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INSTITUTE OF ENERGY TECHNOLOGY
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MASTER’S THESIS

ENERGY AND DYNAMICS OF THE SOLAR AGRICULTURAL ROBOT “SolarSprayer”

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ABSTRACT

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Energy and dynamics of the solar agricultural robot "SolarSprayer"

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The main objective of the present study was to design an agricultural robot, which work is based on the generation of the electricity by the solar panel. To achieve the proper operation of the robot according to the assumed working cycle the detailed design of the main equipment was made. By analysing the possible areas of implementation together with developments, the economic forecast was held.

As a result a decision about possibility of such device working in agricultural sector was made and the probable topics of the further study were found out.

Table of contents

ABSTRACT 2

Table of contents 3

Abbreviations and symbols 5

Acknowledgements 7

1. Introduction 8
    - 1.1 Statement of the problem 11
    - 1.2 Plantation model 12
    - 1.3 Working cycle 12
2. Robot model 16
    - 2.1 Main requirements 16
    - 2.2 Main parts 17
    - 2.3 Robot outlook sketch 18
3. Physics of the robot 19
    - 3.1 Movement analysis 19
    - 3.2 Spraying analysis 22
    - 3.3 Lifting and lowering of the spraying hood 23
4. Power concumption analysis 26
5. Motors selection 30
6. Solar station design 37
    - 6.1 Main components 37
    - 6.2 Solar panel selection 38
    - 6.3 Charge controller selection 41
    - 6.4 Battery selection 45
7. Energy balance of the system 49
    - 7.1 Charging process 49
    - 7.2 Discharging process 52
    - 7.3 Energy balance 55
8. Control of the robot 56
    - 8.1 Control types 56
    - 8.2 Control decision 60
    - 8.3 Robot control block diagram 60

9. Possible application place analysis 62
10. Possible add-ons and changes 64
Conclusion 66
References 68

Abbreviations and symbols

AC – Alternating Current

DC – Direct Current

DoD – Depth of Discharge

GPS – Global Positioning System

Li-ion – Lithium-ion

MPPT – Maximum Power Point Tracking

PDA – Personal Digital Assistant

PI – Proportional Integral

PVC – Polyvynil chloride

PV – Photovoltaic

PWM – pulse width modulation

R/C – remote control

RF – radio frequency

STC – standard test conditions

TCP/IP – transmission control protocol/internet protocol

UAV – unmanned aerial vehicles

A – aerodynamic area

C – numerical value of rated capacity

C_{bat} – required capacity of the battery

C_{D} – aerodynamic coefficient

C_{R} – rolling friction coefficient

D – droplet size

E_{bat} – required energy of the battery

F_{lift} – lifting force

g – free fall acceleration

h – average height of the plant

I – charge/discharge current

I_{av} – average battery discharging current

$I_{\mathrm{discharge}}$ – discharging current

M –multiple or fraction of capacity

m – mass of the robot

n – Peukert's exponent

n_1 – time in hours at which capacity is declared

P_1 – mechanical power for straight movement

P_{11} – mechanical power of wheel 1

P_2 – mechanical power for Turn 1

P_{22} – mechanical power of wheel 2

P_3 – mechanical power for Turn 2

P_{33} – mechanical power of wheel 3

P_{44} – mechanical power of wheel 4

P_{D} – aerodynamic friction power factor

P_{G} – surface gradient power factor

P_{lift} – lifting mechanical power

P_{mech} – output mechanical power of motor UFR1

P_{move} – mechanical power of robot’s movement

P_{peak} – peak output inverter power

P_{R} – rolling resistance power factor

P_{S} – mechanical power of spraying

P_{T} – total power factor

$P_{\mathrm{T\_max}}$ – maximum total mechanical power

Q – flow rate of the chemical

S – surface area created in unit time

$t_{\mathrm{ch\_ideal}}$ – ideal maximum charging time

$t_{\mathrm{ch\_real}}$ – real maximum charging time

$t_{\mathrm{discharge}}$ – discharge time

ν – robot’s speed

ν_1 – speed during straight movement

ν_2 – speed during Turn 1

ν_3 – speed during Turn 2

ν_{lift} – lifting speed

γ – surface tension of the herbicide

η – efficiency of atomizing

η_{av} – electrical motors assumed average efficiency

θ – surface angle

ρ – air density

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1. Introduction

Solar is a unique source of energy which can be used in a great variety of ways (see [1]). Its availability depends on the number of sunny days in the particular region and sun activity (see Fig. 1). The reason of great interest connected with this energy source is the lack of emissions and requirements needed to implement it.

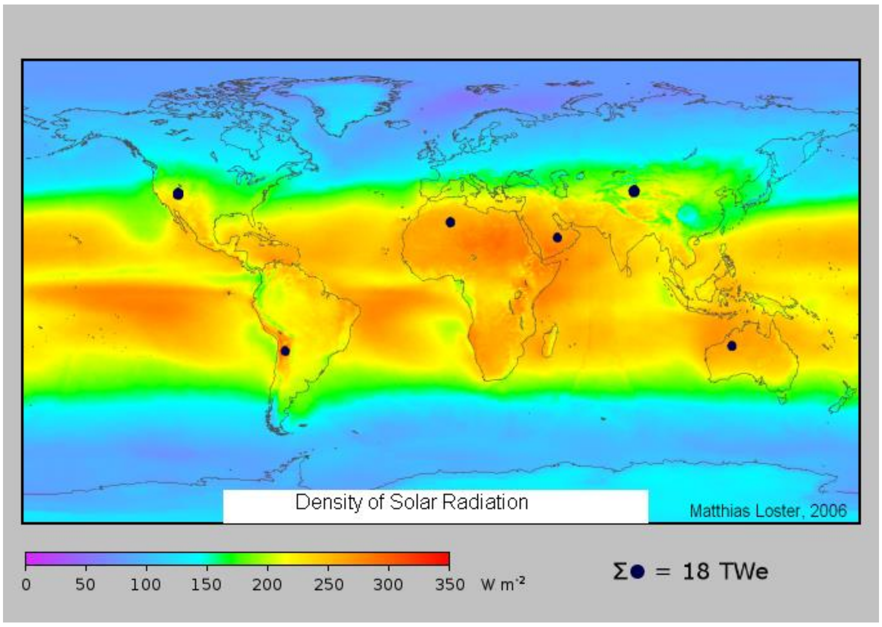

Fig.1: Solar radiation on Earth

Nowadays solar energy finds applications in many different tasks and science fields, one of which is agricultural processes. The automation of processes (see [2]) can make the life of farmers much easier, considering that the work under the sun in hot countries is hard and exhausting, which is usually done by common local citizens. Besides sometimes it is very difficult to find working force for such work. Due to the lack of low cost labor, the man work is substituted with fossil-fuel based machines and increasing farm sizes.

These problems could be solved by using agricultural robots. There are already several technical solutions of agricultural automation with the help of robots (see [3]). For example, robotic milking machines become more and more popular on dairy farms. In the fields, new tractors now commonly come with GPS-based automated steering, allowing them to make more efficient use of the fuel they burn, by reducing overlap from one pass to the next and to preserve soil conservation measures, such as terraces, by following contours more accurately.

Spraying equipment, whether tractor-mounted or self-propelled, can now meter out fertilizer, pesticides, herbicides, and fungicides, applying more on parts of the field where the need is greater. While perhaps not yet commercially available, automated pruners for vineyards and automated fruit harvesters (see Fig. 2) are in an advanced stage of development, and should soon be commonplace (see [4]).

Fig.2: Automated fruit harvester

And the last, but not the least, UAVs, also known as drones, which can make an abundance of valuable information available for farmers, and the business of providing such services is set to take off just as soon as the machine determines that the time is right (see Fig. 3). There is also an option to make 24 hours monitoring and gathering important information in a real-time mode, so that it would be easier to control all the plants individually and improve the efficiency.

Fig.3: UAVs outlook

One of the most interesting solutions was named AgriRover (see Fig. 4) designed by a team led by Dr. Andrew Manderson from AgResearch from New Zealand (see [5]). The basic idea behind AgriRover is, instead of using conventional methods of tending to entire fields at one time, the farmer uses robotics and other technologies to deal with problems on a much smaller scale.

Fig.4: AgriRover

A livestock paddock, for example, may look uniform, but under the grass there's a great deal of variability of soil and conditions. Levels of potassium, sulfur, and acidity can be very different even within a single square meter. Ideally, paddocks can be made healthier and more productive if they can be surveyed on a very small scale and each problem area addressed with individual treatment. That is where AgriRover can be applied.

The idea is to have a robot that can autonomously navigate its way around a paddock, send back real-time data on each area, provide on-the-spot treatments or dye markings for each problem encountered, generate prescription maps, and return to base for recharging and resupply. AgriRover is powered by lithium phosphate batteries supplemented with a solar panel for additional range during daylight hours. It's also designed to be small enough to go under two-wire fences and gates.

All this brings up a final topic of the thesis, which main aim is to study the possibility of implementing an agricultural process using solar energy in a robot that is powered with the help of solar panels. The chosen process is spraying fertilizers and chemicals on grape trees, because this is quite important requirement for a proper plant growth and should be done regularly during its growing season (see [6]). Usually grape plantations are located in the sunny countries, which makes the plantation a feasible place to use solar panels. Besides, for farmers such device could be an economically sound alternative with high efficiency that can work almost any time they need.

1.1 Statement of the problem

The main objective of the study is to calculate the energy consumption of the spraying robot for processing during a particular working cycle, and according to the required power, design the robot by selecting all the necessary equipment and its characteristics, which includes: design of the working cycle and robot model, analysis of its mechanics; electrical motors, solar panel, charge controller, battery and inverter selection; energy yield and consumption analysis; application options analysis. As soon as all the grape plantations are different and there are no strict standards of dividing the whole plantation into parts, it was decided that the work of the device will be examined on the example of the plantation model, which is built on the basis of popular sizes and basic regulations that are usually followed. The whole operation will be implemented with the help of electrical drives and solar station which charges the battery of the device and helps to take care of the grape trees.

Thereby the research objective is to examine the possibility of implementing the chosen process on the example of a particular working cycle. First, the assumed model of plantation and working cycle will be analyzed; the results will allow having an idea about overall energy consumption of the system. To achieve that, robot movement and spraying physics will be examined. The amount of needed energy for each process during the working cycle is going to be the basis for electrical motors selection. After motors selection, all the requirements for a solar station, which will provide the system with energy, are examined and all the set of equipment is selected. Then different possible types of control that could be applied in the system are considered. Next, the possible location where the robot could be applied is analyzed on the basis of static information about solar radiation in different countries. Finally, probable add-ons, system integration and the possible directions of the next research made on this topic are discussed.

1.2 Plantation model

As a result it was assumed that an area which the robot will serve during one working cycle includes processing of 450 plants, which form a rectangular with 30 plants in a row and 15 rows (see Fig. 5). The distance between each row is

2.5m, between each plant – 1.5m. The average height of a grape tree is assumed to be 0.8m.

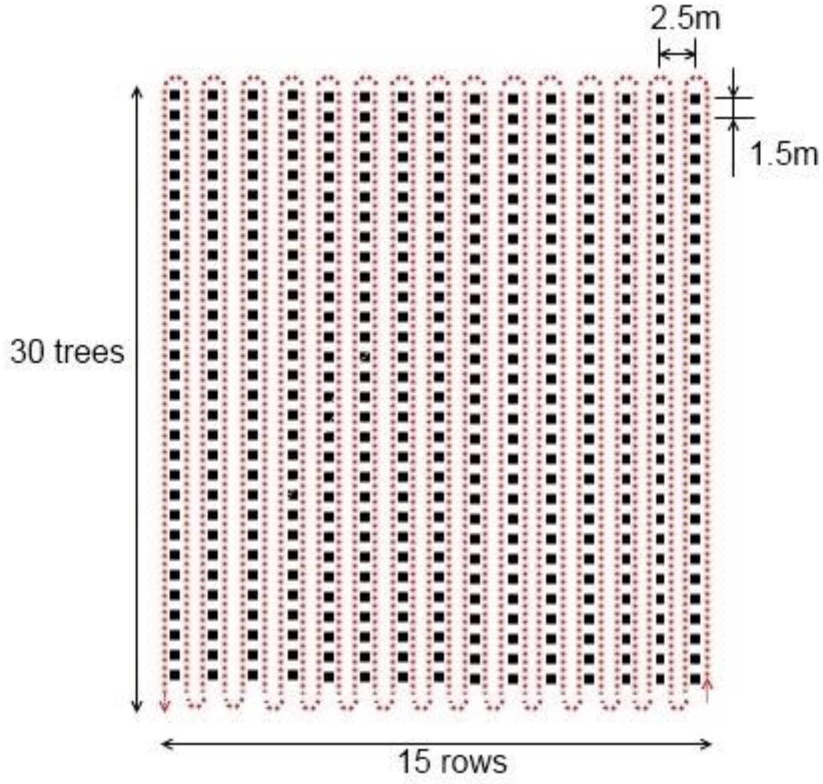

Fig.5: Plantation model

Where, the black square is a grape plant and red dots show the trajectory of the robot during the working cycle

1.3 Working cycle

The robot must spray the chemicals on the trees from both sides and stop in front of each tree to spray it from the earth to the top. From the very beginning the spray hood will be in the down position and when the robot will stop in front of the 1st tree the hood starts going up spraying chemicals at the same time, when the up position is reached, a movement towards the next tree is made and then the hood starts going down.

So the work over the whole area can be described as a number of lifting and lowering of the hood while spraying and moving from one tree to another with turns between rows. For the proper work the strict trajectory must be followed, so the movement should be organized with the minimum mistake and optimal route. This will help to minimize the energy consumption.

The next step is more detailed analysis of the working cycle. To design all the parts of the device there were assumed next time limits for each part of the cycle which can be seen in Table 1. In the beginning of the cycle robot should be placed 1.5m before the first plant:

Table 1: Working cycle time limits

Process	Time, s
Starting motion	5
Movement between plants in one row	5
Spraying	5
Lifting of the spraying hood	5
Lowering of the spraying hood	5
Direct motion before Turn 1	5
Turn 1	5
Direct motion after Turn 1	5
Direct motion before Turn 2	5
Turn 2	8
Direct motion after Turn 2	5

To have an idea how the operations are implemented during the working cycle the following picture (see Fig. 6) shows how the robot movement is organized on the example of the last three trees in a row. All the other operations are implemented the same way so there is no need to illustrate the whole plantation.

