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Designing and Prototyping of a Hybrid Robotic Lawnmower

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Abstract: In this paper, the designing and prototyping of a hybrid robotic lawnmower is presented. The main system components required for functionality are briefly described. All parts of the system are selected in order to enable coordinated operation of electrical and mechanical components. Robotic lawnmower prototyping is preceded by a design process that consists of a phase of selecting the main components and CAD modeling of parts and components. The goal is to position components and parts of the chassis with maximum compactness. The main subsystems of the prototype, the differential drive configuration, and the hybrid subsystem with a belt transmission for starting the alternator and the lawnmower blade are shown. The parts of the subsystem were tested and the final testing of the robotic lawnmower in the case of remote control was carried out. This prototype was made with total costs many times lower than similar commercial robotic lawnmowers.

Keywords: CAD; differential drive configuration; hybrid robotic lawnmower; prototyping; transmission

1 INTRODUCTION

Lawn mowing is considered a boring and tedious routine household task, therefore it is one of the more promising robotic fields. One of the classifications of lawnmowers is according to the axis of rotation of the blade, where two main types are lawnmowers with a horizontal reel and rotary vertical lawnmowers which will be further discussed in this paper. The blades on the rotor achieve a clean cut and are adapted to different cutting heights. Furthermore, with regard to the drive and the energy source, there are manual, electric, or internal combustion engine (ICE) mowers. Rotary mowers are mostly powered by an ICE or an electric motor, where the main power source is engaged for rotating the cutting blades. The opening on the mower body is used to throw out the mowed grass, and some versions have an attached collection basket. There are already many commercial robots for mowing grass, and many prototypes [1, 2]. Some predictions indicate that robotic lawnmowers will further push the boundaries in robotics, as a kind of continuation after the great expansion of robotic vacuum cleaners. The significance of such research lies in the potentially large market in the field of personal robotics [3].

These types of robots usually come with similar features such as the ability to work within a defined space and the ability to avoid static obstacles. In the initial stages of robotic lawnmower research, modeling and motion mechanisms were considered, as shown in the paper [4]. A robotic lawnmower can be remotely controlled, semi-autonomous [5], or, in the most sophisticated version, an autonomous robot used to cut grass. Over the years, there have been numerous advances in lawnmower technology. In the early stages of using robotic lawnmowers, a sensor wire was used to define the boundaries of the mowed area, just as Lawrence Bellinger did in his patent, back in 1969 [6]. In this case, the wire needs to be placed around the edges of the lawn area as well as around any static obstacles. This requires additional work by the operator, which causes a higher cost of mowing. The industry also got involved in the development of robotic lawnmowers, and Husqvarna presented the Solar Mower lawnmower model in 1995, and a step further was taken in 1998 when the same company presented the Automower with a rechargeable battery and the ability to work in various weather conditions.

Nevertheless, this area of robotics is still suitable for further development [7], especially from the aspect of autonomy, given the methods of positioning, detection, and avoidance of obstacles. Due to specific circumstances, fully autonomous lawnmowers are often replaced with human control and remote control. Obstacle avoidance algorithms work with static obstacles, but there are more challenges with dynamic obstacles that are common in mowing grass. Although there are many problems, there are more and more solutions. Today's models of robotic lawnmowers can be controlled in a variety of ways, such as mobile application control. Unlike the models used in the past, modern lawnmowers do not need physical borders along the edge of the plot but use sensor systems that include GPS, cameras, distance sensors, and other types of sensors [8, 9]. With the help of a sensor package, they determine the work area intended for mowing and avoid obstacles alongside other features. In paper [10], a solar photovoltaic (PV) panel-powered smart lawn mower, employing an Internet of Things (IoT)-based control system is presented. New features increase the price and robotic lawnmower systems are expensive, which is probably the main barrier for a larger number of users. From an economic point of view, the paper [11] presents an evaluation of life cycle influence and costs associated with autonomous solutions in the agricultural sector.

