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ENVIRONMENTALLY FRIENDLY BIO-INSPIRED TURTLE ROBOT

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ABSTRACT

Inspired by the movement of a turtle in nature, a low-budget turtle-like robot was designed and developed to operate on natural terrain. Applying affordable additive manufacturing (3D printing) leads into creating unique 3-D structure with potential of flexibility, multi-functionality and multi-movement. By implementing solar panels, the energy from the sun is used, which makes the robot self-sustainable. The robot is controlled remotely with an android application designed for the need of this work.

The bio-inspired robot can play an interesting role in real-life applications, such as monitoring in hardly accessible terrain, video and data collection for environmental friendly application, animals' observation and others. The main application of the robot is for animal observation in the zoo, so it will often need to move across not even landscape in order to allow surveillance of that area. By implementing smart materials, the movement of the turtle can be improved.

This paper presents the design concepts and functionality, together with CAD model of the robot, the prototyping (hardware, control and application design) and the results from the measurements.

KEYWORDS: Bio-inspired robot, mechatronics, turtle's movement

NOMENCLATURE

m_{total}	Total mass of the robot
m_{leg}	Mass deployed on each leg
F	Force required lifting each leg
M_C	Calculated torque
M_m	Torque of the motor
$T_{i,charge}$	Ideal battery charging time
$T_{a,charge}$	Actual battery charging time
$E_{ep,day}$	Daily average electricity production
T_{total}	Time for the robot to operate continuously
A_{sp}	Area of all solar panels

1. INTRODUCTION

Bio-inspired design is a multidisciplinary research field, seeking for inspiration in the nature and mimic shape, functionality and/or behaviour. Recent research merging mechatronics and bio-inspired engineering results in design of trendy and unique solutions in various applications. More and more autonomous robots are being applied to assist humans for various periodic or high-risk tasks in land, ocean and other complex environments. Many researchers have performed research on walking robots [1, 2] or underwater robots [3] in a single environment with the ability to perform multi-locomotion. Low adaptability to different environments disable the conventional robots from completing more advanced and intelligent tasks, such as mine clearing, terrain mapping, scouting potential approach lanes for amphibious naval operations, observing the endemic animals and other exploration or transportation tasks between terrestrial. Animals in nature have good adaptability to the environment through the long process of evolution. Hence, amphibious robots with high environmental adaptability and high load capacity are needed.

Inspired by the animal's movement, a robot with autonomous environmental adaptability and highly efficient performance remains a challenge. By observing the animals' adaptability in the environment through their long process of evolution, using the bio-inspired engineering, efficient locomotion is established. Turtles are famous for the slowness of their movements, their possibility to spread off, slowly walk and protect themselves in their own shell when in danger. Inspired by their movement, a multi-locomotion robot able to imitate the turtle's movement was prototyped. As the turtles are very adaptive and can be found on every continent, this turtle robot could find its application in multiple applications. The turtle-inspired robot can play an important role in real-world applications, such as monitoring and recovery operations on land and underwater. The researchers in [4] designed the robot AQUA, which is capable of aquatic and terrestrial locomotion that can manually transform from walking to swimming. A turtle-inspired spherical micro robot was developed in [5], capable of walking on land and cruising underwater. An amphibian robotic turtle with high environmental adaptability was presented in [6]. The motivation in do design and prototype a cost-efficient bio-inspired turtle robot is to achieve amphibious efficiently movement with environmental adaptability.

Observing the movement of a turtle that could produce different locomotion, a low-budget turtle-like robot was designed and prototyped, having the ability to operate on natural landscape. The main application of the bio-inspired robot is monitoring in hardly accessible terrain, video and data collection in environmental friendly applications with the ability to be controlled from android application. Because of the low-budget components, the robot could only operate on the ground, while for underwater use, it has to be upgraded as explained below in the design concept.