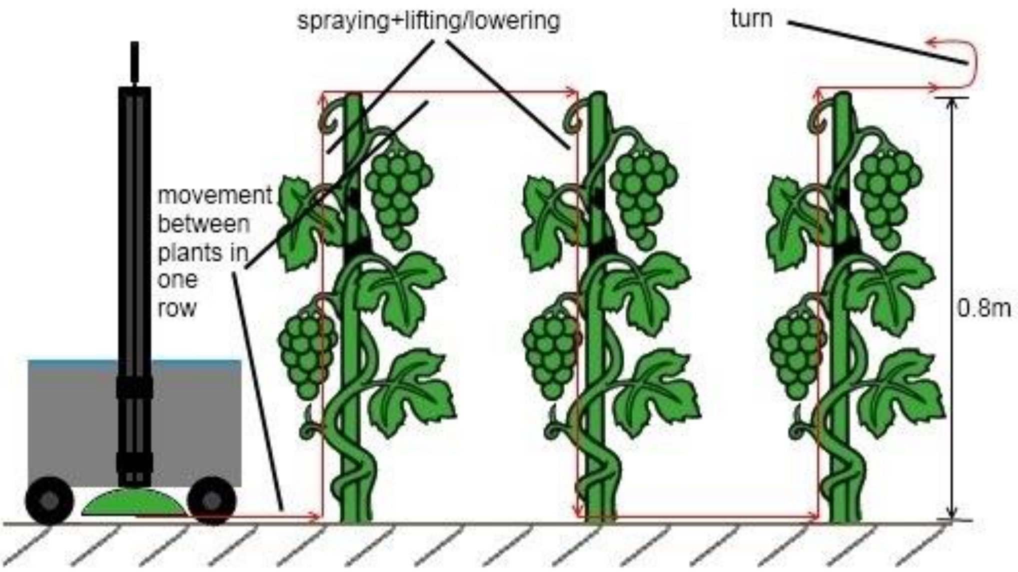

Fig.6: Working cycle operations side view illustration

Thereby the full working cycle is:

- the robot starts working with the Row 1 from the initial point and stops in front of the first tree (wheels' motors, 5 sec.);
- The spraying hood starts going up at the same time processing the plant (lifting motor and spraying motor, 5 sec.);
- The device moves to the second tree (wheels' motors, 5 sec.);
- Processes the tree, while spraying hood is going down (lifting motor and spraying motor, 5 sec.);
- Then the work continues the same way until the robot reaches the last tree in a row;
- After that the robot moves straight to prepare for the turn (wheels' motors, 5 sec.);
- Makes a Turn 1 to get to the other side of row 1, the turn is implemented by the different angular speed of the left and right front wheels (wheel's motors, 5 sec.)
- Then makes a straight move to get to the last tree of Row 1 from the other side (wheels' motors, 5 sec.);
- Process continues the same way as with the first side of Row 1, until the robot comes back to the first tree in Row 1;
- Next the robot starts going to Row 2: makes direct motion before Turn 2 (wheels' motors, 5 sec.);

- Makes Turn 2 using the same method as in Turn 1, but now the speed of the left wheel is higher than the right one (wheels’ motors, 8 sec.);
- Makes direct motion after Turn 2 and stops in front of the first tree in Row 2 (wheels’ motors, 5 sec.);
- After that robot repeats all the previous operations until it stops processing the last tree of Row 15

As a result, the whole work over the plantation model will take 9337 seconds or 2 hours 35 minute 37 seconds to process all the 450 trees. The operations time was assumed to make the speed of the robot constant and is not final and can be changed later according to the sizes of the device and motors power.

2. Robot model

In order to define the most important tools of the device and start designing the separate parts, its characteristics and energy consumption, the list of the main requirements is formed, which come straight out of the working cycle features. Also the auxiliary requirements are analyzed which will help to arrange the connections of separate parts and put everything together.

2.1 Main requirements

On the basis of the requirements of the working cycle the main parts of the device can be sorted out.

The main requirements are:

- The movement of all the parts of the robot should be reliable and with constant speed, that results in needs for electrical motors and their accurate selection to achieve reliable movement with constant speed;
- The main idea is to make the devise almost autonomous with minimum energy consumption; this brings necessity for the solar station design, which includes solar panel, battery, charge controller and inverter. All of them should be sorted out and balanced accurately to achieve optimal operation and charging;
- The process of spraying will be implemented on the basis of device “Mini Mantra” (see [7]);
- The spraying process requires chemical liquid, the whole work and idea of operating is impossible without installation of a tank on the framework of the device, which in addition should have enough volume for optimal operation;

Auxiliary requirements are:

- The movement of the spraying hood also must be implemented with constant speed;
- The movement must follow strict commands in the right order, that is why an installing of the embedded microcontroller is possible;

- The robot positioning should be pretty accurate to achieve high efficient spraying, so an on board GPS sensor is possible;
- To reduce the cost of the device it is better to design it so that one type of electrical drive could suite all the operations;
- Also some sensors are required: the sensor of the level of liquid in the tank and also installment of a camera is possible to achieve more accurate positioning, voltmeter for checking the charge of the battery;
- Lifting and lowering operations require some transmission which will result in additional tools needed for connection of the electrical motor with transmission and spraying hood

2.2 Main parts

The analysis of important requirements allows forming a list of the main parts:

1) Solar panel;
2) Battery;
3) Charge controller
4) Inverter
5) Electrical drives (4 for each wheel, 1 for lifting and lowering the spraying hood, 1 for spraying);
6) Tank with liquid chemicals (volume = 500 mg);
7) Four wheels;
8) Framework;
9) Sensors: liquid level sensor, voltmeter;
10) Microcontroller;
11) Spraying hood;
12) Metal rod for spraying hood movement;

2.3 Robot’s external view

It is important to have an idea how the whole system will look like. Considering that list of the most important devices is already done, it is possible to sketch the robot’s external view (see Fig. 7):

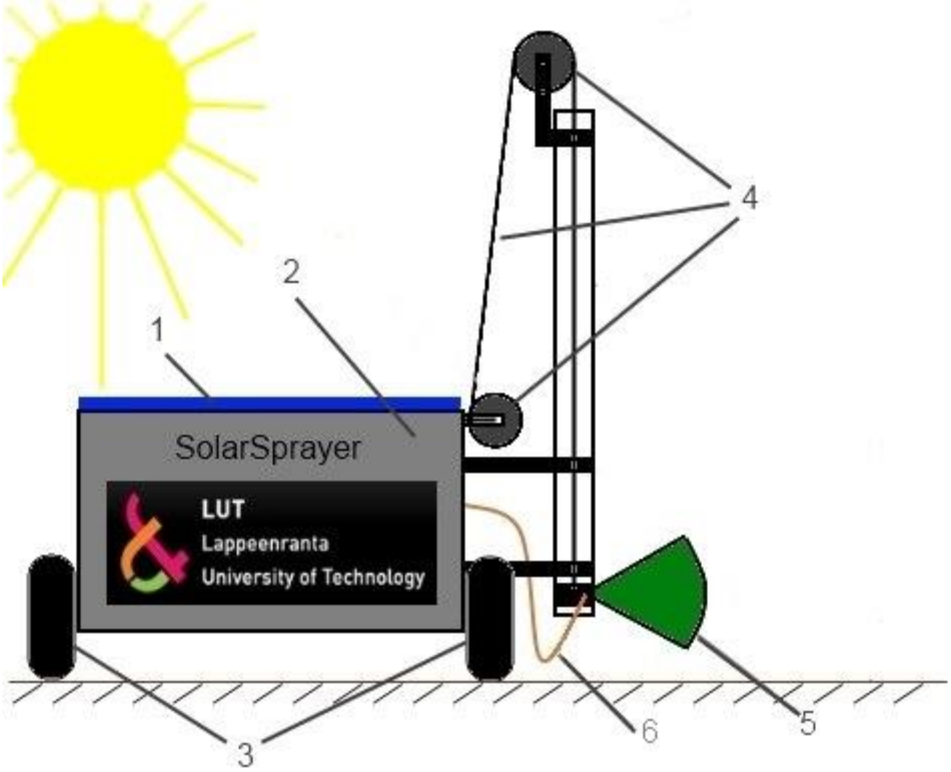

Fig.7: Robot’s external view sketch

Where, solar panel is marked with number 1, number 2 is the robot’s framework, inside which the battery, charge controller, inverter, microcontroller, sensors and liquid tank are placed. Wheels together with electric motors placed on them are marked with number 3. Number 4 is the belt-and-pulley arrangement. Spraying hood is shown by number 5. And a PVC tube is number 6.

3. Physics of the robot

To sort out which particular solar panel and battery the device will need, it is necessary to define the total energy consumption. All the energy which the robot will need is consumed by the electrical drives which make all the movements of the working cycle. So the crucial fact in calculating energy consumption is the power of the electrical drives. To calculate the power it was assumed that the total mass of the robot is 30 kg, considering that only solar panel weights from 5 to 20 kg.

This is the first step of design process and after the mass can be corrected according to the features of the finally chosen parts of the whole system.

3.1 Movement analysis

To move the whole device 4 electric motors must overcome the resisting forces which can be represented as the following power factors (see [8]):

$$P_{\mathrm{T}} = P_{\mathrm{J}} + P_{\mathrm{D}} + P_{\mathrm{R}} + P_{\mathrm{G}} \qquad (1)$$

This formula shows the total power of all the motors together, where

P_{J} – Represents the inertia factor;

P_{D} – Aerodynamic friction power factor;

P_{R} – Rolling resistance power factor;

P_{G}– Surface gradient power factor;

$$P_{\mathrm{D}} = \frac{1}{2}\rho v^3 C_{\mathrm{D}} A \qquad (2)$$

Where ρ – is the air density, v – is the robot’s speed, C_{D} – is the aerodynamic coefficient and A– is the area;

$$P_{\mathrm{R}} = C_{\mathrm{R}} m g v \qquad (3)$$

Where C_R – is the rolling friction coefficient, *m* – is the mass of the robot, *g* – is the free fall acceleration and ν is the speed of the robot;

$$P_\mathrm{J} = \frac{1}{2} m \frac{(\Delta v)^2}{\Delta t} \tag{4}$$

Where *m* – is the mass of the robot, Δ*v* is the change of the speed and Δ*t* is the time during which this change of the speed was made;

$$P_\mathrm{G} = mgvsin\theta \tag{5}$$

Where *m* – is the mass of the robot, *g* – is the free fall acceleration, *v* – is the speed of the robot and θ is the surface angle;

Considering that inertia factor (P_J) is periodically negative and part of energy can be recovered, surface gradient factor (P_G) is close to zero, assuming that the grape plantation is flat and aerodynamic friction factors (P_D) is relatively small because of the low speed, it can be assumed that the total power consists only from rolling resistance (P_R).

$$P_\mathrm{T} = P_\mathrm{R} = C_\mathrm{R} mgv \tag{6}$$

As the surface on which the device will have to work can be considered sand or just ordinary ground we can assume that according to the [9] the rolling resistance coefficient is $C_\mathrm{R} = 0.2$, because the value 0.3 is related to the ordinary car tires on sand. As the power needed for operation of the robot is a function of the speed and the speed varies during the working cycle, so to calculate the power, the maximum speed should be taken into account. Therefore velocity during different movements should be analyzed:

1) Speed during moving in 5 seconds:

During the processes “starting motion”, “moving between plants in one row”, “direct motion before Turn 1”, “direct motion after Turn 1”, “direct motion before Turn 2”, “direct motion after Turn 2” the device crosses 1.5m in 5 seconds, so the speed is:

$$v_1 = \frac{1.5\mathrm{m}}{5\mathrm{s}} = 0.3\frac{\mathrm{m}}{\mathrm{s}} \tag{7}$$

$$P_1 = C_{\mathrm{R}} m g v_1 = 0.2 \cdot 30\mathrm{kg} \cdot 9.8 \frac{\mathrm{N}}{\mathrm{kg}} \cdot 0.3 \frac{\mathrm{m}}{\mathrm{s}} = 17.6\mathrm{W} \tag{8}$$

2) Speed during Turn 1:

During this movement the robot has to make half of a circle in order to make a turn, the diameter of which is 1m in 5 seconds (see Fig. 8)

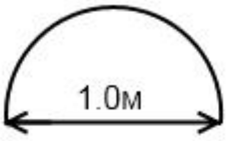

Fig.8: Turn 1 sketch

$$v_2 = \frac{\pi d}{2 \cdot 5\mathrm{s}} = \frac{3.14 \cdot 1\mathrm{m}}{2 \cdot 5\mathrm{s}} = 0.314 \frac{\mathrm{m}}{\mathrm{s}} \tag{9}$$

$$P_2 = C_{\mathrm{R}} m g v_2 = 0.2 \cdot 30\mathrm{kg} \cdot 9.8 \frac{\mathrm{N}}{\mathrm{kg}} \cdot 0.314 \frac{\mathrm{m}}{\mathrm{s}} = 18.5\mathrm{W} \tag{10}$$

3) Speed during Turn 2:

During this movement the robot makes half of a circle which diameter is 2m in 8 seconds (see Fig. 9)

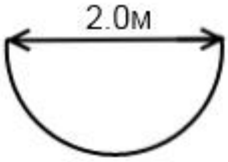

Fig.9: Turn 2 sketch

$$v_3 = \frac{\pi D}{2 \cdot 8\mathrm{s}} = \frac{3.14 \cdot 2\mathrm{m}}{2 \cdot 5\mathrm{s}} = 0.628 \frac{\mathrm{m}}{\mathrm{s}} \tag{11}$$

$$P_3 = C_{\mathrm{R}} m g v_3 = 0.2 \cdot 30\mathrm{kg} \cdot 9.8 \frac{\mathrm{N}}{\mathrm{kg}} \cdot 0.628 \frac{\mathrm{m}}{\mathrm{s}} = 36.9\mathrm{W} \tag{12}$$

So the maximum speed is achieved during Turn 2, as a result this speed will be taken into account for calculating the maximum power needed for movement processes:

It was assumed that robot is designed so that the central point is the center of mass; this allows examining only one wheel because all the others are driven by analogy.