As control systems and sensors advance, hardware also progresses in parallel. Hardware solutions primarily rely on factors such as the terrain configuration, plot size, and the dimensions of the grass and plants. For instance, robotic lawnmowers find application in orchards [12, 13], artichoke fields [14], and various other crop fields. Although there are numerous works related to the design of robotic lawnmowers, they are mostly conceptual designs or scaled prototypes [15]. As an illustration, the paper [16] introduced the conceptual synthesis of a multifunctional lawnmower and demonstrated a prototype. Additionally, the same group of authors presented in the paper [17] the conceptual design of a smart lawnmower for uneven grassland using the Theory of Inventive Problem Solving (TRIZ). A review of the literature revealed a lack of papers in which the process of designing a robotic lawnmower is described in more detail.

The goal of this research is to create a prototype of a hybrid robotic lawnmower based on an ICE that is used to turn the lawnmower's blade using a right-angle gear reducer and to propel an alternator through which the batteries are charged with electricity. A differential drive configuration, made with two electric motor drives and four wheels, was chosen for the drive system that realizes the movement of the lawnmower. After selecting the components, the construction process was carried out and the key assemblies of the system were presented. The created prototype was extensively tested and successfully performed the tasks. The considered hybrid system has great autonomy in terms of the length of mowing time and is suitable for use in larger areas such as orchards. The main advantage of the prototype compared to commercial lawnmowers is the much lower price.

2 THE MAIN COMPONENTS OF A HYBRID ROBOTIC LAWNMOWER PROTOTYPE

The presented lawnmower prototype works according to the operating principle of hybrid systems known in the automotive industry, where different types of energy and drive components are used. The gasoline four-stroke ICE is the main driver of all systems and at the same time the only source of kinetic energy necessary for the operation of the lawnmower blade, which converts from the chemical energy of 95-octane gasoline. A clone of the Honda GX200 engine was selected, which has a volume of 196 cc, a power of 5.5 kW, and a torque of 13.2 Nm with a horizontal output rotating shaft. The engine operation is controlled by a servomotor that moves the engine's throttle lever. Fig. 1 shows a 3D subassembly of the motor with a double pulley, servomotor, and rubber bumpers that mitigate unwanted vibrations that are transmitted to other parts of the chassis.

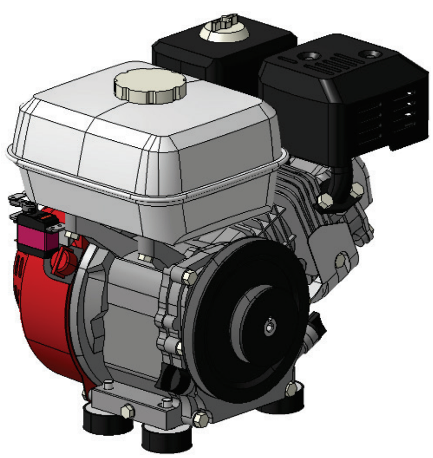

Figure 1 Internal combustion engine subassembly with servo motor, rubber bumpers, and a double pulley

The key part of the lawnmower, intended for the transfer of kinetic energy, necessary for turning the blade during mowing, is the angle gear reducer (manufacturer Coberg, model L-155J). For this prototype, a reducer with a transmission angle of 90°, and a gear ratio of 1:1.14, is used. The rotation axis of the gasoline engine rotates around the horizontal central axis, therefore, the rotation is transmitted to the vertical axis of the blade using the internal gears of the reducer. The rotation of the blade in a counterclockwise (CCW) direction is enabled. The input shaft of the angle gear reducer is a cardan shaft with 6 teeth, used in agricultural machines, while the output shaft is 25 mm in diameter. Fig. 2 shows a 3D model of the reducer in its original state on the upper part of the picture, and with modifications where the shafts are shortened and adapted, on the lower part of the picture.

