Considerations Regarding the Hybrid Propulsion System of a Ground Robot

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***Abstract*—This paper describes the process of designing, building and testing an experimental model of tracked mobile robot with a hybrid drive train. This conceptual model has been designed using the SolidWorks software. It is intended for performing reconnaissance and monitoring missions in structured environments. The hybrid propulsion system has the role of allowing the robot to climb certain obstacles in order to increase its terrain advancement capacity without having to bypass various obstacles, or to climb the stairs of a building. The robot also has a system of sensors that are meant to identify the obstacles. The implemented algorithm focuses on the identification of obstacles and the way in which they are to be bypassed. The system has been validated in the CERAS laboratory (Center of Excellence in Robotics and Autonomous Systems), where it has been put to function and tested.**

***Index Terms*—robot, tracked, teleoperation, algorithm, hybrid.**

I. Introduction

A mobile robot is a type of robot that can perform various tasks and can move with the help of wheels, tracks, legs or other means of locomotion. These robots are designed to move in a specific environment and can be remotely controlled or can be programmed to make autonomous decisions with the help of sensors and algorithms [1, 2]. The kinematics of the mobile robot is defined by the number, type and display of wheels and/or tracks of the mobile platform. The ways in which these different types of wheels and/or tracks are combined and arranged determine the mobile robot's type of kinematic model.

According to this criteria, mobile robots can be classified as follows:

- With conventional wheels:
  - Non-orientable;
  - Centered orientable;
  - Off-centered orientable;
- With tracks;
- Spheric wheels.

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The configuration of the robot's mobile platform includes:

- The geometric configuration of the propulsion system;
- Arrangement of the center of mass;
- The configuration of the platform's movement system.

All of the aforementioned elements determine the mobility and stability of the mobile platform during its specific missions in various types of environments.

The most common robots are the ones equipped with a wheel propulsion system (Fig. 1, Fig. 2). This offers good stability, but we can encounter sliding problems during turns because of differential control on all four wheels.

Figure 1. Example of a robot with four-wheel drive - https://www.artstation.com/artwork/q95rW2

Figure 2. Example of a robot with six-wheel drive [3]

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Robots with tracked locomotion systems have been created in order to eliminate these disadvantages of the ground robots on wheels. Track robots have a better motion efficiency, as their specific ground pressure is lower. Moreover, when climbing over obstacles or ascending stairs, tracks have a very good ground adherence (Fig. 3).

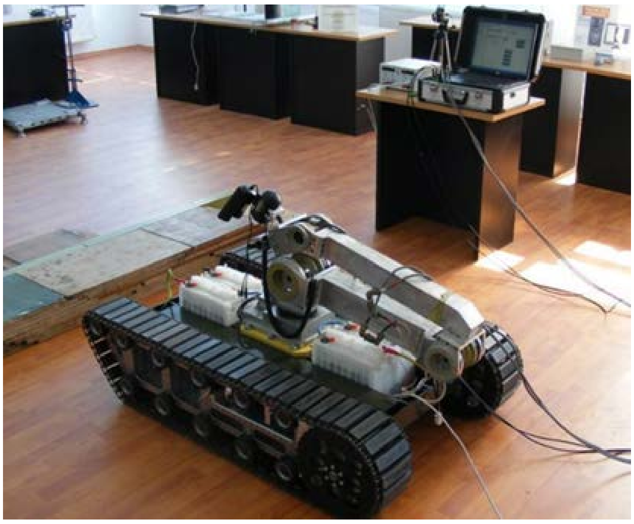

Figure 3. Example of a robot with a tracked propulsion system [4]

The main disadvantage of wheeled and tracked ground mobile robots is their inability to climb over obstacles that are higher than the limit of their center of gravity, this refers to the ability of a ground mobile robot to overcome obstacles bigger than the maximum height that can be reached by its center of gravity. This problem led to the construction of robots equipped with articulated propulsion elements, with swing arms.

An effective robot, capable of successfully climbing obstacles, is one equipped with a tracked propulsion system, or even with complementary gripper tracks, which also has an oscillating mechanism, also with a tracked mechanism (Fig. 4).