Also the mass that is related to one wheel equals to one quarter of the whole mass, so the needed power of the electrical motor placed on each wheel is the same and is ¼ of the maximum power $P_{\mathrm{T\_max}}$:

$$P_{\mathrm{move}} = P_{11} = P_{22} = P_{33} = P_{44} = \frac{P_{T\_max}}{4} = \frac{36.9264W}{4} = 9.2\mathrm{W} \tag{13}$$

3.2 Spraying analysis

For efficient spraying process an atomizer is designed according to the characteristics of the particular chemical and the needs of the grape plants. A single electric motor is involved in the spraying process of the herbicide which, according to the theory of grape plantation maintenance, is the best for protection from pests.

The spraying is implemented on the basis of the device “Mini Mantra Plus”. One of the most important parts of the atomizer is the segment rotary nozzle for the electric motor (see Fig. 10)

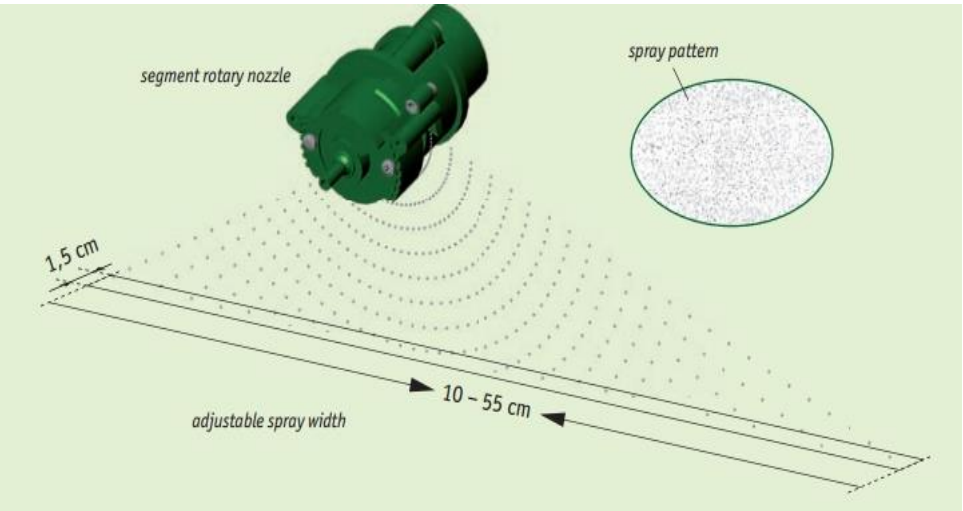

Fig.10: Atomizer external view

For selecting a proper electric motor for the process one of the most important criteria is the maximum rotational speed, which is needed to achieve the desired droplet size (35-45 microns, see [7]). Standard electric motors with variable rotational speed up to 18000 rpm are available now on the market, and usually they do not have any stability or cooling problems.

Another important criterion is the power, which should be high enough to accelerate the herbicide to a high velocity and break it up into droplets. In the process of atomization of liquids, usually the amount of power needed for creating the droplets is quite small. Atomization technology of different liquids has an energy efficiency that usually does not vary much. The centrifugal atomization energy efficiency is typically in the region of 0.5% [11].

The minimum power of the electric motor can be calculated using the following formula, according to [11]:

$$P_\mathrm{S} = \frac{\gamma S}{\eta} \tag{14}$$

Where S – is the total surface area created in unit time, γ – is the surface tension of the herbicide and η – is the typical efficiency of the process

The total surface area can be represented as:

$$S = \frac{6Q}{D} \tag{15}$$

Where Q – is the flow rate of the chemical and D – is the droplet size

So the formula for calculation the power needed for the electric motor used in spraying process can be rewritten as:

$$P_\mathrm{S} = \frac{6\gamma Q}{\eta D} \tag{16}$$

Considering that the surface tension of the herbicide nitrophen is: $\gamma = 64.7 \cdot 10^{-3}\,\frac{\mathrm{N}}{\mathrm{m}}$ and average flow rate in Mini Mantra Plus $Q = 3\frac{\mathrm{ml}}{\mathrm{min}}$, according to [10],

$$P_\mathrm{S} = \frac{6 \cdot 64.7 \cdot 10^{-3}\,\frac{\mathrm{N}}{\mathrm{m}} \cdot 15 \cdot 10^{-8}\,\frac{\mathrm{m}^3}{\mathrm{s}}}{0.005 \cdot 35 \cdot 10^{-6}\,\mathrm{m}} = 0.3\mathrm{W} \tag{17}$$

As it was said before the power needed for the electric motor for atomization process is quite low and can be achieved using one of the micro motors with high rotational speed.

3.3 Lifting and lowering of the spraying hood

To implement lifting of the hood during the process of spraying an electric motor will be used from which the torque will be transferred with the help of the belt transmission and 2 fixed pulleys (see Fig. 11):

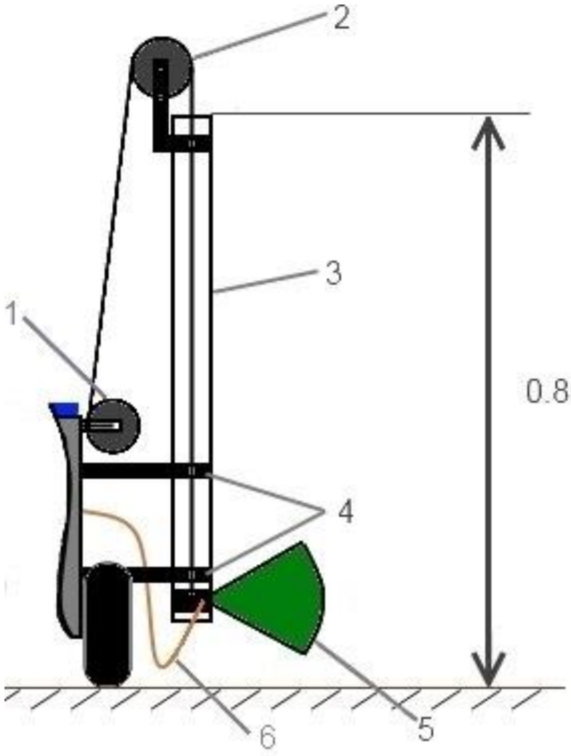

Fig.11: SolarSprayer belt-and-pulley transmission

In the Fig. 11 the organization of the process of lifting and lowering of the spraying hood is explained. The first fixed pulley, marked with number 1, is directly attached to the electric motor, with the help of which it rotates, bringing the torque. The first pulley is connected by virtue of a belt with the second fixed pulley, marked as 2. The second pulley is attached rigidly by means of metal construction to the metal framework 3, which controls the hood's vertical movement. The framework is attached rigidly to the main body of the robot by means of metal bars, marked as 4, so that the whole construction is stable and fixed. During the movement, the electric motor brings the torque to the pulley transmission and spraying hood 5 together with the PVC tube 6 go up the metal framework spraying the plant from the bottom to the top. The flux of the chemical is controlled by the switch/valve unit (complete) gold-plated electrodes, attached to the liquid tank. The pulley pair is designed so that that belt can move only during the motor work, when the top position is reached the electric motor stops and the hood is fixed. During the lowering of the hood the principle is the same, but the motor works in the reverse mode.

To calculate the energy consumed by the device during this particular process the lifting process will be examined, as it requires more power due to the overcoming of the gravity.

The mass of the hood together with the micro motor, PVC tube and herbicide inside it is assumed to be 0.5 kg, during the process the tube goes up and the quantity of the liquid the motor has to lift enlarges, but the difference of the mass, due to the small section of the tube, is neglibly small. So the mass that the motor has to lift is considered to be constant.

To calculate the needed power of the motor, first the velocity of the hood must be found, according to the working cycle this process has to be done in *t*=5 seconds and the average height of the plant is h=0.8m:

$$v_{\text{lift}} = \frac{h}{t} = \frac{0.8\text{m}}{5\text{s}} = 0.16\frac{\text{m}}{\text{s}} \tag{18}$$

Besides that, the force which the motor will have to overcome, represented by the weight of the hood, must be calculated (assuming that the friction between hood and metal frame is close to zero, as well as between belt transmission and pulley pair):

$$F_{\text{lift}} = mg = 0.5\text{kg} \cdot 9.8\frac{\text{N}}{\text{kg}} = 4.9\text{N} \tag{19}$$

Where *m* – is the mass which the motor has to lift

Thereby the power of the motor needed for the lifting process can be calculated as:

$$P_{\text{lift}} = F_{\text{lift}} \cdot v_{\text{lift}} = mgv_{\text{lift}} = 4.9\text{N} \cdot 0.16\frac{\text{m}}{\text{s}} = 0.8\text{W} \tag{20}$$

The power needed for the lifting is quite small, due to the small mass of the hood with chemical and small lifting speed.

4. Power consumption analysis

Thereby, when the needed mechanical power for every operation is calculated the energy consumption can be represented as a table or a cyclogram during the whole working cycle or during the part of the working cycle which is repeated.

The following Table 2 shows the power needed during different operations of the grape plantation processing:

Table 2: Mechanical power consumption during the working cycle

Process	Power, W.
Starting motion	17.6
Movement between plants in one row	17.6
Spraying	0.3
Lifting of the spraying hood	0.3
Lowering of the spraying hood	0.3
Direct motion before Turn 1	17.6
Turn 1	18.5
Direct motion after Turn 1	17.6
Direct motion before Turn 2	17.6
Turn 2	36.9
Direct motion after Turn 2	17.6

It is obvious that the biggest amount of energy needed for robot operation is connected with the movement, especially doing the Turn 2, because it is the fastest movement during the whole working cycle. On the basis of the mechanical power requirements for each process the selection of the main parts of the robot will be made.

As there should be some reserve amount of power due to some calculation inaccuracy or variable weather conditions, the mechanical power of the electric motors which will be taken into account when selecting them is rounded to bigger value and presented in the Table 3. Due to the possibility of changing the size of the droplets and for unification of the required motors the power of the spraying motor is rounded to 1W, the efficiency of the motors will be taken into account when selecting the particular motor types.

Table 3: Motors’ mechanical power

Type of the motor	Power, W
Wheel motor 1	10
Wheel motor 2	10
Wheel motor 3	10
Wheel motor 4	10
Lifting motor	1
Spraying motor	1

According to the selected electric motors, the power consumption of the whole system will change a little and the maximum possible needed power is shown in Table 4:

Table 4: Maximum power consumption during the working cycle

Process	Mechanical power, W.
Starting motion	40
Movement between plants in one row	40
Spraying	1
Lifting of the spraying hood	1
Lowering of the spraying hood	1
Direct motion before Turn 1	40
Turn 1	40
Direct motion after Turn 1	40
Direct motion before Turn 2	40
Turn 2	40
Direct motion after Turn 2	40

To describe the power needs of the whole system during the working cycle, the cyclograms of power consumption of the robot during processing one row of plantation were plotted in the examined mode and also in the mode of maximum power demand mode (see Fig.12, Fig.13):

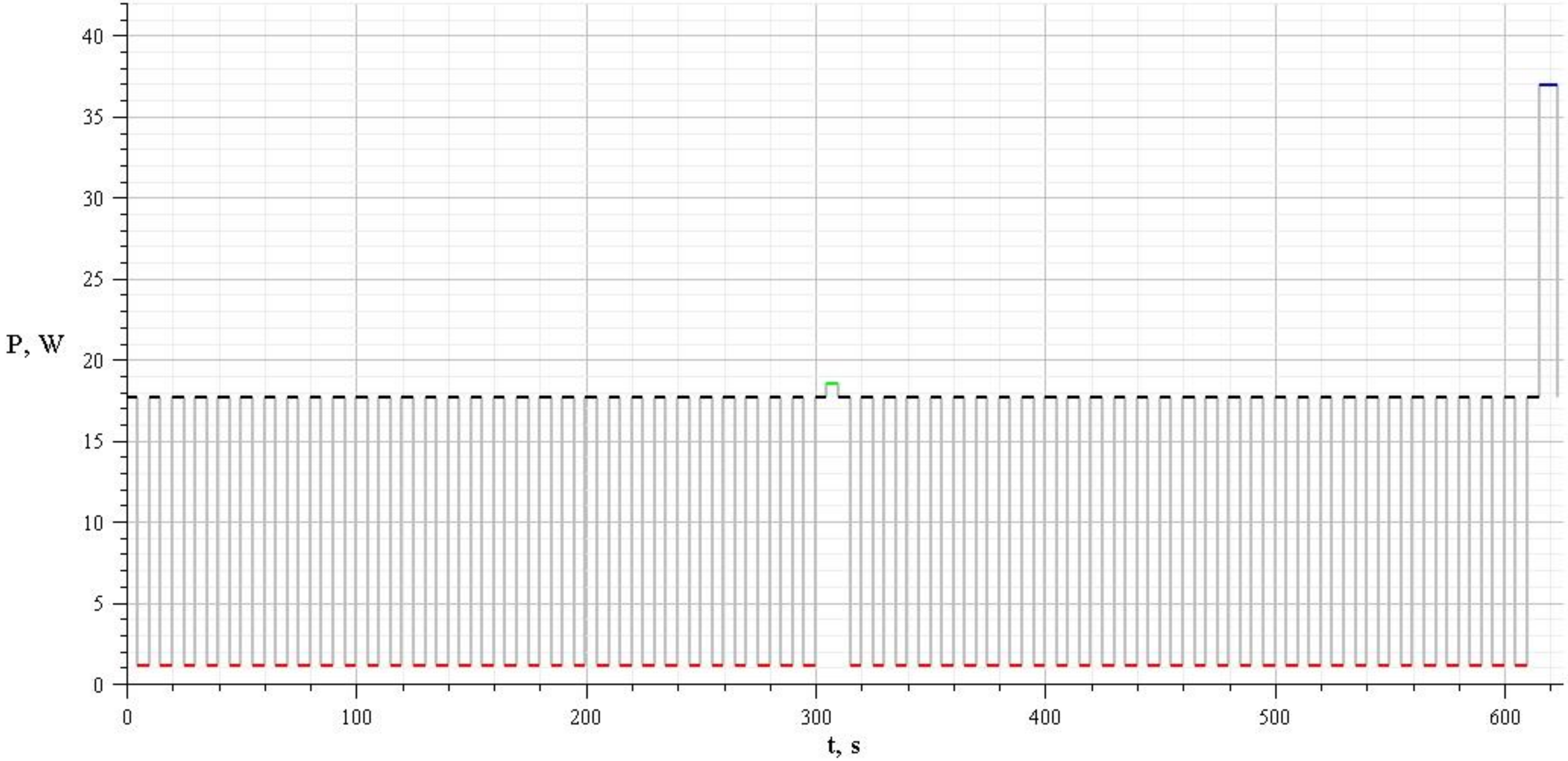

Fig.12: Mechanical power consumption cyclogram in examined mode

Where, red color shows the energy consumption during spraying+lowering/lifting process, black color - during robot movement between the trees in the same row, green color stands for Turn 1 power need, and blue – shows the biggest energy consumption during the whole working cycle – during Turn 2.