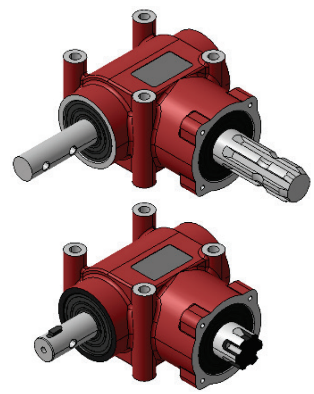

Figure 2 Angle gear reducer original version and revision

The main source of electricity for the movement of the lawnmower is the electricity generator, the so-called alternator. It is driven via a belt drive by a gasoline engine and converts the received kinetic energy into electricity. An alternator with an output DC voltage of 24 V was selected, and the charging current is 35 A, which is enough to start the electric motors of the drive configuration, as well as to recharge the lawnmower's battery at the same time. Two batteries are placed within the housing of the prototype. The voltage of these batteries is 12 V, and they have a capacity of 3 Ah. The batteries are connected in series, considering that the required voltage of the lawnmower electric motors is 24 V.

The prototype drive configuration consists of two electric motor actuators (manufacturer Vevor, model BY1016Z) which convert electrical energy into kinetic energy. Electric motors are collector designs, with graphite brushes. Considered actuators have a built-in gearbox to reduce the angle velocity on the output shaft, and to simultaneously increase output torque. According to the specifications, the maximum number of revolutions is 309 RPM, the nominal power of the motor is 350 W, and the operating voltage is 24 V. The motors are independent of each other, and they are mounted separately on the lawnmower as a left and right motor. The motors are controlled by a driver (H-bridge) which receives a PWM signal based on which it controls the electric motors. This type of driver (control unit) is based on the principle of changing the polarity of DC collector motors, which can turn in one direction or the other. Drive configuration consists of two single-channel drivers.

In the testing phase of the hybrid robotic lawnmower prototype, a remote control system will be used, where information is transmitted via a wireless communication link, using electromagnetic waves. Components were selected that are compatible with the six-channel Flysky FS-i6 transmitter. For the complete control of this prototype, five communication channels are used, two for electric motors, and one channel each for the linear actuator of the belt tensioner, the servomotor that controls the operation of the gasoline engine, and the relay for shutting down the gasoline engine.

3 DESIGNING A HYBRID ROBOTIC LAWNMOWER SYSTEM

3.1 Designing the Drive Configuration of the Robotic Lawnmower

The most common drive configuration of unmanned ground vehicles (UGV) or ground mobile robots is a differential drive where two actuators are used for the robot's movements. The differential drive enables translational motion but also rotation in place around the vertical axis, which is convenient considering the purpose of the presented robot. Most of these configurations consist of two wheels that are directly or via a transmission connected to the actuator. In this paper, the prototype is made as a differential drive with four wheels, as shown in Fig. 3. Different wheel velocities achieve rotation, i.e., turning the mower, while the same velocities cause straight-line motion. During straight-line motion, all four axles are equally loaded at the same time. Turning the lawnmower in operation is very simple, thus faster and more efficient mowing is possible, given that no uncut marks are left in place when turning. All-wheel drive contributes to mowing on uneven and hilly terrain, and in case of minimal slippage, all wheels exert equal forces and moments. The front and rear wheels on one side are therefore synchronized and are maximally close to each other for the compactness of the lawnmower. It is necessary to design a system for transferring energy from the electric motor to the wheels.

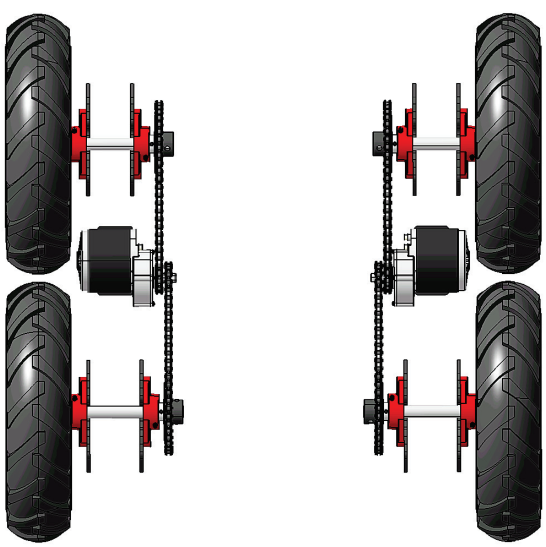

Figure 3 Prototype differential drive configuration [18]