By applying additive manufacturing technologies, design with potential of achieving several functionalities was established. 3D printing is an additive manufacturing process technology where the products are built on a layer by layer basis, through a series of cross sectional slices [7, 8]. 3-D printing offers a potential route to the rapid fabrication of customized components, enabled this technology to be employed across a various range of applications. The geometry of the structure enables the design to achieve complete gathering of the robot, as is the hiding in their own shell of the real-living turtles.

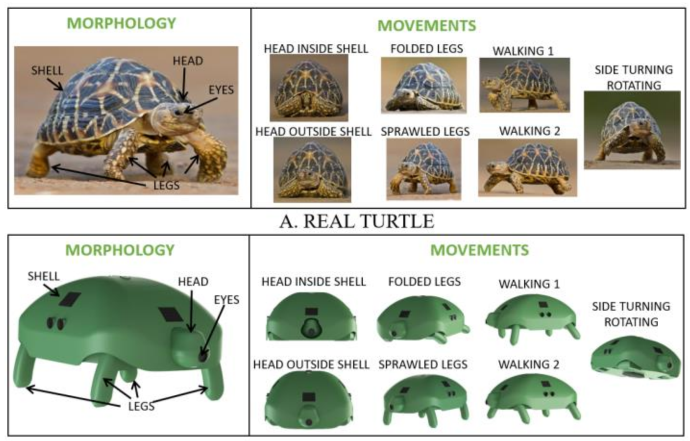
The motivation for the research effort aims to explore bio-inspired design combined with mechatronics that may be useful for the design of engineering applications that could be potentially used in complex environments and tasks. Research combining the new technologies show an improvement while designing and prototyping the turtle's inspired robot, leading into creating a trendy functional design that can be used for many solutions. The concepts explored in this work are based on affordable components and allowed students hands on experience.

This paper presents a low-budget turtle-inspired robot based on biological locomotion principle. A robot imitating the turtle's movement is constructed and tested. The locomotion of the robot is described, and the possible concepts are analyzed and implemented. The organization of this paper is as follows: Section 2 presents the design concept and application, providing a CAD model for 3-D printing; Section 3 provides the prototyping, including hardware, software implementation and application control of the robot; Section 4 presents the results; and Section 5 discusses the conclusions and the proposed future work.

2. DESIGN CONCEPT

To design the turtle robot, a real turtle was analyzed in its shape, size and locomotion. The turtle morphology and its movements are shown on Figure 1, where 1.A shows the morphology and movements of real land turtles, while 1.B shows the created CAD model and the desired movements.

Based on the morphology, the fundamental parts are legs, shell, head and eyes. The turtle's main movement is walking, which is established with its legs. The legs of the turtle can fold inside the shell when the turtle's resting, and sprawls its legs when walking and rotating. The walking of the turtle is established through two main movements. The turtle moves its head inside and outside the shell, and the eyes placed on the head serve for observing the nature. Observing the real land turtle, the required design and movements for the turtle-like robot are shown on the CAD model (Figure 1.B).



B. CAD MODEL

FIGURE 1: TURTLE'S MORPHOLOGY AND MOVEMENTS (A. REAL TURTLE; B. CAD MODEL)

Inspired by the turtle's movement, robot with the ability to establish multi-locomotion was designed. The turtle-like robot has a compact structure, consisted of four legs and head that can gather themselves into the turtle's shell. The turtle like-robot can achieve several movements: sprawling its legs and head, rotating in a desired direction, walking and gathering itself. Despite these abilities, a camera is inserted inside the head of the turtle-like robot for recording and monitoring

The turtle-like robot requires a constant power supply to the batteries, so that it can operate continuously and without further human intervention. The goal is to reach a point where the robot could be able to operate completely independent, therefore the power is provided by small solar panels that convert solar energy into electricity. By implementing solar panels for power supply on the turtle's shell, energy sustainability of the robot is achieved. The controlling of the movements is done by an android application. Figure 2 shows the design framework of the robot, where it can be noticed the sustainability of the robot in terms of controlling and energy supply.