Figure 4. Example of a robot with a hybrid tracked propulsion system – https://www.army-technology.com/projects/cameleon-e-unmanned-ground-vehicle-ugv/

The following are some of the existing possible hybrid propulsion configurations:

- Wheels propulsion system for ground movement and an arms system with wheels for climbing obstacles;
- Wheels and tracks propulsion system: the movement component is equipped with wheels and the retractable arms are equipped with tracks;
- Tracks and wheels propulsion systems: the elements used for moving are tracked and the retractable part is wheeled;
- Track propulsion system for propulsion and track system for climbing obstacles/stairs (Fig. 5);
- Articulated arms propulsion system;
- Tracked propulsion system and retractable lever system;
- Tracked propulsion system containing several articulated elements.

Figure 5. EOD Dual propulsion system robot – https://www.avinc.com/ugv/telemax-evo

II. Designing the Hybrid Propulsion Robot

For the present research, we decided for the articulated arms hybrid propulsion (Fig. 6) [5]. The propeller is equipped with eight servo motors, four of which are destined for the actual propulsion (moving on the ground) and four for climbing obstacles.

According to its positioning (the rotational angle of the servo motors), their geometric configuration allows the organization of the four tracks into a plan. By modifying the rotational angle of the retractable servo motors, the active part of the tracks is diminished.

Thus, the ground robot we are referring to could be an efficient solution for various tasks, such as inspecting and monitoring a field, as well as an industrial or construction environment. Being equipped with distance sensors for detecting obstacles, the robot can also be used for detecting possible threats. Its practical uses can be easily extended as it is equipped with various components, cameras or sensors.

The robot has been tested both in rectilinear motion and while scaling various types of obstacles, such as stairs or ditches. The sizes of the stairs used are 500×500×60 [mm×mm×mm]. As shown in Fig. 6, the mobile platform is symmetrical on the two axes.

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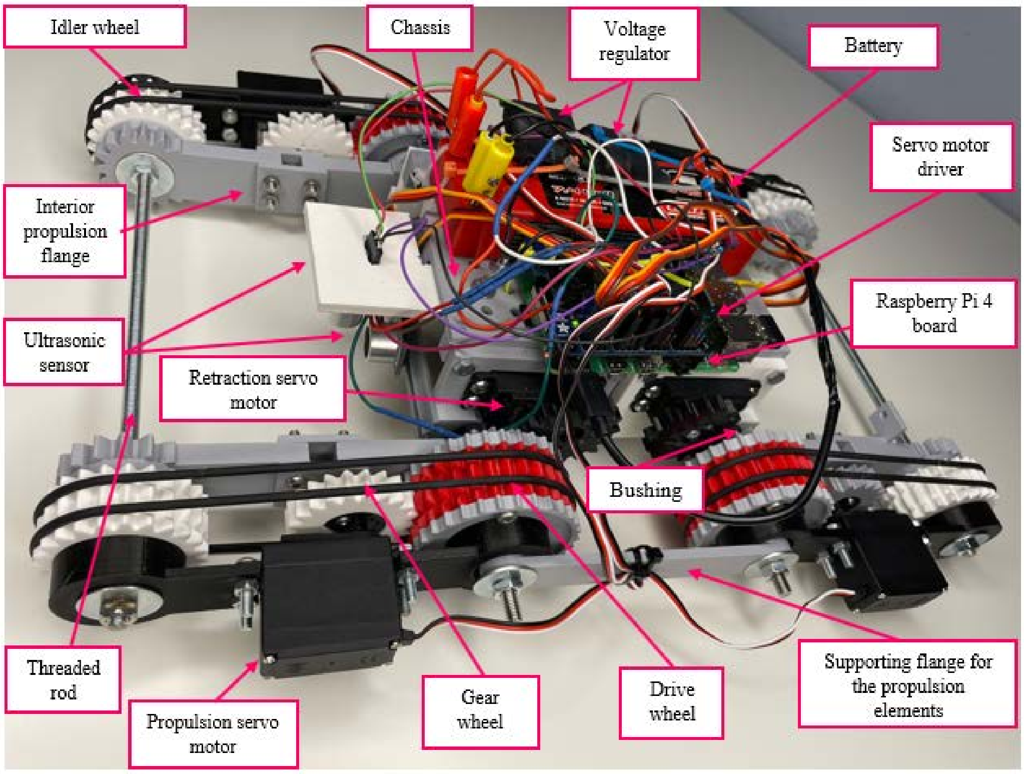

Figure 6. Robot with articulated arms and double tracks propulsion

The designed geometric model is presented in Fig. 7 and Fig. 8.