Chain transmission is selected for the transmission of moments from the shaft of the electric motor to the shafts of the prototype driving wheels, which forms the basis of the differential drive of the robotic lawnmower. Three key components of chain transmission are the sprocket as the torque transmitter, the sprocket that receives the torque, and between them a flexible chain link. The chain transmission is relatively easy to install, has high efficiency, and compared to gears, works better under shock load conditions. In chain transmission, the working load is distributed among the teeth, and proper lubrication is required. A total of four chains of equal length are required for the proposed differential drive configuration, as each wheel uses a separate chain link. The front and rear wheels of one electric motor on each side of the lawnmower are driven synchronously. Since two wheels are synchronized on one side, it is necessary to design and manufacture a double sprocket of the electric motor shaft consisting of 410H sprockets with 10 teeth. In order to obtain a slower speed of movement of the mower and higher torque, the sprocket of each wheel has 32 teeth, therefore the ratio of teeth between the sprockets is 10:32. Larger sprockets are bolted to the wheel shafts via flanges located at the ends of the axles and attached with a pin. The sprockets of the wheel shaft and the electric motor are connected by 415H chains. Fig. 4 shows the subassembly of one side of the differential drive configuration of the proposed robotic lawnmower prototype.

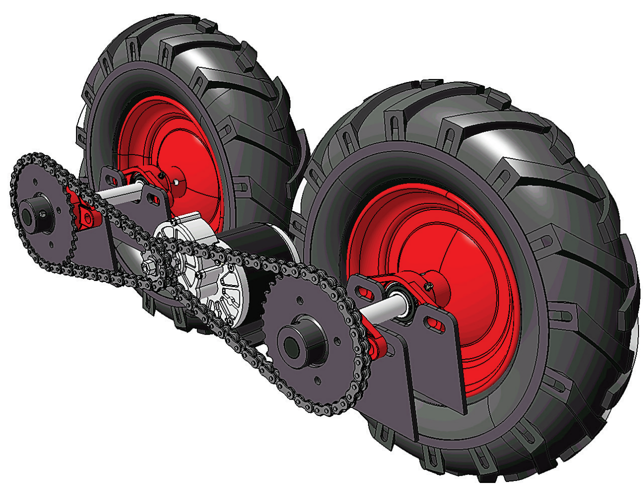

Figure 4 Subassembly of one side of the differential drive configuration [18]

As shown, one side of the mower's differential drive consists of two wheels, drive shafts, pairs of bearings, flanges, and a chain transmission connected to the electric motor actuator. The wheels consist of a metal rim on which a pneumatic tire under pressure is mounted. The width of the tire is 100 mm, while the outer diameter is 400 mm. The wheel drive shaft is attached, using a split pin, to the axle hole of the wheel. It is made by turning from a structural steel round bar, and the shaft diameter is 22 mm on the wheel side and 20 mm on the bearing side. The shaft is connected to the main housing of the robotic lawnmower utilizing bearings that serve as support for the moving parts of the robot and for the proper direction of kinetic energy. The model used for the prototype is a ball bearing in a housing, model UCFL204, which is mounted with M12 screws on the bearing supports. Vertical bearing support was constructed, taking into account the dimensions and shape of the bearing housing, and enabling adjustment of the chain transmission tension. Simplified expression for the translational speed of the wheel

$$v_V = r_V \cdot i_{CT} \cdot \omega_M, \tag{1}$$

where r_V is the wheel radius, i_{CT} is the gear ratio of the chain transmission, and ω_M is the angular velocity of the DC motor with gearbox. In the case of the declared motor speed of 309 RPM, at the declared torque of 13 Nm, it turns out that the translational speed is v_V = 2 m/s.