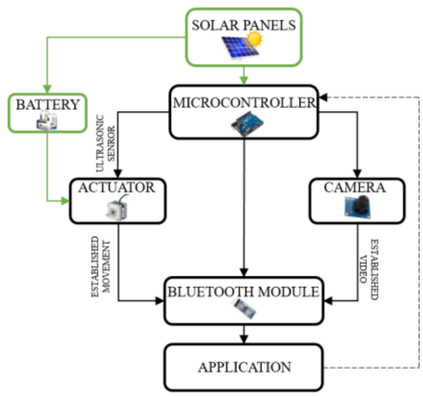


FIGURE 2: DESIGN FRAMEWORK OF THE TURTLE-LIKE ROBOT

The design of the environmentally friendly turtle-like robot is particularly important as it strives to get closer to the true look of the turtles from the nature. This is important because the space and surroundings for which this robot is intended, require it not to cause disturbance, uncertainty or danger to the environment, and to be as acceptable as possible in the certain surrounding. Inspired by the turtle's movement, a multi-locomotion robot was created. The design of the structure together with its geometry enables complete gathering into the shell. Figure 3 shows the CAD model of the turtle-like robot in its gathered (closed) position and in its sprawled position. When the robot is in their closed position, the whole construction (shell) could rotate in the desired position (Figure 3.A), and afterwards, it sprawls its legs and head, and starts walking (Figure 3.B).

The main function of the robot is performed by a system consisting of a large number of connected mechatronic components, all together put up in 3D printed PLA shell. Additive manufacturing was used to 3D print a designed box where all the components for the final device were assembled, connected and placed. There are two main requirements for the design of the 3D printed construction, first, the design has to be bio-inspired and look like turtle, and second, the box has to fit all of the used components and enable protection from outdoor conditions.

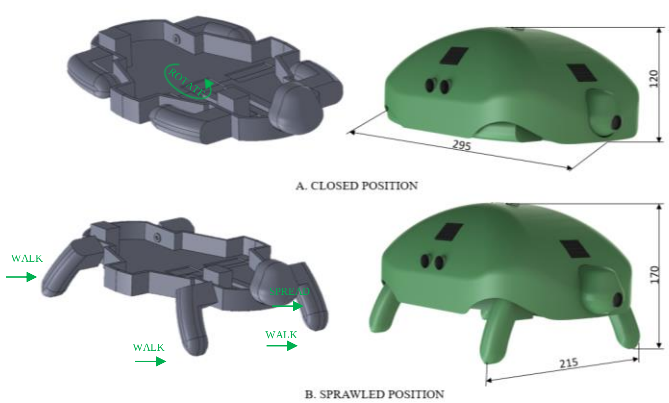


FIGURE 3: CAD MODEL OF THE TURTLE-LIKE ROBOT (A. CLOSED POSITION; B. SPRAWLED POSITION), the dimensions are given in [mm]

The main purpose of the robot is to be used for animal observation, so it will often need to move across on hardly accessible terrains, to allow observation of that area. The turtle-like robot will have the ability to track animals that live in forests, parks or large zoos. Animals of endemic nature, ones that are endangered in the immediate vicinity of humans could be also observed. These animals are constantly on the move, so in order to be observed in different situations and circumstances, the turtle-like robot must move along with them. In addition, the robot could also be used as a device that helps parents easily monitor their children in real time, through an audio and video recorder, while the robot is in children's surrounding. The robot would not harm the observed animals or children, because of the natural look like turtle and in the same time as toy. The robot could also find its use when scaled in safe transport for hazard liquids and guardiancies during nighttime.

In order to find more applications of the robot and its motion in different areas and thus increase its functionality, the robot should be adjusted and protected from water, so it could be used for underwater operations. The preservation from the water will make the robot fully capable of performing its tasks under rainy conditions and moving under water. Improved ground motion can be achieved by replacing existing PLA 3D printed legs with flexible 3D material in combination with smart springs for achievement of smart material actuation, as shown on Figure 4.

