kW
Max. continuous output	5 kW
Current consumption under continuous duty	158 A
Maximum instantaneous speed	6000 min^{-1}
Speed under continuous duty	3200 min^{-1}
Max. instantaneous torque	27.7 Nm
Torque under continuous duty	14 Nm
Generator and inverter weight	14.5 kg
Dimensions (Length x Width x Height)	206 mm x 206 mm x 126 mm

Table 10. Specifications of the 10 kW generator

Voltage	**72 V**
Max. instantaneous output	20 kW
Max. continuous output	10 kW
Current consumption under continuous duty	194 A
Maximum instantaneous speed	6000 min^{-1}
Speed under continuous duty	2000 min^{-1}
Max. instantaneous torque	35 Nm
Torque under continuous duty	12 Nm
Generator and inverter weight	20.2 kg
Dimensions (Length x Width x Height)	206 mm x 206 mm x 170 mm

Two Diesel engines were selected for driving the generators: one single-cylinder engine with an output of 7.5 kW and one two-cylinder engine with an output of 17 kW. Table 11 lists specifications of the 7.5 kW engine, and Table 12 that of the 17 kW engine.

Table 11. Specifications of the 7.5 kW engine

Fuel type	**Diesel oil**
Cubic capacity	460 cm^3
Max. output at rpm	3600 min^{-1}
Output	7.5 kW
Maximum torque	24.9 Nm
Weight	48 kg
Dimensions (Length x Width x Height)	392 mm x 480 mm x 335 mm

Table 12. Specifications of the 17 kW engine

Fuel type	**Diesel oil**
Cubic capacity	1000 cm^3
Max. output at rpm	3000 min^{-1}
Output	17 kW
Maximum torque	50 Nm
Weight	100 kg
Dimensions (Length x Width x Height)	582 mm x 587 mm x 461 mm

7. SUMMARY

The determined dynamic loads acting on the vehicle drive system enable formulating a concept of a hybrid drive with account taken of the parameters required for the planned platform and optimization of the drive system to determine the required parameters of its components. The tool for selecting the optimal design of the drive and traction systems were the results of multi-criteria analysis the subject of which were both the widely known solutions applied in drive and traction systems, as well as prospective solutions (fuel cell for drive) and less widespread solutions (screw and stepping drive). Results of the multi-criteria analysis led to the choice of the commonly applied design in the form of a series hybrid drive and the 6 x 6 system.

Dynamic analysis and preliminary sizing of components of the selected drive and traction systems were carried out. The adopted mode of turning the vehicle was by varying the speed of wheels on opposite sides of the vehicle. Calculations performed for the selected load cases confirm the correct sizing of the drive components for the medium-sized unmanned platform under design.

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