3.2 Designing the Lawnmower Blade Mechanism

The angle gear reducer is a mechanical assembly for the transmission of kinetic energy, where a blade adapter is mounted on the output shaft of the reducer. Before mounting on the lower vertical output shaft, the blade adapter must be redesigned and manufactured as shown in Fig. 5. The lawnmower blade is a mechanical metal piece with sharp edges and is mounted with screws on the blade adapter. The blade model of this prototype has a symmetrical shape, length of 580 mm, width of 55 mm, and thickness of 5 mm. The blade rotates around the vertical axis and, passing through the grass and vegetation cuts the plants hit by the sharpened edge. The proposed prototype does not use a grass collector, therefore the blade is made without rear ejectors. Due to a rotary motion, centrifugal forces throw the cut plants out of the blade area.

Figure 5 Lawnmower blade mounting

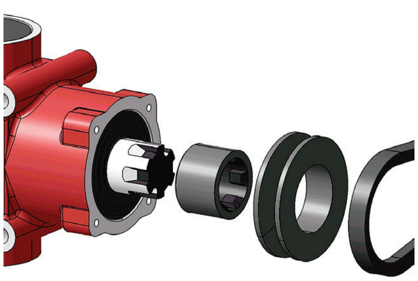

Figure 6 Angle gear reducer pulley mounting

The transmission of kinetic energy is made possible by the internal parts of the angle reducer, which transfer the rotation of the input shaft to the rotation of the blade around the vertical axis of the lawnmower. To transfer the kinetic energy from the gasoline engine to the reducer, a belt transmission was chosen. The transmission ratio of the belt transmission between the gasoline engine and the reducer is 1:1. Subassembly exploded view of the angle reducer input shaft, pulley, and section of the belt is shown in Fig. 6.

3.3 Designing the Belt Transmission of a Hybrid Lawnmower

From the aspect of designing the hybrid system of the robotic lawnmower, it is necessary to design the belt transmission [19] that connects the gasoline engine with the angle reducer and the alternator, therefore two belts are needed. The belt transmission system consists of conical pulleys and V-belts. Two 13 mm wide V-belts were chosen, models AVX 13x1100 and AVX 13×670, where the shorter belt for the angle reducer is 670 mm long and the longer belt for the alternator is 1100 mm long. The belts are reinforced with additional outer plating for strength and toughness. The basic pulley is a specially made double pulley and is mounted on the output shaft of the gasoline engine, from which it transmits moments to the other belt transmission parts. As stated, the transmission ratio between the gasoline engine pulleys and the angle reducer is 1:1, and the outer diameters of the pulleys are 80 mm. A ratio of 2:1 was chosen for torque transmission to the alternator. The pulley on the alternator is 80 mm in diameter, while that on the gasoline engine is 160 mm. The reason for such a ratio is the need for a higher nominal rotational speed of the alternator. The electrical energy of the prototype must be sufficient for the electric drive of all its components, and simultaneously for charging two batteries.

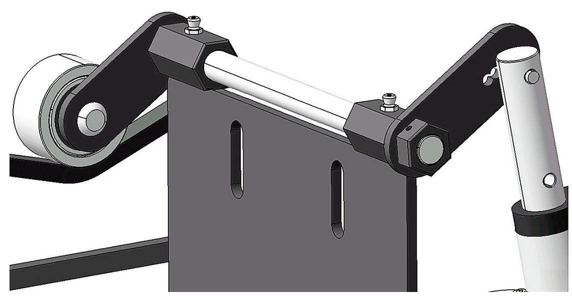

Figure 7 Belt tensioner mechanism

Belt tension is important when designing a belt transmission. The alternator belt is permanently tensioned, and it is tightened by moving the alternator away from the gasoline engine, via a lever that is an integral part of the alternator support. The belt tensioner of the angle reducer is specially designed keeping in mind the engaging and disengaging of the lawnmower blade. This reducer belt tensioner model consists of a lever that presses the belt and is mounted on the reducer bracket as shown in Fig. 7. It is mounted on top of the angle reducer bracket using two drilled M14 extended metric nuts. One end of the tensioner moves the linear actuator via a lever, while on the other side, on another lever, there are ball bearings inside a metal cover. The cover freely rotates on the outside of the angle reducer belt return connection, and in this way performs belt tensioning and therefore blade rotation. A used linear actuator is a device that performs work via an output shaft that pulls or pushes the tensioner lever. It consists of an electric motor and gears, and the maximum pushing force of this prototype actuator is 800 N. The linear actuator is controlled by the electronic speed controller (ESC) based on the received signal via the remote control receiver. Fig. 8 shows the main components and parts that are mounted on the robot chassis. If we assume that there are no losses, expression for the moment of the blade is