In order to mimic the real turtle's movement, flexible legs could be installed, which will perform the movement of the robot. Flexibility is achieved by constructing the legs of several different flexible materials, while the movement of the foot is achieved with the help of a stepper motor enabling the rotation, while the springs will enable sprawling and closing the leg.

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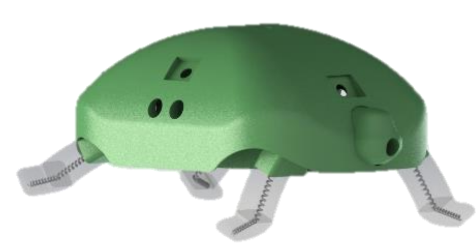


FIGURE 4: SMART MATERIAL ACTUATION OF THE MOVEMENT OF THE TURTLE (THE LEGS OF THE TURTLE ARE MADE ON NITI SPRINGS)

With the help of smart springs made of nickel, titanium and copper (NiTiCu), the sprawling and closing of the leg is performed. The movement of the spring is generated with a flow of current through the spring or with increased temperature. For this experiment, the compression and the elongation effect is generated using current flow through the spring.

Figure 5 shows one the whole construction of the leg of the turtle made from smart springs.

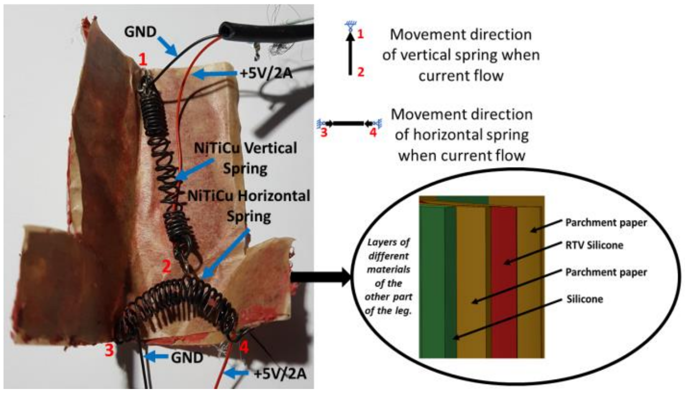


FIGURE 5: THE CONSTRUCTION OF TURTLE'S LEGS MADE ACTUATED BY SMART SPRINGS

First, the springs are placed in stretched starting position. The two ends of each of the springs are connected by cable where direct current flows with 5V voltage and 2A electric current. On one side, the positive pole (+) is connected, where on the other side the negative pole (-) is coupled. The other side of the cable is connected to the Arduino microcontroller, which gives the command to let the electric current flow through the line for a certain period of time. The springs are positioned so that they can achieve the effect of stretch and compression of the spring. One of the springs is placed vertically, while the other is placed horizontally on the lower part of the leg. The vertical end is attached to the upper leg, while the other end is attached to the horizontal line in the middle. When the leg is compressed, current flows through the vertical spring. When the leg is sprawled, the flow of current in the vertical spring is interrupted and a flow of current is released through the horizontal spring. The horizontal spring stretches the vertical spring and returns the leg to the stretched or initial state.

The appearance of the turtle's leg in the reality and its movement is quite complex. To bring the design of the foot closer to reality, 3 different materials were used, applied in 4 layers(as shown on Figure 5): silicon, parchment paper, high temperature silicone (RTV silicone) and parchment paper. The silicone gives the shape of the leg that needs to be achieved. This silicone has good elasticity and in some parts, if applied in large quantities, a relatively high strength can be achieved. The silicone mold is coated with high temperature paper. On high temperature paper, RTV silicon resistant to high temperatures (343˚C) is applied, and after, another piece of paper resistant to high temperatures is applied because the RTV silicone is soft after application and needs to be re-applied. The paper placed between the two silicones is necessary because of the intolerance between the two silicones (the RTV silicone destroys the ordinary silicone).

By integrating NiTi springs, smart material actuation of the robot could be achieved, improving the terrain movement of the robot. Also, by integrating GPS module the current location of the robot will be detected, and by adding microphone, recording of the sound would be achieved.