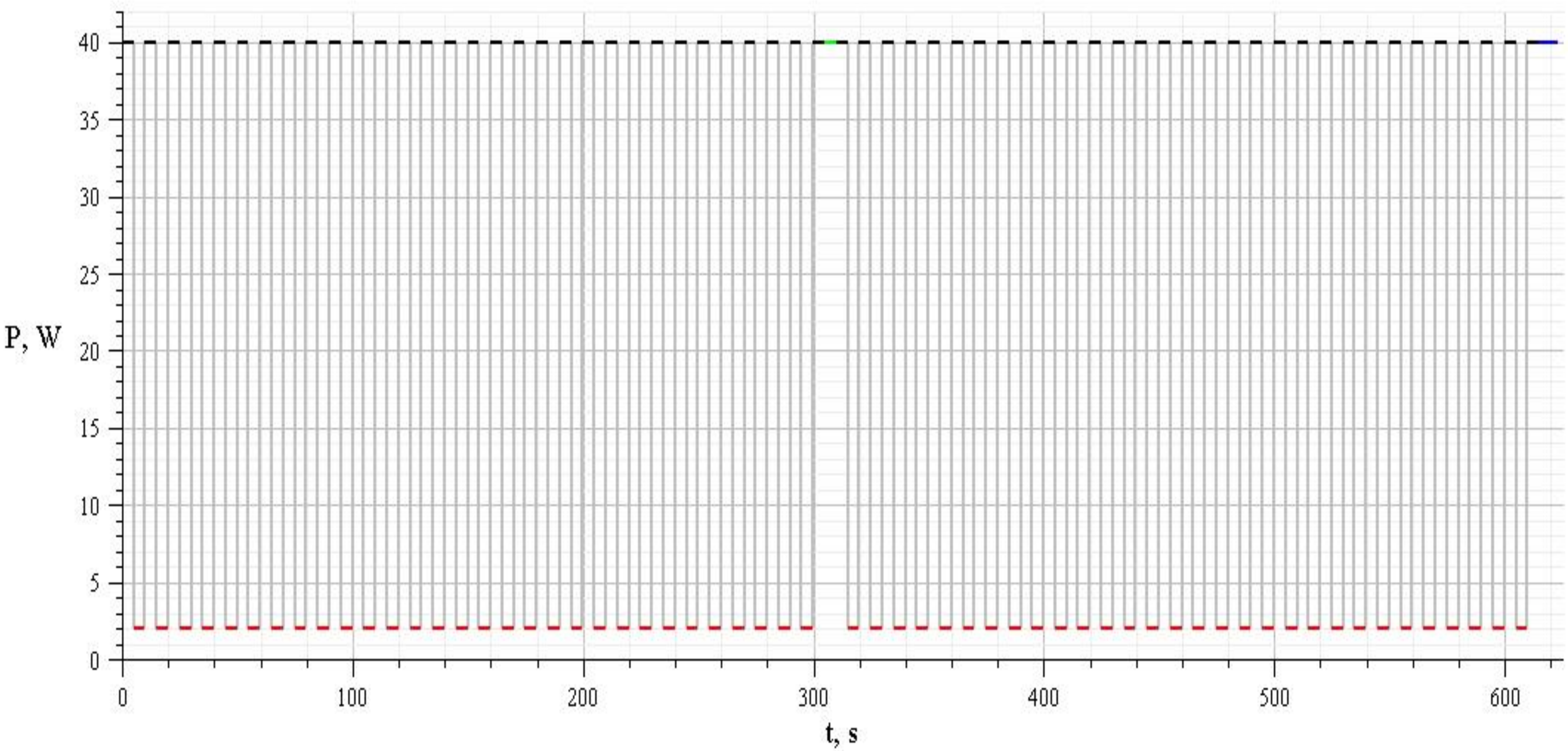

Fig.13: Mechanical power consumption cyclogram in maximum power demand mode

Where, the same colors represent needed power during the same operations.

5. Motor and drive selection

As the most important features for the motors are already calculated, it is possible to select the real motor types for implementing the work of the system, taking into account that high ingress protection characteristic is extremely important for the proper operation. Three different types of motors will allow proper implementation of the whole working cycle. One type was chosen for wheels movement operations, the other one for lifting/lowering and the last one for spraying operations. The electrical power of the motors is selected according to the assumed average efficiency $\eta_{\mathrm{av}} = 50\%$ of the motors of this size, which was assumed after the analysis of ABB technical note (see [12]), taking into account the needed torque.

Movement operation motors ($\mathbf{M_1, M_2, M_3, M_4}$):

For the wheels movement operations there was chosen a geared DC brush motor, model IG-90GM produced by Shayang Ye. (see Fig. 14).

Fig.14: IG-90GM geared DC brush motor

The chosen motor technical data is presented in the Table 5:

Table 5: IG-90GM characteristics

Input voltage	12V
Nominal torque	3700 g*cm
Nominal speed	1800 rpm
Nominal current	<7000 mA
No load speed	2000 rpm
No load current	<1500 mA
Output power	90W

The geared motor has the following characteristics, presented in Table 6:

Table 6: IG-90GM geared characteristics:

Rated torque	48 kg*cm
Rated speed	96 rpm

This will satisfy the needs of the robot during all the movement processes.

Lifting/lowering operation motor (M_5):

For the lifting/lowering operations there was chosen a geared DC Carbon-brush motor IG-32PGM produced by Shayang Ye. (see Fig. 15):

Fig.15: IG-32PGM geared DC brush motor

The chosen DC motor has the following features, presented in the Table 7:

Table 7: DC motor IG-32PGM features

Input voltage	12V
Nominal torque	250 g*cm
Nominal speed	4930 rpm
Nominal current	<1600 mA
No load speed	6000 rpm
No load current	<250 mA
Output power	12.8 W
Weight	220 g

The geared motor has the following characteristics, presented in Table 8:

Table 8: IG-32PGM geared characteristics:

Rated torque	2.4 kg*cm
Rated speed	359 rpm

This will satisfy the needs of the lifting and lowering processes.

This motor has the following characteristics and dimensions (see Fig. 16, Fig. 17):

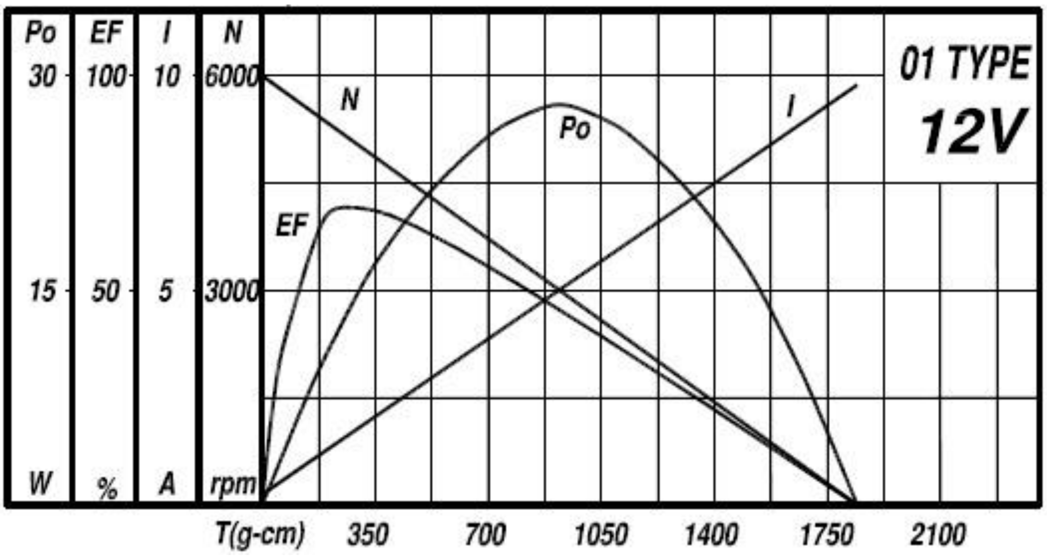

Fig.16: IG-32PGM characteristics

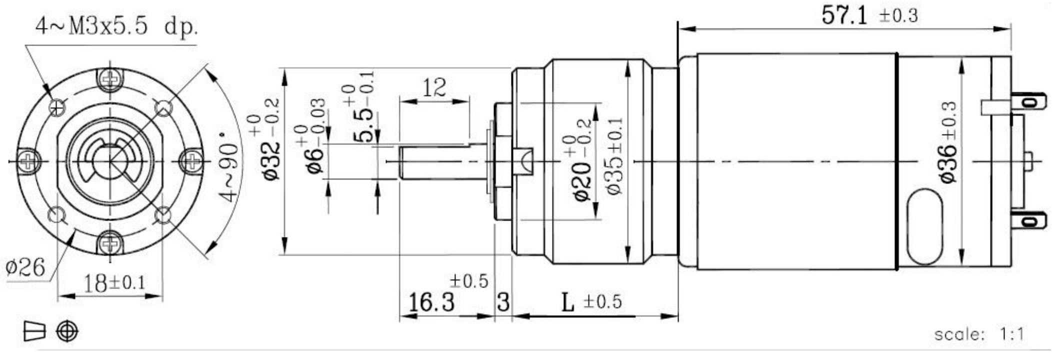

Fig. 17: IG-32PGM dimensions

Spraying operation motor (M_6):

For the spraying operation there was chosen a DC Carbon-brush motor IG-22GM produced by Shayang Ye. (see Fig. 18):

Fig. 18: IG-22GM DC brush motor

The chosen DC motor has the following features, presented in the Table 9:

Table 9: DC motor IG-22GM features

Input voltage	12V
Nominal torque	22 g*cm
Nominal speed	6700 rpm
Nominal current	<200 mA
No load speed	8000 rpm
No load current	<70 mA
Output power	1.5 W
Weight	32 g

This will satisfy the needs of the spraying processes.

This motor has the following characteristics and dimensions (see Fig. 19, Fig. 20):

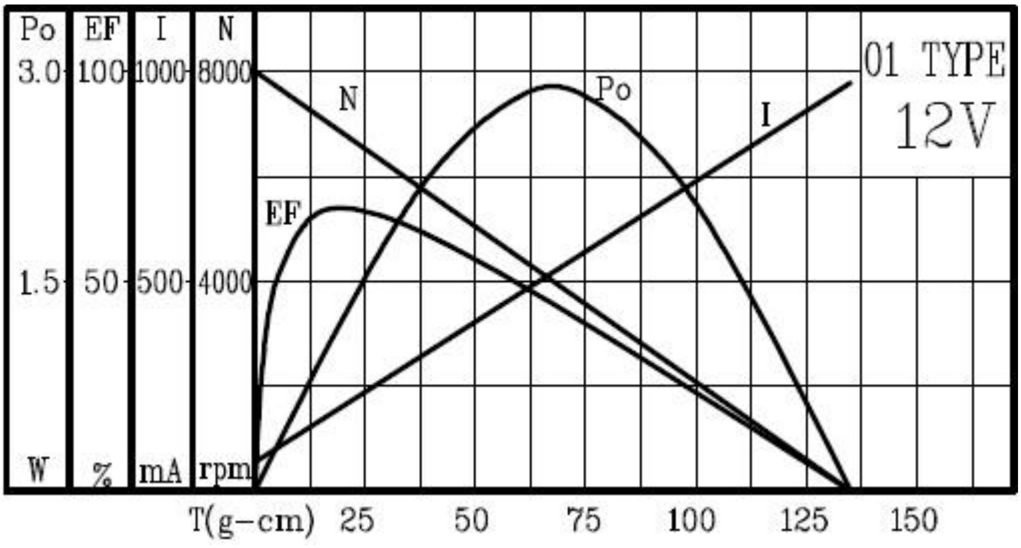

Fig.19: IG-22GM characteristics

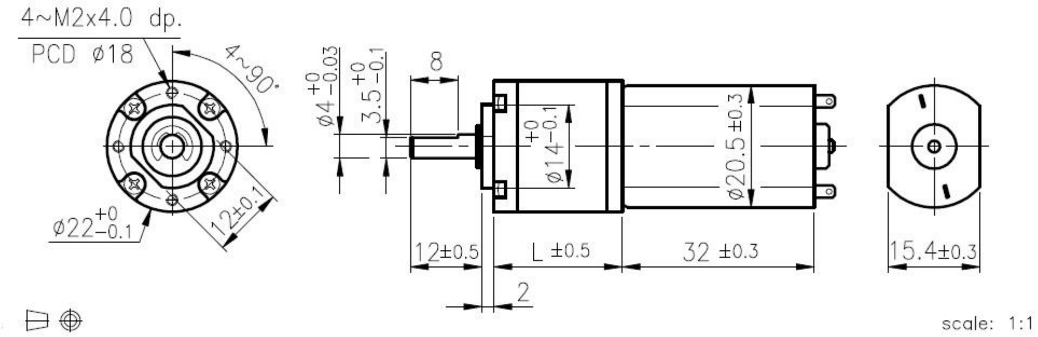

Fig. 20: IG-22GM dimensions

Motors protection:

As it is very hard to find the motors of this size with high ingress protection rating, it was decided in order to protect the motors from moisture, water, dust and different other undesirable small particles, to place them inside an additional protection frame represented by a plastic or polymer box attached to the motors.

Electrical drive:

The process motors which are planned to be controlled are only motors M_1, M_2 because others do not need to change the speed during their operation. The spraying process is implemented using the same speed of the motor M_6, which will be turned on and off by the command from the microcontroller. The same way will operate wheels motors M_3, M_4 which will be turned on when the movement process starts and rotate at constant speed. The motor M_5 will operate at the constant needed speed; the only specific requirement is the possibility of reversed operation, which will be realized by the change of the polarity by the microcontroller. Thereby there are two motors which will need drives for the proper operation, because during the turns the speed of the left and right front wheels should be changed. Thereby the chosen device for implementing this task is a DC1212 brushed DC motor controller, presented in Fig. 21.