$$M_{\mathrm{B}} = i_{\mathrm{AR}} \cdot i_{\mathrm{BT}} \cdot M_{\mathrm{ICE}}, \tag{2}$$

where i_{AR} is the ratio of the angle gear reducer, i_{BT} is the ratio of the belt transmission, and M_{ICE} is the ICE torque.

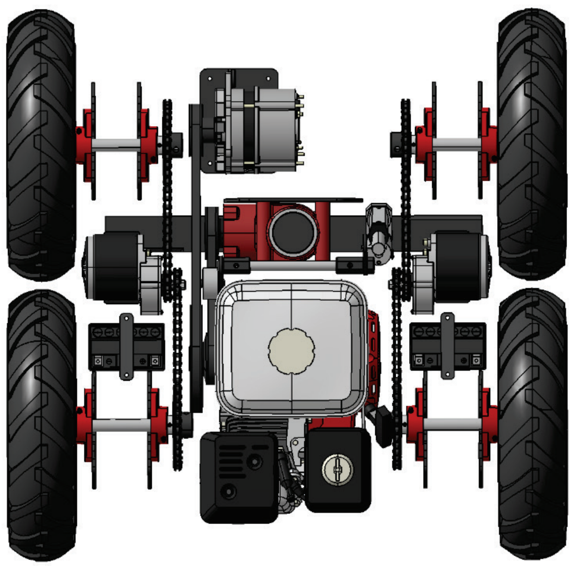

Figure 8 Arrangement of system components

3.4 Chassis of the Hybrid Robotic Lawnmower Prototype

The chassis of the hybrid robotic lawnmower is designed, which has the function of carrying all the components of the system. The back and front of the housing are completely open, which allows the grass and plants to be ejected smoothly, and prevents the blade from being blocked. A hole with a diameter of 62 mm is cut in the middle of the housing, through which the lower vertical shaft of the angle gear reducer passes. The chassis dimensions are 630 mm wide and 700 mm long. The vertical shaft bearing supports, as well as the angle reducer supports, are welded to the housing. Each wheel axle contains two supports. The brackets of the angle reducer also have the role of moving the reducer along the vertical axis, and this consequently determines the cutting height of the blade. For the production, a template was made which is shown in Fig. 9.

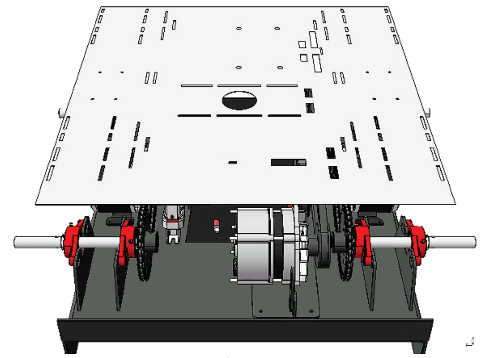

Figure 9 A template for making a robot chassis

The system components are mounted to the chassis of the lawnmower. The compactness of the entire system is achieved, and Fig. 10 shows the assembly of the hybrid robotic lawnmower. The height of the lower part of the chassis, measured from the ground, is 125 mm. Therefore, the height of the blade is set at approximately half the height of the chassis. Since the height of the blade can be moved, the lowest position of the blade is 58 mm, while the highest cutting height of the blade is 83 mm.