3. PROTOTYPING

In order to build the turtle-inspired robot, the following main components are needed: microcontroller, sensor, actuator, a 3D designed shell and a camera. All components of the robot have a total mass of $m_{total} = 0.8\ [kg]$. Due to the sprawled and closed position that has to be performed, each leg of the robot needs to be powered by an electric motor. All of the four legs need to be powered by a separate electromotor, i.e. four motors total are needed to sprawl the legs and make movement. The four legs of the turtle are evenly distributed, so each leg is loaded with a mass of $m_{leg} = \frac{m_{total}}{4} = \frac{0.8}{4} = 0.2[kg]$. The force required to lift each leg is $F = m_{leg} \cdot g = 0.2 \cdot 9.81 = 1.9\ [N]$. Figure 6 shows one leg of the robot, where the total length of the leg is 66.04 [mm], while the length of the leg needed to be lifted is 47.5 [mm]. In order to determine the torque that each engine must perform in order to be able to lift the robot, we perform a static calculation (the friction is neglected): $M_C = F \cdot L = 0.09\ [Nm]$.

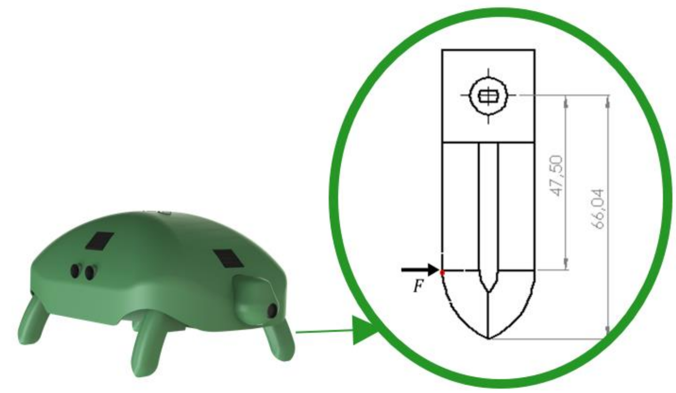


FIGURE 6: ONE LEG OF THE ROBOT (the dimensions are given in mm)

Each electric motor needs to deliver torque greater than the calculated torque, i.e. $M_m \geq M_C$. Based on the calculation, electric motors 28BYL-48 that are able to deliver the torque were selected.

To achieve the rotation of the turtle in order to move in the desired direction, another servomotor is added, which serves to rotate the turtle when it is in its assembled position. In the closed position, the turtle rotates in a direction determined by the steering wheel, and after the robot's legs are sprawled and begin to move.

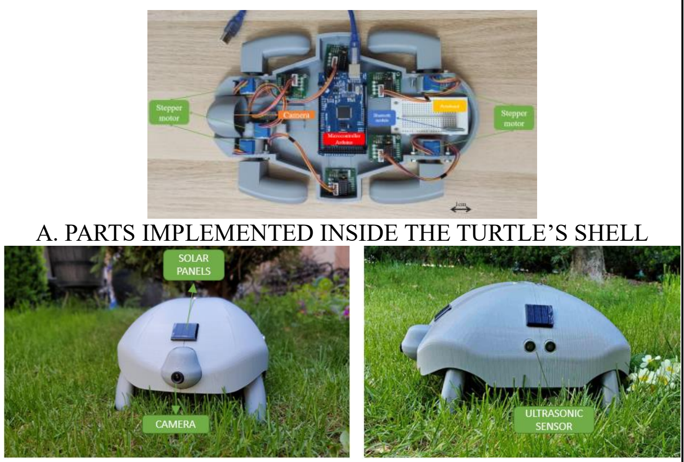
In addition, the basic parts for the prototyping performed are shown: hardware, control and application design.

3.1. Hardware design

The components needed to construct the turtle-inspired robots are shown in Table 1, where it can be seen that 90€ are spent to construct the low-budget robot. Figure 7 shows the final look of the prototype, the whole look and the inner section, where the components are put.