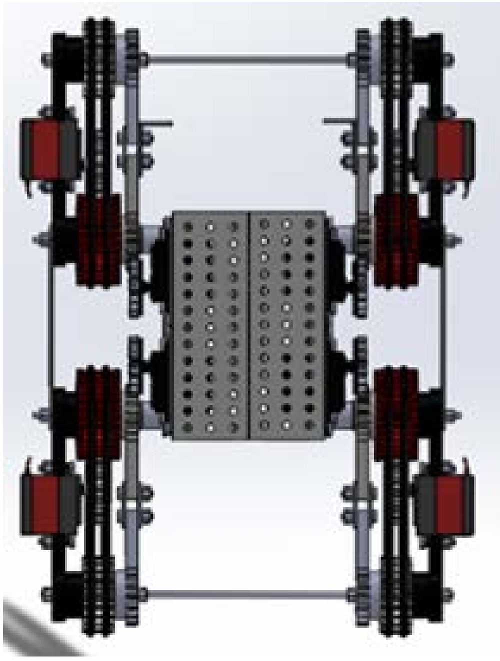

Figure 7. Top view of the robot

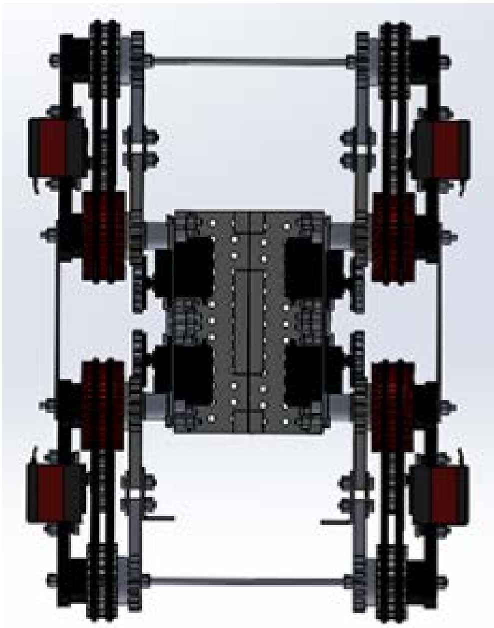

Figure 8. Bottom view of the robot

Nine (extreme) positions have been selected for the simulation. Each position has two angle constraints (the angle between the chassis, the front arm of the platform and the back arm, respectively). The angles are: 0°, +90°, –90° and the resulted positions are the following (Fig. 9).

The positions shown in Fig. 9 are not real functional positions, they have been configured only to check the functionality of the servo motors.

Figure 9. The robot's extreme positions

III. TEC Calculation Methodology

As shown by Fig. 9, the robot can produce multiple configurations by combining the two back and front modules, supported by the central part.

In order to define the various functional configurations of the propulsion system, we established an octagonal system of coordinates (xO_4y), as shown in Fig. 10. The x axis is parallel to the ground, while the y axis is normal [6].

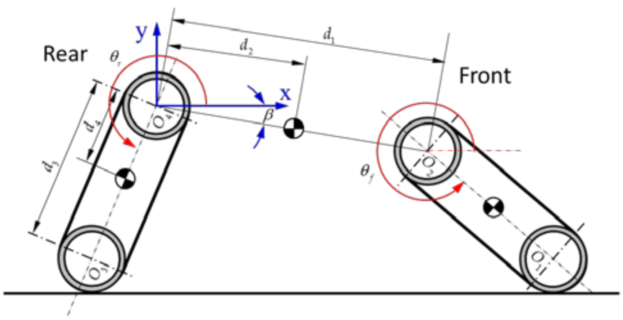

Figure 10. The geometric characteristics of the four-track hybrid propulsion robot. θ_r is the rear track module's rotation angle from the x axis to the connecting frame of the rear module; the front angle θ_f is the front track's rotation angle from the x axis to the connecting frame of the front module

The different combinations between the front angle θ_f and rear angle θ_r can generate typical possible configurations when both the front angle θ_f, and rear angle θ_r vary from 0° to 360°.