Fig. 21 DC1212 controller

The task of the device is to control the speed of the DC brushed motor with the help of control signal, which could be represented by potentiometer or analog signal 0…5V.

The device dimensions are shown in Fig. 22

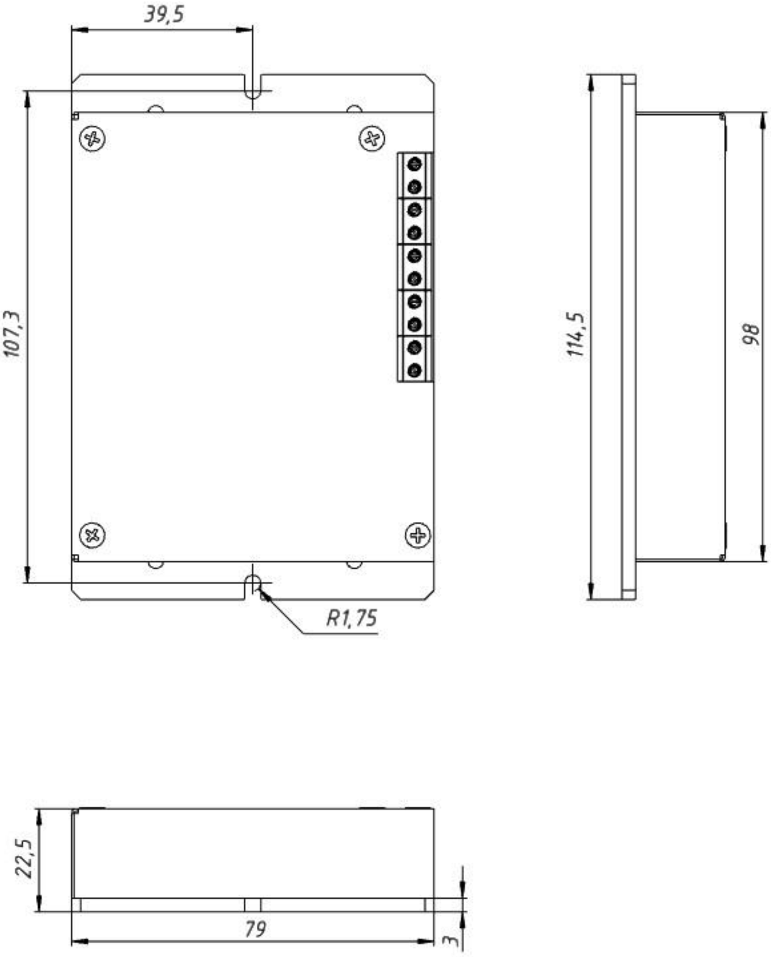

Fig. 22 DC1212 controller dimensions

The DC1212 controller technical specification is presented in Table 10:

Table 10: DC1212 technical data

Nominal output current	12 A
Maximum output current	18 A
Dimensions	115x79x23 mm
Weight	0.2 kg
Input voltage	10…15 V
Analog signal voltage	0…5 V
Working temperature	-25…+40ºC
Ingress protection	IP20

The controller inputs can be seen in Fig. 23:

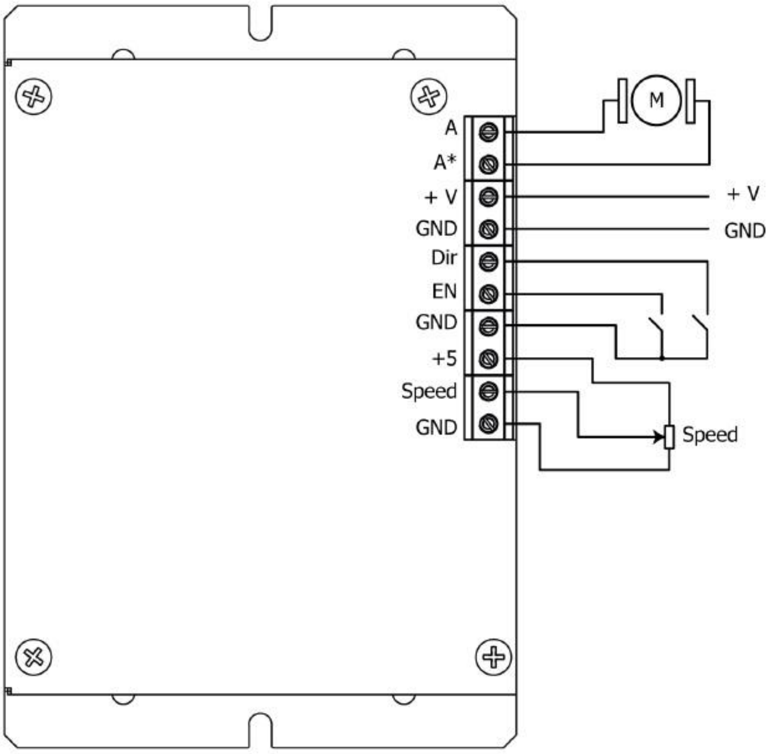

Fig. 23 DC1212 control inputs

Input Dir – controls the direction of motor’s rotation. Input En controls the voltage supply to the motor (voltage supplied/not supplied). Thereby with the help of the control signal coming from the microcontroller the speed of the front wheels is controlled, which allows the robot to make turns.

6. Solar station design

In this chapter the mobile mini solar station is designed for the robot and the main components' characteristics are selected. All the main components are selected according to the needs of the electrical drives selected and the energy production of the panel is analyzed.

Usually the output voltage of the solar panel is direct low-voltage, the nominal as a rule is multiple 12v, but depending on the work conditions it can be 50% less or more. For the proper operation of the system it is needed to have direct and constant voltage. That is why it is necessary to realize the accumulation and storage of the energy for using it during the insufficient sun activity.

6.1 Main components

According to these requirements, the system should have 4 main components (see Fig. 24):

1) Solar panel, which gain energy;
2) Charge controller, which realizes normalization of the output voltage, the charging of the battery;
3) Battery, accumulating the energy when there is an excess of energy in the system and supplying it when there is insufficient amount of energy, when the sun is not so active already or the energy consumption rises;
4) Inverter, which realizes the low-volt current from the battery to the one the system needs (not required as the chosen motors are DC motors)

All the components should be carefully balanced with each other, because the imbalance can lead to inefficiency of the whole system, extra costs and even to failure of the weakest element or even to the battery explosion and fire.

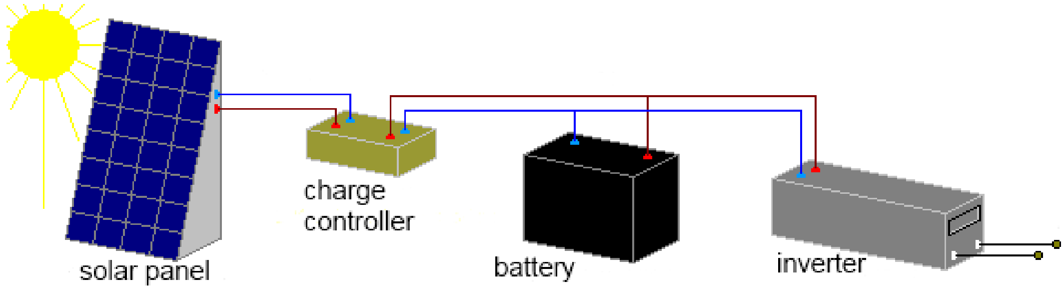

Fig.24: Solar station components

For selecting the components of the whole solar station two values are the most important criterions:

- the nominal output power of the solar panel
- maximum electrical power consumption of the system

When the design process comes to the selecting of the particular models of components, first of all the low-voltage which will be used inside the solar station system should be selected. The output voltage of the solar station should be selected according to the parameters of inverter. If with the output voltage everything is defined by the electric motors, the selected low-voltage inside the solar station, which is the input voltage of inverter, nominal voltage of the battery and nominal output voltage of the solar panel, has quite wide possible range.

Most of the inverters are designed to have the direct current with 12 V voltage. The standard batteries voltage is also 12 V. Usually the solar panels with power of 50 W and more have 12 V or 24 V output voltages. According to these standard voltages, the voltage inside the solar station system is chosen to be 12 V.

6.2 Solar panel selection

For solar panel selection there are three most important factors:

1) panel's output power

This requirement comes directly from the electrical power value needed for the operation of the robot. As far as half of the working cycle the needed power is 90W (assuming that the losses in the control circuit are 10% and the electrical power needed for motors' operation is 80W) and another half it is 4W, the average needed power is 47W. Taking in to account the part of the energy consumed by the motors will be gained back by the panel and the capacity of the battery should be enough for at least one working cycle; the output power of the panel should be the same as the average needed power or even less.

2) the nominal output voltage

This criterion is not so important because it can be adjusted with the help of the charge controller. There are two main values of output voltage for off-grid solar panels: 12V and 24V. The difference is the operating current, which is two times smaller in case of using 24V. The panels with output voltage higher than 24V are really seldom used and usually are made up out of lower voltage panels. As far as the input voltage of the inverter and the voltage of the battery are chosen to be 12V, then the same requirement is used for the selection of the solar panel output voltage.

3) the type

Nowadays most popular types are monocrystalline silicon panels and polycrystalline silicon panels. The monocrystalline silicon solar panel efficiency rates are typically 16-25% and polycrystalline has 13-16% efficiency range, but its advantage is that it is cheaper. But the price for one watt from the ready-made panel of both types is almost the same. At the same time monocrystalline type can supply with nominal voltage for longer time than the polycrystalline, this makes possible to gain at least some energy even when it is quite cloudy or during the twilight. And in the end the monocrystalline silicon panel is more preferable for this application because this type panels are more compact than polycrystalline silicon panel with the same power.

According to all the important factors there was chosen a monocrystalline silicon panel EXMORK with the output power of 40W and nominal output voltage of 12V (see Fig. 25):

Fig.25: EXMORK monocrystalline 40W, 12V solar panel

The panel has the following characteristics, shown in Table 11:

Table 11: Solar panel characteristics

Rated maximum power (Pm)	40W Mono
Tolerance	±3%
Voltage at Pmax (Vmp)	17.5V
Current at Pmax (Imp)	2.29A
Open circuit voltage (Voc)	22.0V
Short-circuit current (Isc)	2.46A
Normal operating cell temp (NOCT)	47°C±2°C

Maximum system voltage (Voc)	600V DC
Maximum series fuse rating	16A
Operating temperature	-40°C~+85°C
Application class	Class A
Weight	3.9 kg
Dimension (mm)	580x550x25

Solar panel power production

The output panel power depends on the weather conditions (irradiation and temperature). The output power can be analyzed on the example of Spain, taking into account the average irradiation (see [14]) in the country (see Fig. 26).

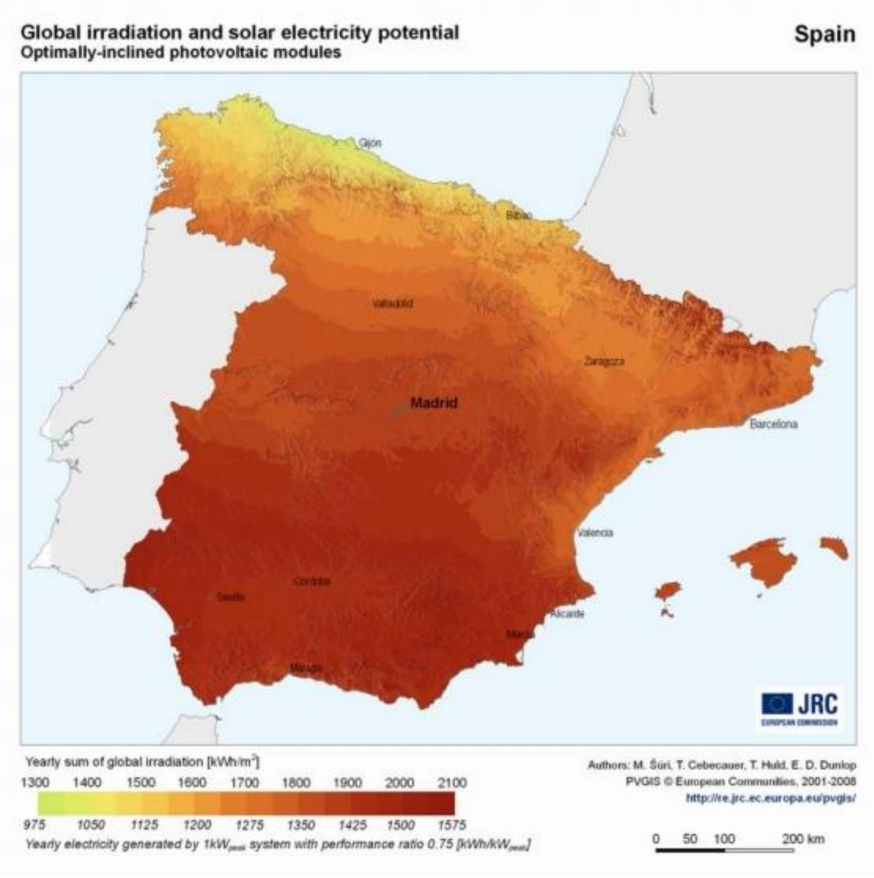

Fig. 26 Average solar radiation in Spain in kWh/$\mathbf{m^2}$

Considering that energy conversion efficiency can reach 20% an array of cells can therefore generate about 200 Watts of electrical power per square metre when illuminated by solar radiation of 1000 Watts per square metre. But usually the energy conversion efficiency of single panel cannot reach 20%. According to the manufacturer of the chosen panel the maximum output power of the panel is 40W with a square of about 0.3m^2, measured according to a set of Standard Test

Conditions (STC). The conditions are: normal irradiance of 1000w/m^2, cell temperature 25 °C and Air Mass =1.5. That means that the efficiency of the solar panel is about 15%. The graph of the efficiency vs. irradiance (see [15]) is presented in the Fig. 27:

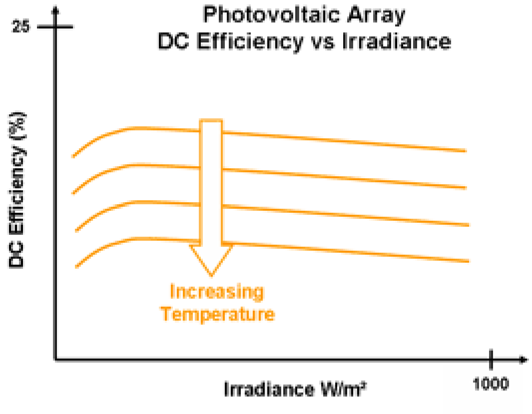

Fig. 27 PV efficiency vs. Irradiance

So the maximum which can be achieved with the selected solar panel could be even more than mentioned by the manufacturer, considering the irradiation in the south of Spain, but in this work the case is analyzed when the robot is considered to operate during 1 working cycle (about 3 hours) when the sun activity is so that the panel power of 40W is achieved and according to this the battery selection will be made. In case when there is not enough irradiation a bigger battery or solar panel can be required.