TABLE 1: PARTS OF THE TURTLE-LIKE ROBOT

Part	Type	Price
Main board	Arduino MEGA 2560	10€
Sensor	Ultrasonic sensor HC-SR04	5€
Camera	OV767	5€
Module	Bluetooth module	3€
Battery	Solar panels 30x25 mm, 3 pieces, Battery 9B, 4 pieces	10 €
Motor	Stepper motors (5) Servo motor (1)	40 €
Shell	3D printed	7 €
Components	Cables, Protoboard	10 €
Total price per unit		**90€**



A. PARTS IMPLEMENTED INSIDE THE TURTLE'S SHELL

B. PARTS ON THE OUTTER OF THE TURTLE

FIGURE 7: FINAL LOOK OF THE PROTOTYPE

The main component of the device is the processing unit, which is also used for the connecting and controlling all the components. For achieving the established requirements, Arduino MEGA microcontroller was used. The four stepper motors were used for controlling the legs, one four each leg, while one was used for controlling the head. Each one of the stepper has a driver which makes connection with the Arduino. The stepper motors for the legs each one is powered by 9V battery, except the stepper motor for the head which is powered directly from the Arduino. The Arduino is powered from the solar panels in order to maintain sustainability. The front left leg with the rear right leg are working together receiving the same signal from the Arduino and making the same move, which is also used for the other two legs front right leg with rear left leg. The servo motor is positioned at the bottom of the construction, and it serves for establishing rotation of 360°. When the turtle is in its closed position, the robot rotates in the desired position, and after that it sprawls its legs and continues with the movement. The ultrasonic sensor is used to give signal when one the robot is near some object at distance of 4cm. When the robot is at that distance, it gathers itself. The camera is placed inside the head of the turtle robot, connected directly to the Arduino and it starts recording when the turtle is turned on. All of the components are placed in 3D printed turtle-like design box. The mini solar panels are connected to the rechargeable battery that gives power for the Arduino, making the robot totally energy sustainable.

Finally, the controlling of the turtle's robot movement is done by an android application, which is connected to the robot by the Bluetooth module that is integrated in the robot.

3.2. Control design

In order to program the bio-inspired turtle robot, the Arduino C++ based programming language was used, using the Arduino IDE application. Figure 8 shows the block diagram that explains the code used for programming of the robot.

All of the five AC stepper motors have separate rotation directions in order to manipulate with the movement more easily. There is an additional function, with the sensor data as input and the distance measured in 'cm' as output. The main loop function begins by collecting data from the HC-SR04 ultrasonic sensor, with 30ms delay between cycles, and receiving this data back measured in cm with the help of the external function.

In order to determine whether the robot should move the legs when starting, i.e. if there is an obstacle within 4cm of the robot, keeping the turtle from putting its legs outside the shell, a flag is used as an indicator. Once the robot is started and the first three measurement cycles by the sensors are done, the flag changes its value if necessary. In case the robot has no obstacles within the range of 4cm, all 5 stepper motors start rotating simultaneously: first they perform 580 steps, each in their respective direction, after which the motor attached to the head continues with additional 621 steps in order to completely pull the head out of the shell. For the purpose of rotation, an addition DC EM is added in the center of the robot. Once the Arduino receives a signal to rotate the device, the movement pauses and the retraction function is executed, after which the rotation starts. After achieving the desired angle, the rotation stops, new data from the Ultrasonic sensor is collected and the robots acts respectfully.

Once the robot is ready to initiate its movement, all 4 legs move simultaneously. Each of the stepper motors performs 200 steps in the given direction, 350 in the opposite direction and another 150 steps to move back to their initial position. There is a 4ms delay between each cycle (even though the minimal delay in order to achieve perfect performance by the given stepper motor, a longer delay is used to get closer to the real speed of a turtle).