The different combinations have a different geometrical relation between the front module, rear module and the body of the robot (1), whereas the body is lifted by an angle of inclination β in some cases (2):

$$
\begin{aligned}
x_{O_3} &= d_3 \cdot \cos\theta_r & y_{O_3} &= d_3 \cdot \sin\theta_r \\
x_{O_2} &= d_1 \cdot \cos\beta & y_{O_2} &= d_1 \cdot \sin\beta \\
x_{O_1} &= d_1 \cdot \cos\beta + d_3 \cdot \cos\theta_f & y_{O_1} &= d_1 \cdot \sin\beta + d_3 \cdot \sin\theta_f
\end{aligned} \quad (1)
$$

$$\beta = \arcsin\left(\pm\frac{d_3 \cdot \sin\theta_f}{d_1}\right) \quad (2)$$

Table I. Incline Angle β of Robot Body for Each Configurations

θ_r/θ_f	$[0^\circ,180^\circ]$	$[180^\circ,360^\circ]$
$[0^\circ,180^\circ]$	$\beta = 0$	$\beta = \arcsin\frac{-d_3 \cdot \sin\theta_f}{d_1}$
$[180^\circ,360^\circ]$	$\beta = \arcsin\frac{d_3 \cdot \sin\theta_r}{d_1}$	$\beta = \arcsin\frac{d_3 \cdot (\sin\theta_r - \sin\theta_f)}{d_1}$

It is considered that upon contact between the component elements we have normal forces N_r and N_f, and the articulation frictions are F_{rc} and F_{fc}. For these, as shown in Fig. 11, we have (3) and (4).

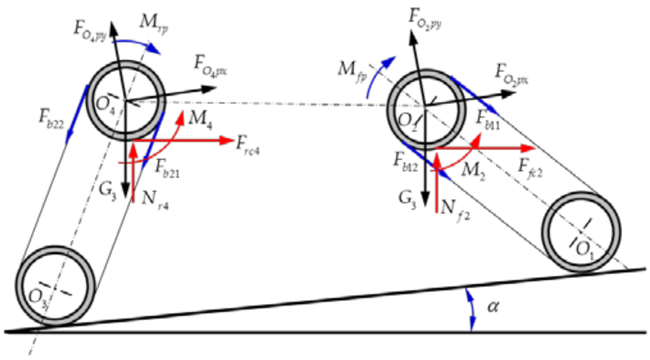

Figure 11. The diagram of forces and moments

$$
\begin{cases}
\sum F_x = F_{O_4px} + (F_{b21} + F_{b22})\cos\theta_r + F_{rc4} - G_3 \sin\alpha \\
\sum F_y = F_{O_4py} + (F_{b21} + F_{b22})\sin\theta_r + N_{r4} - G_3 \cos\alpha \\
\sum M_{O_4} = -F_{b21}R + F_{b22}R + F_{rc4}R - M_{rp} + M_4
\end{cases} \quad (3)
$$

$$
\begin{cases}
\sum F_x = F_{O_2px} + (F_{b11} + F_{b12})\cos\theta_f + F_{fc2} - G_3 \sin\alpha \\
\sum F_y = F_{O_2py} + (F_{b11} + F_{b12})\sin\theta_f + N_{f2} - G_3 \cos\alpha \\
\sum M_{O_2} = -F_{b11}R + F_{b12}R + F_{fc2}R - M_{fp} + M_2
\end{cases} \quad (4)
$$

Stairs are frequent obstacles in urban environments (curbs, stairs in buildings etc.), thus being necessary to study the process thoroughly for an optimal geometric configuration of the tracked propulsor (Fig. 12). Climbing stairs involves two successive stages:

- Approaching the obstacle. This stage takes place from the moment the tracked propulsor touches the obstacle until the branch of track support starts to lift from the ground.
- Scaling the obstacle. This stage takes place from the moment the branch of track support starts to lift from the ground and after climbing obstacle until the platform's center of mass passes the vertical position over the edge of step obstacle.