6.3 Charge controller selection

In the modern solar stations usually the charge controller is placed between the solar panel and the battery. Its main purpose is to normalize the voltage which is produced by solar panel to the voltage needed for the charging of the battery and to perform the maximum power point tracking.

One thing that must be mentioned is that some cheap types of charge controllers can prevent the system only from voltage overcharge, not from current. In this case too weak batteries connected to the too powerful solar panel and too powerful charge controller can overheat and it can lead to the device failure due to the too high charging current, while the voltage is in the proper range. This can easily happen during charging the completely discharged battery because it can take very high current; as a result the battery suffers from overheating and high gas emission, which can lead not only to the reduction of operation life, but to ignition or even explosion. As for expensive controllers, they often have an option to adjust according to the capacity of the battery or to the charging current value, which makes the process of charging quite safe if the value was set carefully.

Types of controllers.

The low-cost models for voltage control usually use the Pulse Width Modulation as the main tool. Basically, they act as an electronic relay with microprocessor control which connects the solar panel with the battery and disconnects, keeping the voltage of the battery on the needed level.

But there are also some modern types of controllers, which can even rise up too low voltage, produced by solar panels during the lack of light, this process is possible due to the reduction of the current.

If the solar panel was selected properly, then it will not be necessary to rise up the voltage. The possibility of reduction of the relatively high panel voltage to allow the needed charging voltage for the battery is much more important. This is realized due to the converting of the extra voltage to the additional current, which helps to achieve the full use of the nominal panel power. This is quite important, because if the load is not optimal, the voltage can be reduced by 15-40% from the required level and the power losses in that case can be higher than 25%.

Maximum Power Point Tracking.

Maximum Power Point Tracking (MPPT) – is the technology which was designed to avoid such huge power losses. It is based on the process of constant measurement of the panel output voltage and current and guaranteeing the optimal relation between them. This technology allows the optimal use of the panel power and to reduce the losses to 3%. But the price of such controllers is much higher than the simple controllers with the same load current.

It is evident that the controller with MPPT has higher efficiency than simple controller with PWM. As the SolarSprayer will work during the day it is better to use the whole panel potential, so it is preferable to design the solar station with the help of charge controller with MPPT but PWM types are also acceptable.

The selection of power for the controller.

The most popular types of charge controllers work with the current of 10A, 20A and sometimes 30A. More powerful controllers are quite uncommon and much more expensive.

For proper system design it is important to check that the peak solar panel current is not higher than 80%-90% of the nominal controller current. This stock is necessary, because when the load rises over the optimal value, the voltage begins to decrease, but the current continues to rise, and the controller must overcome this current overloading. For most of the solar panels the short circuit current is 15% higher than the optimal value. Also there is a possibility that in some particular conditions the panel output can exceed the nominal value and the controller must overcome this redundant yield.

Thereby, the PWM charge controller with operating current 5A, can be connected to the panel with output voltage of 24V and power up to 300W or with output voltage of 12V and power up to 150W. And the charge controller with operating current 5A and MPPT which converts the redundant voltage into current, can be connected to the panel with output voltage of 24V and power range 220-240W, or to the 12V panel with output power up to 110-120W. Usually, the manufacturer of the controller mentions the maximum total power and nominal current of the panel that can be connected.

Charge controller selection.

As far as the system is supplied with energy due to 40W solar panel, there is no need in high current charge controllers and according to relatively small solar panel power needed for proper robot operation there was selected the Guardian 12V charge controller (see Fig. 28).The operation current will be adjusted according to the selected battery.

Fig.17: Guardian 12V charge controller

The technical specification of the device (see Fig. 29):

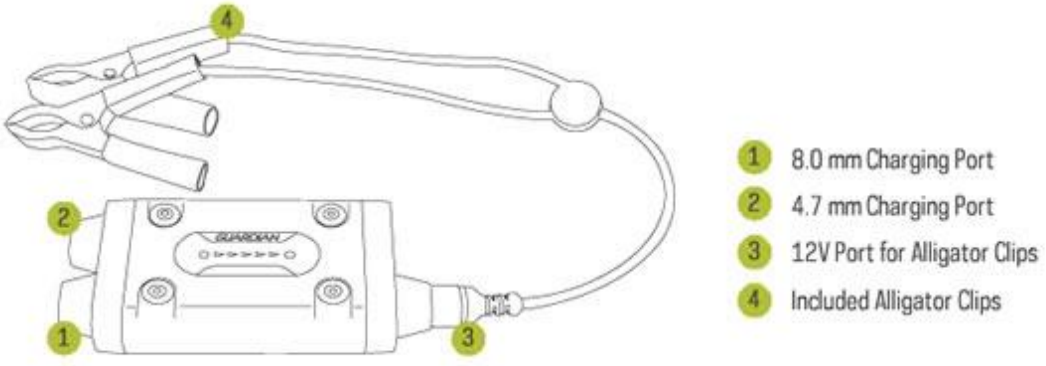

Fig. 29: Charge controller technical specification

The selected charge controller’s features are presented in Table 12:

Table 12: Guardian 12V charge controller characteristics

Input ports	Solar Port (4.7 mm): 15-20V, 0-6A (90W max) Solar Port (8.0 mm): 15-20V, 0-6A (90W max)
Outputs	12V Port (6.0mm), for Alligator Clips (90W max): 11-14V, up to 6A Output: 60Hz, modified sine wave
Internal	Charge Controller: Built-in PWM Lead-Acid. Supports up to 90W solar panels

	Left LED: Indicates solar panel is connected RightLED: Indicates battery connection and will blink when a battery and solar panel (or other power supplies) are connected.
General	Product SKU: 14002 Weight: 0.4 lbs (0.18 kg) Dimensions: 5 x 2.5 x 1 in (12.7 x 6.4 x 2.5 cm) Warranty: 12 Months Certifications: FCC, CE Optimal Operating Temp: 32-104 F (0-40 C)

6.4 Battery selection

The most popular batteries have the operation voltage of 12V. Battery blocks with operation voltage multiple of 12 such as 24V, 48V and 96V can be made up by connecting few 12V batteries. The battery block of any system of autonomous power supply has the following main characteristics:

- operational capacity
- charge current
- discharge current

Types of batteries.

Nowadays there are two most popular types of batteries:

- lithium-ion battery
- lead-acid battery

Due to the gradual decreasing of the price, powerful lithium-ion batteries begin to compete with the traditional lead-acid batteries. One of the benefits of lithium-ion batteries is much higher capacitivity and as a result much smaller unit weight, which together with smaller sizes is one of the most important factors for mobile systems. Besides they allow almost complete use of its nominal capacity. They are almost twice more effective than lead-acid batteries during working in the buffer mode, which is typical for the systems of energy supply with compensation of brief energy insufficient. They still have minors: they are much more expensive and some of them are more flammable. Considering all these pluses and minuses, different lifetime, weight, and also that the system was designed as a mobile vehicle it is better to focus on smaller lithium-ion batteries.

However lead-acid batteries by-turn could also be applied. They have few different variations. For the system of autonomous energy supply, the traction batteries could be a good option. They allow using the nominal capacity more effectively, comparing to the starter batteries. The best in the question of price-quality-comfort relation nowadays is the gel lead-acid battery. Common automobile (starter batteries) are also quite acceptable. Besides they are less sensible to the coldness, and even during few seconds with the capacity of 50Ah most of them are able to produce 200A output current without any harm to itself.

Preliminary selection of capacity. Operational and buffer energy reserve.

First of all, it is necessary to select the total energy capacity of the battery. In most cases, the operational energy capacity should be selected according to the average daily energy consumption. The following assumptions were made to calculate the required capacity of the battery:

- charge controller efficiency is 80%
- charging/discharging efficiency is 85%

As far as the inverter needs about 50W of average input power and according to the discharging efficiency the battery has to give away 58.8W. At the same time the solar panel output power passing through the charge controller and charging the battery reduces to 27.2W. Thus the final output power that the battery has to give away in the analyzed case is 31.6W. These assumptions allow calculating the required battery capacity for implementing at least one working cycle, it means that the capacity of the battery should be enough to supply the average output power of 31.6W for at least 3 hours (one working cycle time):

$$E_{\text{bat}} = 31.6\text{W} \cdot 3\text{h} = 94.8\ \text{Wh} \tag{22}$$

Considering that the battery voltage is 12V, it is possible to calculate the battery capacity for operation of at least one working cycle:

$$C_{\text{bat}} = \frac{94.8W}{12\text{V}} = 7.9\ \text{Ah} \tag{23}$$

Taking in to account that the depth of discharge is planned to be 70%, the system will need a battery with at least 11.3Ah capacity. The capacity was calculated for the ideal case, when the solar panel’s output power is the maximum that could be achieved, that means that the robot starts working in the middle of the day when there is enough sunlight. In reality, this will not be true, so that can result in a need of bigger battery or more powerful panel. Both variants are possible.

Charging and discharging currents.

To design a proper solar station and not to damage the battery it is very important to take into account few important rules of selection the current, which should be followed. The charging current (the maximum current, coming from the solar panel) should not exceed the maximum value of charging current, mentioned by manufacturer for the particular battery model. If the current exceeds that value, this can lead not only to the battery failure, but to its inflammation or even explosion. On the other hand, too small current will not be able to charge the battery. If the battery will be charged like that for a while, it will just lead to discharge; but if it will work for a long time in this mode, it will lead to the capacity and life time reduction. Besides all, the inverter input current should not be bigger than the maximum discharging current of the battery. For providing the best operational conditions it is better if the discharging current will be half or even one fifth of the maximum value.

The preliminary selection of the currents can be summed up to the following rules:

- The maximum discharging current numerically equals to the maximum inverter input current which is allowed only for few seconds;
- The optimal discharging current is 20% of the maximum inverter input current;
- The optimal charging current is 5... 10% of the maximum charging current mentioned by manufacturer;
- The maximum charging current is not more than 20% of the maximum charging current mentioned by manufacturer;

Final battery selection.

So the battery capacity should be the same or even more than 11.3 Ah, considering this, there was chosen a rechargeable 12V 14Ah Li-ion battery pack 18650 3S7P produced by Ancoo (see Fig. 30):

Fig.30: Ancoo 12V 14Ah Li-ion battery pack 18650 3S7P battery

The manufacturer provides the following technique characteristics of the battery geometry and materials which are presented in Table 13:

Table 13: Ancoo 18650 3S7P Li-ion battery characteristics

Model	ICR18650-3S7P
Nominal capacity (Ah)	14Ah
Nominal voltage (V)	12V
Standard charge current (A)	2A
Continuous discharge current (A)	0.2C
Pulse discharge current (A)	5A
Over-Charge voltage:	12.75V
Over-discharge voltage	8.4V

As the needed energy reserve of the battery required for the proper operation of the charging/discharging processes and whole system in general should be more or equal to the average daily power consumption, it can be said that the selected battery should meet all the requirements.

7. Energy balance of the system

It is very important to analyze the energy balance of the system to understand if the design process has some weak points and will the main final purpose of the device be achieved using the selected equipment for the particular working cycle. The main question of the work is how the charging and the discharging process will be implemented at the same time, how the charge of the battery will be balanced throughout the whole working cycle/time.

To understand how the energy balance of the system can be achieved, first, both processes are analyzed separately and then the possible ways of their combination are studied.

7.1 Charging process

The way the battery is exploited plays the key role in the life time and reliability of one. The rate of charge or discharge often is expressed in relation to the capacity of the battery. This rate is known as the C-rate and equates to a charge or discharge current and is defined as:

$$I = M \cdot C_{\mathrm{n1}} \tag{24}$$

where I is the charge or discharge current, expressed in amperes (A); M is a multiple or fraction of C; C is a numerical value of rated capacity expressed in ampere-hour(Ah); and n_1 is the time in hours at which C is declared (see [16]).

A battery discharging at a C-rate of 1 will deliver its nominal-rated capacity in 1 hr. For example, if the rated capacity is 14000 mAh, a discharge rate of 1 C corresponds to a discharge current of 14000 mA. A rate of C/5 corresponds to a discharge current of 2.800 mA.

Usually, the capacitance of the battery is specified by manufacturers at a 5-hr rate, where n=5, according to the selected battery it is also5-hr rate (0.2C). For example, the mentioned battery can provide 5hr of working time discharging at a constant current of 2.8A. Theoretically, the battery would provide 1hr of working time operating with the constant discharge current of 14A. In practice, however, the operating time will be less than 1hr because of inefficiencies in the discharge cycle.

The preferred charge algorithm for Li-ion battery chemistries is a constant current-constant voltage (CC-CV) algorithm. The charge cycle can be broken up into four stages: trickle charge, constant current charge, constant voltage charge and charge termination (see [16]) presented in Fig. 31.