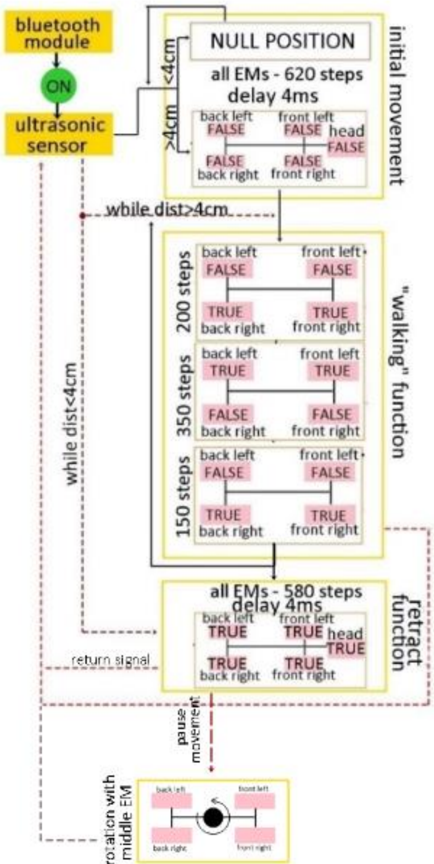


FIGURE 8: BLOCK DIAGRAM OF THE SOFTWARE IMPLEMENTATION

The reason the movement is split in four separate cycles is to avoid the use of a rotary encoder to determine to position of each leg at the exact time the robot is approached by a potential obstacle, as used in [9]. In this way, using a separate integer which increments its value by 1 with each next cycle, we can determine where the leg is at the given time and can ensure that the legs will return back to their original position inside the shell until the obstacle is gone.

3.3. Application design

A custom-made Android application is used for remotely controlling the turtle robot. The application is programmed in Android Studio with the programming language JAVA. The wireless connection is achieved using the Bluetooth module HC-05 with a signal span of 10m.

The application has a simple and user-friendly interface: one slider, three buttons, battery indicator and a screen, as shown on figure 9. By pressing the slider, the turtle is activated, whereas the screen has the purpose to project the images the head camera is recording. The buttons below the video screen are used to start or stop the movement, or to rotate in the desired position. Also, there is battery indicator which shows the power status of the robot.

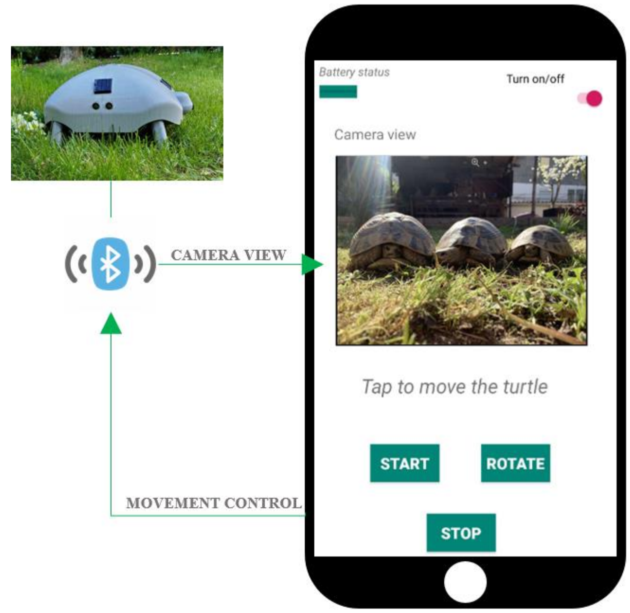


FIGURE 9: APPLICATION INTERFACE

As it can be seen on figure 9, the camera view of the turtle shows that turtle was put in animal friendly surrounding, between real turtles. The turtle-like robot did not cause disturbance between the animals.

4. RESULTS

The power supply and storage of the electricity required by the robot turtle are delivered by an electrical system consisting of solar panels and batteries. Solar panels are serially connected and supply electricity to parallel connected batteries. When serially connecting four solar panels with a separate voltage of 2V each, a total voltage of 8V is provided. The ideal time required to charge five batteries with a capacity of 580 [mAh] is: $T_{i,charge} = \frac{E_{ch,b}}{I_{c,sp}} = \frac{5 \cdot 0.58}{0.1} = \frac{2.9}{0.1} = 29\ [h]$. However, since this way of charging causes optimal heat losses (20%), the actual battery charging time increases by that percentage and is $\mathrm{T}_{a,charge} = T + 20\% = 34.8\ [h]$.