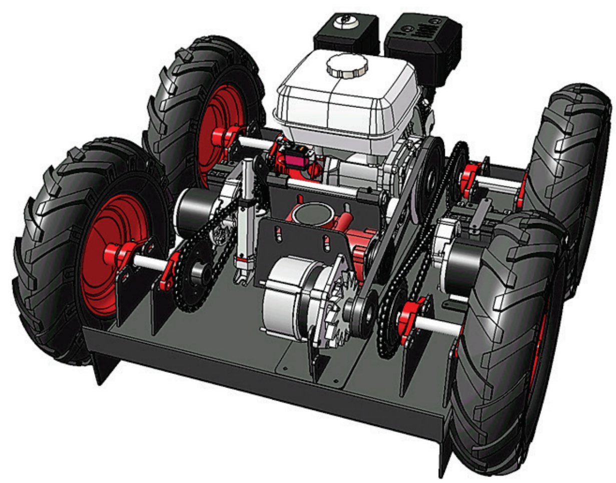

Figure 10 3D model of the assembly of the hybrid robotic lawnmower

4 PROTOTYPING AND TESTING A ROBOTIC LAWNMOWER SYSTEM

In the prototyping phase, modification and production of the necessary parts were carried out according to the 3D models and related documentation. First, chain and belt transmission components modifications and parts needed to mount the components on the chassis of the robotic lawnmower were made. Turning and laser cutting were used in the production phase. Then, laser cutting, bending, and welding of the supports were used in the stage of making the chassis of the robotic lawnmower. The final external dimensions of the lawnmower chassis after bending are 630 mm wide and 700 mm long. After the parts of the system were made, the assembly of the components and parts was done, and Fig. 11 shows the final assembly of the hybrid robotic lawnmower.

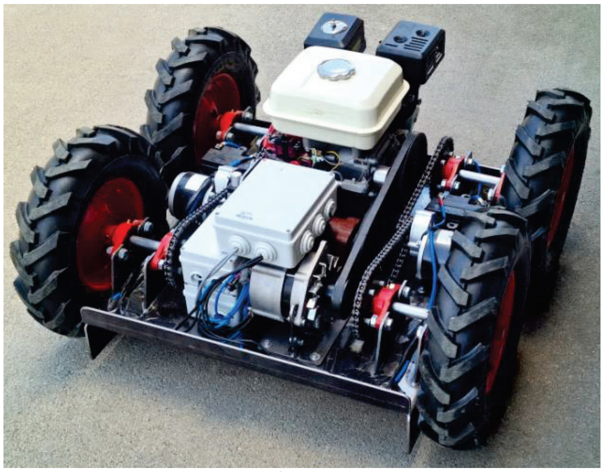

Figure 11 Prototype of a hybrid robotic lawnmower

After the assembly of the prototype, for the purpose of final implementation, testing of individual mechanical and electrical subsystems of the lawnmower prototype was carried out via remote control. The drive configuration of the robot was controlled using two channels of the remote control, one channel was used for the left wheels and the other channel for the right wheels. Gasoline engine control is tested for throttle regulation using a servo motor, and the switch for turning off the gasoline engine using a relay. Next, the engaging of the lawnmower blade was tested using a linear actuator and belt tensioner mechanism. After all the systems responded positively to the tests, the lawnmower was tested in real conditions. Fig. 12 shows the use of the presented prototype of the hybrid robotic lawnmower. Extensive testing of the prototype was done in conditions of different terrains and grass heights, and the prototype successfully performed the task of mowing. Through testing, minor defects were eliminated and segments of the prototype that were exposed during mowing were observed, for which protective housings will be made in future upgrades.

5 CONCLUSION

This paper presents the design and prototyping of a hybrid robotic lawnmower. The main components of the system are listed and explained. Parts of the electrical and mechanical systems of the prototype are connected and are mutually compatible when performing tasks. The process of designing the system through the phase of CAD modeling in the CATIA software package is presented. With regard to the selected components, chain, and belt transmission systems were designed that connect the electrical and mechanical systems. The complete prototype was made with total costs of less than 2,000 euros, which is many times less than commercial solutions, and further system upgrades are possible. After the manufacturing and assembly phase, all subsystems of this prototype were tested, and they all responded positively and successfully to the test. In further work, the increase in the degree of autonomy of the lawnmower prototype will be investigated in the form of the use of different sensors and control systems.

Figure 12 Prototype during testing

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