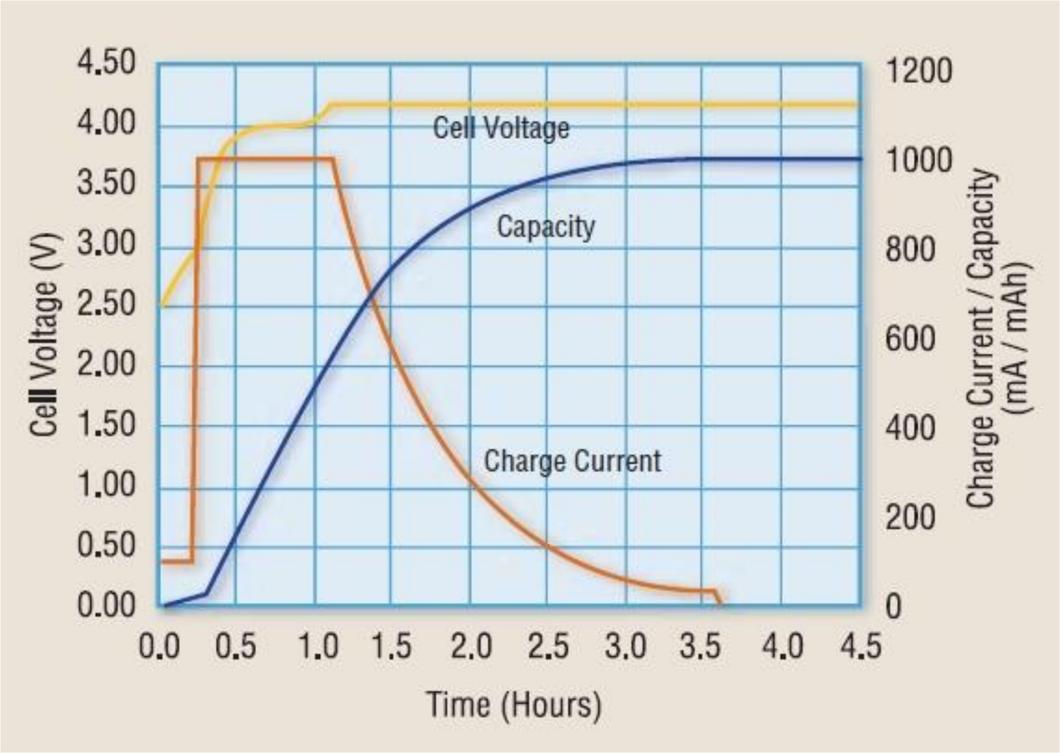

Fig. 31: Charge cycle of Li-ion battery

In stage one, a trickle charge is employed to restore charge to deeply depleted cells. These are cells in which the cell voltage is below approximately 3V. During this stage, the cell is charged with a constant current of 0.1C maximum. After the cell voltage has risen above the trickle charge threshold, the charge current is raised to perform constant current charging (stage two). The constant current charge should be in the 0.2 C to 1 C range. The constant current does not need to be precise and semi-constant current is allowed.

The constant-current charge ends when the cell voltage reaches 4.2 V. At that point, the third stage of charging – the constant voltage stage – begins. To maximize performance, the voltage regulation tolerance on the voltage applied to the cell should be better than ±1%.

In the fourth and final stage, the constant voltage charging is terminated. Unlike nickel-based batteries, it is not recommended to continue to trickle charge Li-ion batteries, which can cause plating of metallic lithium, a condition that makes the battery unstable. The result can be sudden, automatic and rapid disassembly.

Charging is typically terminated by one of two methods – a minimum charge current or a timer. However, a combination of the two techniques also may be applied. The minimum current approach monitors the charge current during the constant – voltage stage and terminates the charge when the charge current is in the range of the 0.02 to 0.07 C.

The second method determines when the constant-voltage stage is invoked. Charging continues for an additional 2hr, and then the charge is terminated. Charging in this manner replenishes a deeply depleted battery in about 2.5 hr to 3hr (see [17]).

Despite the reliability of the described charge algorithm it has some disadvantages which make the charging process much more complicated, for example it is difficult to evaluate the precise remaining capacity of a lithium ion battery prior to recharging. That is why it was assumed to use the standard convention, which means calculating the maximum recharge time: the time it would take to recharge a near fully depleted cell. The first step is to determine the standard recharging current level, which is provided in the battery characteristics table. According to the manufacturer of the selected battery the standard charge current is 2400mA=2.4A (0.2C). The next step is, knowing the capacity of the battery, to calculate the ideal maximum charging time in hours by dividing the capacity by the standard charge current:

$$t_{\mathrm{ch\_ideal}} = \frac{14000\mathrm{mAh}}{2.4\mathrm{A}} = 5\mathrm{hr} \tag{25}$$

The last step is important to take into account the average inefficiency of the charging process (assumed to be 87%). The result is the estimated maximum real charging time for the battery:

$$t_{\mathrm{ch\_real}} = \frac{t_{\mathrm{ch\_ideal}}}{0.87} = 5.75\mathrm{hr} \tag{26}$$

This result can be taken into account while studying the balance between charging and discharging, which will allow having an idea if the equipment including battery were chosen properly or which possible adjustments could be brought into life.

In practice, the charging process is organized by the charge controller. When the battery voltage reaches a particular value, the PWM algorithm gradually reduces the charging current to avoid the overheating of the battery. However, the battery charging continues to achieve the maximum amount of energy stored.

Besides, the charging time reduces. As a result, there is a higher efficiency of the charging process, quick charging and completely charged battery. The batteries which are charged with the use of PWM algorithm will be kept at a high level average charge in a typical solar station. Except the high reserve amount of capacity in the system, the life time of the battery can be also significantly enlarged.

7.2 Discharging process

Basically, the discharging process can be described with the help of the same equation as charging process (26).Also for studying this battery mode it is important to analyze such concept as the depth of discharge (DoD) which is a characteristic of the battery. It is used to describe how deeply the battery is discharged. In the Table 14 is compared the number of discharge/charge cycles Li-ion can deliver at various DoD levels before the battery capacity drops to 70 percent (see [18]). The number of discharge cycles depends on many conditions and includes charge voltage, temperature and load currents. Not all Li-ion systems behave the same.

Table 14: Cycle life as a function of DoD

Depth of discharge	Discharge cycles
100% DoD	300-500
50% DoD	1200-1500
25% DoD	2000-2500
10% DoD	3750-4700

According to the selected equipment, especially electrical drives it can be estimated how much energy from the battery the robot will need during the working cycle, considering the power consumption, the currents and the voltage at which the system is expected to operate. As the battery is expected to supply the average energy of 31.6W at the rated voltage of 12V then the average discharge current which is required during the whole working cycle can be assumed:

$$I_{\mathrm{av}} = \frac{31.6\mathrm{W}}{12\mathrm{V}} = 2.63\mathrm{A} \qquad (27)$$

The method which is used to calculate the discharge time is taking into account such constant as a Peukert's exponent, which takes into account the fact that the amount of electrical energy gained from the battery depends on the discharge current:

$$t_{\text{discharge}} = \frac{C}{I_{\text{discharge}}{}^{n}} \tag{28}$$

Where n – Peukert’s exponent which usually is in the range of 1.1-1.3, C – Peukert’s capacity and $I_{\text{discharge}}$ is the discharging current.

Thereby, taking into account the average discharge current required and the battery capacitance and assuming that the Peukert’s exponent is 1.1, an important data - the time needed for particular DoD was calculated and is presented in the Table 15:

Table 15: DoD vs. time

DoD, %	Discharge time, hours
10	0.54
20	1.07
30	1.61
40	2.14
50	2.68
60	3.21
70	3.75
80	4.29
90	4.82
100	5.36

This method also allows calculating the discharge time of the battery, using different discharge current. The calculated data is represented in the Table 16:

Table 16: Discharging time at different discharge current

Current, A	Discharge time, hours	Equivalent capacity, Ah
0.35	49.25	17.24
0.7	22.97	16.08
1.05	14.71	15.44
1.4	10.72	15.00
1.75	8.38	14.67
2.1	6.86	14.41
2.45	5.79	14.19
2.8	5	14
3.15	4.39	13.84
3.5	3.91	13.69
3.85	3.52	13.56
4.2	3.2	13.44
6.3	2.05	12.91
9.1	1.37	12.44
11.9	1.02	12.11
14	0.85	11.92

On the basis of the data from the table 14, there was built a graph with the help of the mathematical tool “Maple 13” which shows the dependence of the work time on the discharging current and can be seen on Fig. 32:

Fig. 32 Discharge time to discharge current

Considering that the average discharge current, defined before is $I_{\mathrm{av}} = 2.63\mathrm{A}$, it can be said that it will take the robot 5.36 hours to discharge the battery completely, working non-stop. However, in the designed system the battery will never be discharged completely, because its life time is very important for the mobile device. According to the manufacturer recommendations how to prolong the life time of the energy source it is better to operate with the battery so, that the depth of discharge stays in the range of 20-80%, prevent ultra-fast charging and high loads. In the studied working cycle the depth of discharge is assumed to be 70% in order to prolong the lifetime of the whole system. That means that the discharge time will be 3.75 hours, which will allow the operation of the robot during one working cycle after what the robot will have to go to the base to charge.

7.3 Energy balance

The whole process of balancing is defined by charging and discharging currents and the produced and consumed power, thus the relation between them is the most important for energy analysis. As it was said before, the battery is supposed to supply more energy than the solar panel produces that means that the battery will be inevitably discharged after some time (DoD of 70%). The robot is designed so that the capacity of the battery is enough for at least one complete working cycle after what the robot is programmed to return to the energy source and charge. According to the requirements of a customer the size of the panel (to get more power) or the capacity of the battery (to make discharge time longer) could be enlarged, so that the robot could work longer. High amount of losses (especially in electrical motors) makes the whole system efficiency quite small and as a consequence it is quite arguable if the system will be economically profitable, but such technical decision could be applied.

8. Control of the robot

There are a lot of different ways how to control the robot, all of them have its own pros and cons, but for an autonomous system the control should be designed very carefully. To decide which exact type of control will be implemented for efficient system operation, it is necessary to analyze the possible solutions.

8.1 Control types

Direct wired control

It is the easiest way to control a vehicle; the controller which is a handheld is physically connected to the device using a cable. User is able to control the robot by toggling the switches, knobs, levers, joysticks and buttons. The motors and the energy source can be connected directly with a switch in order to control direct motion and reverse mode. Such devices have no intelligence, as a consequence cannot be applied in the SolarSprayer.

Wired computer control

Another option is to connect the microcontroller to one of the computer's I/O ports, which allows to control its actions using a keyboard (or keypad), joystick or other peripheral device. Adding a microcontroller to a project also may require the robot reacts to the input being programmed. Instead of using a laptop or desktop computer, netbooks are often a desirable choice because of their low price, small size and low weight

Radio Frequency (RF)

RF Data Telemetry Commercially available Remote Control (R/C) units use small microcontrollers in the transmitter and receiver to send, receive and interpret data sent via radio frequency (RF). Standard radio frequency devices can allow for data transfer between devices as far away as several kilometers and there is seemingly no limit to the range for more professional RF units.

Many robot builders choose to make semi-autonomous robots with RF capability since it allows the robot to be as autonomous as possible, provide feedback to a user and still give the user some control over some of its functions should the need arise.

Bluetooth

Bluetooth is a form of RF and follows specific protocols for sending and receiving data. Normal Bluetooth range is often limited to about 10m though it does have the advantage of allowing users to control their robot via Bluetooth-enabled devices such as cell-phones, PDAs and laptops (though custom programming may be required to create an interface). Just like RF, Bluetooth offers two-way communication.

Wi-Fi

Wi-Fi is now an option for robots; being able to control a robot wirelessly via the internet presents some significant advantages (and some drawbacks) to wireless control. In order to set up a Wi-Fi robot, a wireless router connected to the internet is needed and a Wi-Fi unit on the robot itself. For the robot, you can also use a device that is TCP/IP enabled with a wireless router.

GPRS/Cellular

Another wireless technology that was originally developed for human to human communication, the cell phone, is now being used to control robots. Since cellular frequencies are regulated, incorporating a cellular module on a robot usually requires added patience for programming as well as an understanding of the cellular network system and the regulations.

Autonomous

The next option is to use the microcontroller in the robot to its full potential and program it to react to input from its sensors. Autonomous control can come in various forms: pre-programmed with no feedback from the environment, limited sensor feedback and finally complex sensor feedback. True “autonomous control” involves a variety of sensors and code to allow the robot to determine by itself the best action to be taken in any given situation.

The most complex methods of control currently implemented on autonomous robots are visual and auditory commands. For visual control, a robot looks to a human or an object in order to get its commands.

The pros and cons of all the control types are presented in the Table 17:

Table 17: Control types pros and cons

Connection method	Control type	Advantages	Disadvantages
Wired method	Direct wired control	- The robot is not limited to an operating time since it can be connected directly to the mains - There is no worry about loss of signal - Minimal electronics and minimal complexity - The robot itself can be light weight or have added payload capacity - The robot can be physically retrieved if something goes wrong (very important for underwater robots)	- The tether can get caught or snagged (and potentially cut) - Distance is limited by the length of the tether - Dragging a long tether adds friction and can slow or even stop the robot from moving -Such devices have no intelligence
	Wired computer control	- Same advantages as with direct wired control - More complex behaviors can be programmed or mapped to single buttons or commands. - Larger controller choice (mouse, keyboard, joystick, etc.) - Added onboard intelligence means it can interface with sensors and make certain decisions on its own	- Cost is higher than a purely tethered robot because of the added electronics - Same disadvantages as with direct wired control
Wireless method	Radio Frequency (RF)	- Considerable distances possible - Setup can be straightforward - Omni directional (impeded but not entirely blocked by walls and obstructions)	- Very low data rate (simple commands only) - Transmission frequencies can be shared

	Bluetooth	- Controllable from any Bluetooth enabled device (usually additional programming is necessary) such as a Smartphone, laptop, desktop etc. - Higher data rates possible - Omnidirectional (does not need line of sight and can travel a little through walls)	- Devices need to be "paired" - Distance is usually about 10m (without obstructions)
	Wi-Fi	- Controllable from anywhere in the world as long as it is within range of a wireless router - High data rates possible	- Added programming required - Maximum range is usually determined by the choice of wireless router
	GPRS/ Cellular	- Robot can be controlled anywhere it has a cellular signal - Direct satellite connection is possible	- Setup and configuration can be complex – NOT for beginners - Each network has its own requirements / restrictions - Cellular service is not free; usually the more data you transmit/receive the more money you will need to pay. - System is not (yet) well setup for robotics use

	Autonomous	-This is “real” robotics -Tasks can be as simple as blinking a light based on one sensor readings to landing a spacecraft on a distant planet.	-It’s only as good as the programmer; if it’s doing something you don’t want it to do, the only option you have is to check your code, modify it and upload the changes to the robot.