Average daily energy in May is $E = 5.25\ [\mathrm{kWh}/m^2]$ with a coefficient of efficiency of the solar power plant $\eta = 0.15$, the daily average electricity production of 4 solar panels with area $Asp = 0.01[m^2]$ will be:

$E_{ep,day} = E \cdot A_{sp} \cdot \eta = 0.007875\ [kWh] = 0.9844\ [Ah]$.

The total time for the robot to operate continuously until the battery discharge, if all actuators operate continuously is:

$$T_{total} = \frac{E_{ch,b}}{I_{c,sm}} = \frac{2900}{5 \cdot 100} - 5\% = 5.51[h]$$

Analyzing the movement of the turtle-like robot, the velocity as parameter was measured. The turtles move on ground with average speed of 3 to 4 meters per hour. The constructed turtle-like robot moves with speed of 1 $[mm]$ per second, achieving movement of 3.6 meters per hour, which fits the boundaries of the real turtle's movement.

After building the physical prototype, series of measurements in reference to the pitch acceleration regarding the stability of the turtle on different patterns were made. Using accelerometer, the data of the pitch acceleration was analyzed during the basic functions of the robot (standing up, retracting) on 3 different patterns with different friction coefficients (laminate floor, grass and concrete). Figure 10 shows the vertical angular acceleration on different patterns.

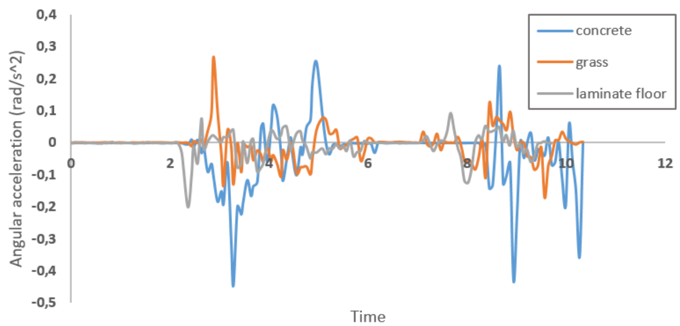


FIGURE 10: VERTICAL ANGULAR ACCELERATION ON DIFFERENT FLOORS

The first sequence of stochastic oscillations, between 2 and 6 seconds, shows the pitch acceleration during the time when the robot is standing up from its retracted position, whereas the next sequence (from 7 seconds until the end) represents the retracting function after being approached by an obstacle. The flat line indicates that the robot is still and waiting for the next command.

According to this data, the robot has the highest stability on laminate floor, which has the lowest coefficient of friction ($\mu = 0{,}43 \div 0{,}59$) among all of the given materials, thus there is no slipping between the four legs of the robot while performing the basic functions. The biggest instability occurs when on concrete, since it has the biggest coefficient of friction ($\mu = 0{,}6 \div 0{,}85$), thus causing different linear velocity of all four legs and losing the stability of the turtle, resulting with an increased value of the pitch acceleration. The friction on the grass is between ($\mu = 0{,}78 \div 1$).

5. CONCLUSION

Understanding bio-inspired engineering concepts, mimicking the movements from nature to design multi-locomotion autonomous robot has been analyzed in this work.

The concept was evaluated through CAD models, and afterwards, the components for constructing the prototype were chosen for building the prototype. An android application was designed for controlling the robot and achieving autonomous movement. The turtle-like robot is energy sustainable as it has implemented solar panels in the structure. The 3D printed robot was tested in environmentally friendly area, i.e. large parks between animals.

This work has shown to be good base for further development of the robot by implementing smart materials in order to achieve smart material actuation.

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