8.2 Control decision

As the robot is planned to be designed as autonomous this inevitably means that the use of the microcontroller is necessary. The microcontroller is supposed to be programmed so that it will have the particular trajectory to follow according to the sizes of the plantation model and required working cycle. There are at least two possible devices which can be applied for this task, they are: MSP430 produced by Texas Instruments and AVR XMEGA produced by Atmel. These two devices have big potential and could be applied to control the required speed and time of the processes as well as the needed trajectory.

The control of the robot is considered as a topic for the further study and can be the next step of SolarSprayer development as well as the possibility of the trajectory real-time tracking and the operator computer supply with the real-time data about the working process. Thus in this particular work the program code for the microcontroller is not built and the final selection of the microcontroller is not made.

8.3 Robot control block diagram

To understand how all the chosen devices will operate all together the block diagram of robot operation is presented in Fig. 33:

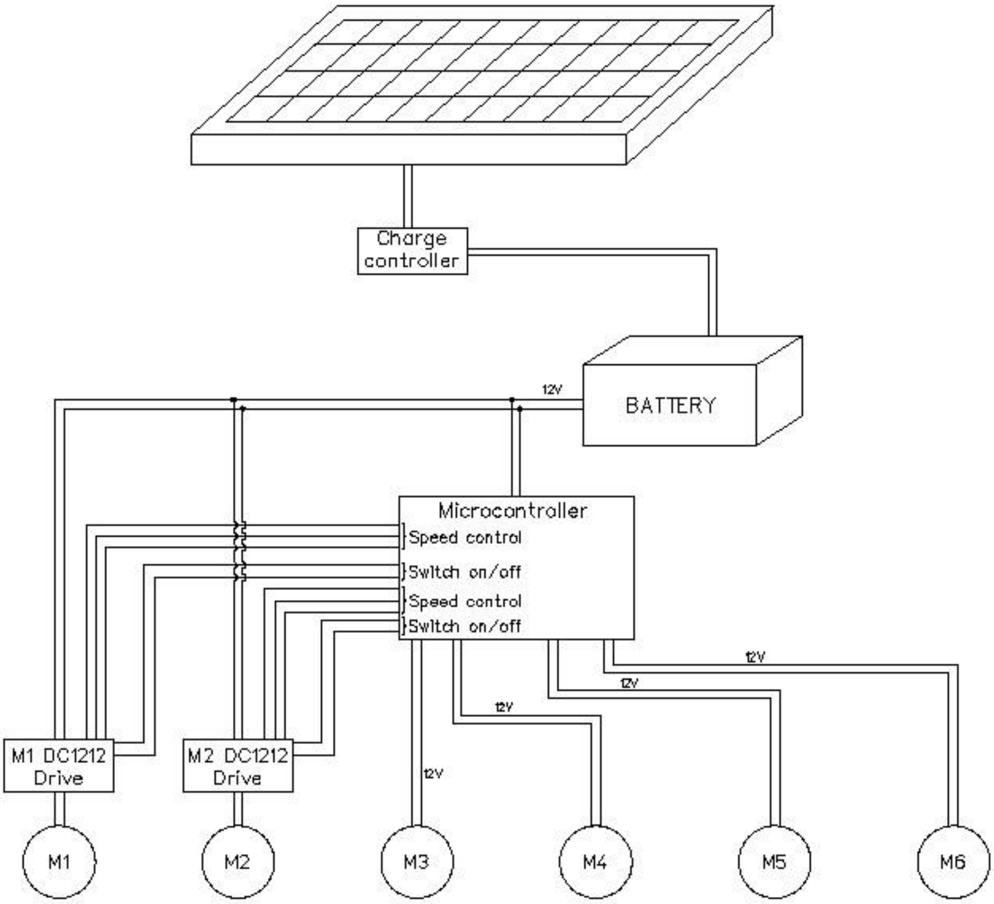

Fig. 33 Robot control block diagram

As it was described before during the electrical drive selection, the microcontroller is planned to be designed so that it switches on/off the motors M_6, M_3, M_4, allows the reversed mode of the motor M_5, and the needed change in the speed of motors M_1, M_2 using the DC1212 drives according to all the required operations.

9. Possible application place analysis

It is obvious that the successful usage of the device directly depends on the solar activity and as a consequence on the place where robot is applied. As activity varies very much it is important to choose the place with sufficient amount of the green energy.

As the robot is designed to work on grape plantations, it should be implemented somewhere, where the wine-making is highly developed. At the same time it means that the solar activity and the number of sunny day a year is high in that place. Thereby the world's biggest grape production countries (see [19]) are presented in Fig. 34:

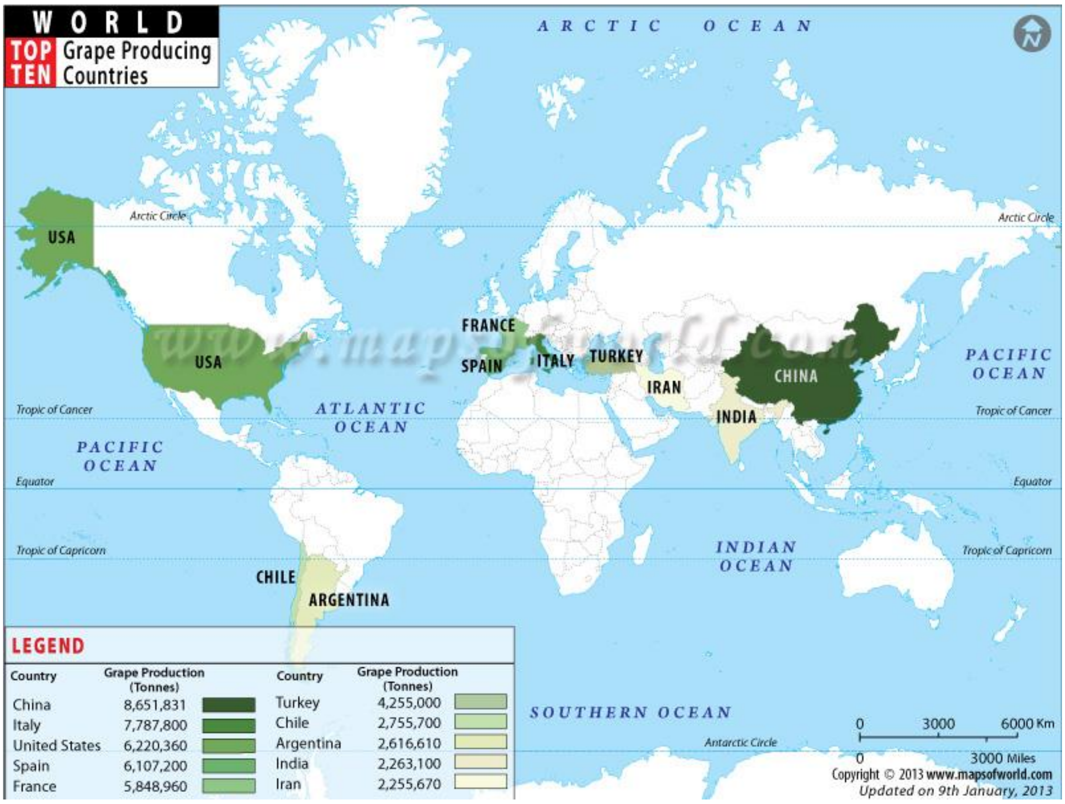

Fig. 34 Grape world production

The other important factor is the amount of solar energy gained a year, which can be seen according to the SolarGIS research (see [20]) in the Fig. 35:

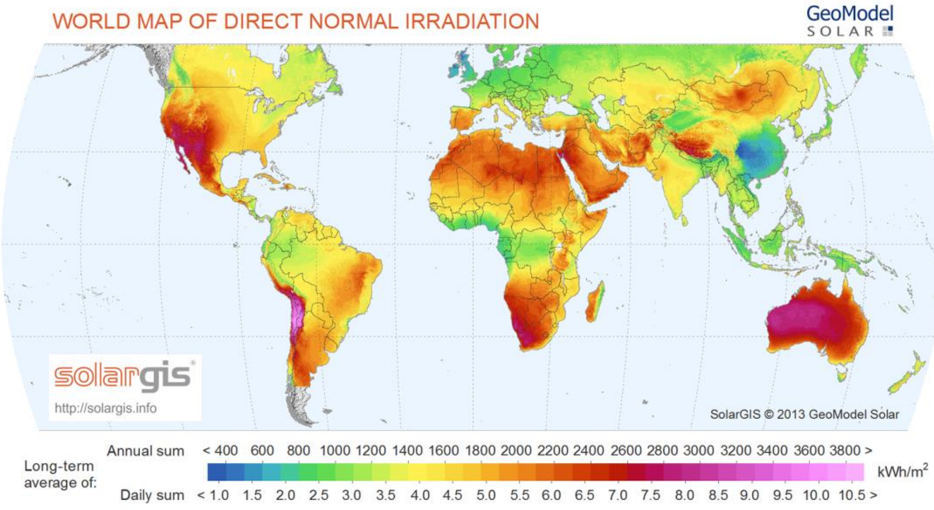

Fig. 35 World map of irradiation

One of the facts that should be mentioned is that the energy of the panel is enough for the robot operation during one working cycle when solar activity allows gaining the maximum energy yield. According to the energy balance calculation it is enough if the irradiation is 1000Wh and more. So basically, any of the countries, considered as a big world exporter of grapes and wine could be chosen.

The other important characteristic is the technology development rate in the country and the authority’s attitude to the green energy, probably some programs run to for development of renewable sources or energy efficiency improvement. In that sense, European countries are very promising for applying the device, famous for its wine and viniculture which at the same time have high level of technological progress. Hereby Italy, France and Spain are the most preferable countries also North America could be a good option.

10. Possible add-ons and changes.

There are a lot of possibilities how the system could be improved. The first thing indicating this fact is the energy insufficiency of the system. While the energy consumption is more than the energy yield the system can be upgraded. It can be done in both directions, whether to enlarge the power of the solar panel or to change the robot tasks.

There is not enough energy in the system during the working day of 8hrs, which happens due to the high losses and it means that some parts of the system could be changed which will allow adding some other functions to already existing. For example, if the more powerful panel is installed, it could be added the function of measuring the quality and characteristics of the soil as implemented in the SolarSprayer's "brother" Agri Rover. The other option is to add the operation of cutting the vine or smart monitoring of the ill plants with the help of artificial mind filter achieved by adding cameras. The cameras also can help to make the system completely autonomous and significantly improve the efficiency, using the real-time visual tracking the device can build the following trajectory and select the optimal working cycle by itself. Another important and practical issue is gathering the information and sending it to the data base on the PC of the operator, who can be located anywhere: whether directly on the plantation service building or at some other point. There is also an opportunity of adding an important feature of checking the chemical liquid level, and calculation of the moment when the robot has to go back to the service building in order to refill the liquid tank, depending on how the processing is implemented at the moment. The other way how to get more power is to make the device more efficient that means another iteration of calculating all the features with the new stage of selecting, connected with the reduced mass, and as a consequence, required power of the system.

All these possible add-ons inevitably lead to the adding of the different devices such as, liquid level sensor, cameras, sensors for measuring the soil quality, GPRS for sending the gathered data to the operator, different auxiliary parts of the chassis.

Another interesting option is system integration of the SolarSprayer on smart vine plantation. That means, that the whole plantation will be energy autonomous, having in its service building the solar station on the roof, combined with the wind farm. That will allow using the whole potential of the robot with the function of recharging the battery by coming back to the station and refilling the charge with the help of the station battery. This kind of system integration can lead to a very high efficiency of the whole vine plantation, making it almost autonomous. The robot can even work 24 hours a day 7 days a week, because there will be all the time some energy to supply from the station battery. Such device could make the life of farmers much easier and enlarge their income together with the efficiency of the process.

Finally, the robot can be transformed into a universal agricultural device which will combine a huge variety of the tasks in itself. In the ideal case, it is possible to process the full cycle of the vine or any other type of fruit growth, also vegetables and other types of food resources with the help of the universal agricultural robot.

These all possible add-ons are considered as probable future topics for the further development and research of the device. As well as the control design, which implies the selection and programming of the microcontroller, being the brain of the whole robot.

Conclusion.

In this work the model of the solar agricultural robot SolarSprayer was designed. Such questions as the robot structure, dynamics, energy balance, required equipment and control methods were analyzed.

First, a review of the applications of the robots in agricultural sector was brought. During the statement of the problem, it was decided that the robot will process the particular assumed plantation model and as a consequence particular working cycle was designed in order to work on 450 plants. The operational time limits and the robot trajectory were set. According to the working cycle, the main and auxiliary system requirements were sorted out, which allowed making a decision about the main parts and devices which the robot should contain. Taking into account the list of the requirements, the robot model was presented. The study of the robot model physics allowed gaining the information about the mechanical power required by the system. As the power was calculated, the next step was to select the electrical motors for proper SolarSprayer operation. After that, one of the most important parts of the work – solar station design was performed; which included the detailed explanation of the selection of solar panel, charge controller, battery and inverter, according to the robot model parameters and requirements. To understand if the system design is correct enough for the operation of the robot only with the help of the solar power, the energy balance research was carried out, which afforded interesting conclusions about robot work, characteristics and potential. In the last paragraphs the possible application area as well as probable add-ons and changes were studied, which helped to understand where the device work could be implemented and to determine the further possible research directions.

As a result, quite interesting information about the possibility of such robot helping the agricultural sector was gained. Basically such device could be manufactured and would have the economic success, reducing the farmers' expenses on a long term scale, which could also afford them to reduce the final price of their products: grape and wine. Another result is that the parameters of the machine could be adjusted according to the particular required work and roughly there is a big potential of adding different other tasks, making from SolarSprayer a universal agricultural robot. The system was designed so that there is a need in additional energy from the grid, when the working cycle is finished. However it is possible if some of the system's characteristics will be changed, that other tasks will be added to the robot operation. It is also possible to realize the "Smart Plantation" project which means integration of the robot in the solar station and wind farm in the plantation service building.

To sum up, the result of the work is that topic of the agricultural solar robots is very promising, especially in the countries with high amount of yearly solar energy gained, and worth further study, in order to improve the efficiency of the cultivation in general, not only on grape plantations, but in almost any agricultural line. The efficient production will also have a positive effect, causing the products prices reduction.

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