Fig. 12 [4] also shows the variation of the minimum coefficient of friction that is necessary for the tracked platform to scale the stair obstacle. It can be stated that the center of gravity has a major influence on the minimum admissible friction coefficient. Thus, the center of gravity

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must be towards the front of the tracked platform. The conditions of obstacle crossing are substantially improved if the axis of the attack wheel of the obstacle it is on the same line with the edge of the obstacle. As a result, the first stage becomes extremely short and the platform's inertia during rectilinear movement plays a very important part.

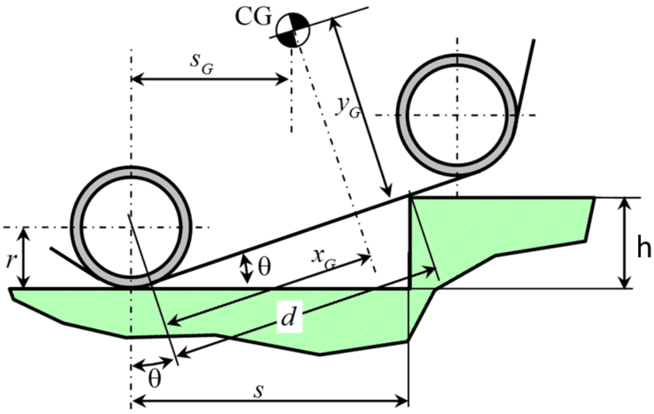

Figure 12. Scheme of climbing a stair-type obstacle, in which the lower branch of the track is mounted on the obstacle

Explanation of the used notations: d distance between the axis of the drive wheel and the point where the lower branch of the track is tangential to the edge of the obstacle; s - distance between the drive wheel's axis and the point where the lower branch of the track is tangential to the edge of the obstacle; θ – the angle of inclination of the longitudinal axis (of the track) from the driving surface, the lower branch of the track being mounted on the obstacle; s_G – the horizontal distance between the rear contact point and the edge of the obstacle.

$$s_G = r\sin\theta + x_G\cos\theta - y_G\sin\theta \tag{5}$$

$$h = r - r\cos\theta + d\sin\theta \tag{6}$$

$$d = \frac{h - r + r\cos\theta}{\sin\theta} \tag{7}$$

$$s = r\sin\theta + d\cos\theta = r\sin\theta + \frac{h - r + r\cos\theta}{\sin\theta} \tag{8}$$

IV. The Electrical Diagram

The electrical diagram (Fig. 13) was made using the PROTEUS software and contains the following hardware elements: RASPBERRY PI 4 board, the Adafruit PCA9685 16-channel servo driver, 4 servo motors with metallic reducer FT 5316M, 4 Futaba S3003 servo motors, a Corally LiPo battery 7.4 V 6000 mAh, 2 UBEC regulators, 2 ultrasonic sensors HC-SR04, 21 kΩ resistors and 22 kΩ resistors.

Due to the fact that the 8 servo motors can not be simultaneously controlled using the RASPBERRY PI 4 board, we made use of an Adafruit Servo HAT (PCA 9685) driver, that occupies only two GPIO pins and communicates via I2C.

The FT 5316M servo motors are used to control the track's retractable wheels. Their maximum range of motion is 180°, and their position has been mechanically adjusted so that the neuter position (the middle of the work range) is 90°.

Moreover, the Futaba S3003 servo motors will ensure the propulsion, which is why it is necessary for them to have a continuous rotation of 360°. Thus, in order for them to be used in this manner, some mechanical changes have been made and the mechanical stopper have been cut.

Both the servo motor driver and the RASPBERRY PI board are powered (through some voltage regulators) by the LI-PO (lithium-polymer) Team Corally Sport Racing battery, with a voltage of 7.4 [V] and a capacity of 6000 [mAh].

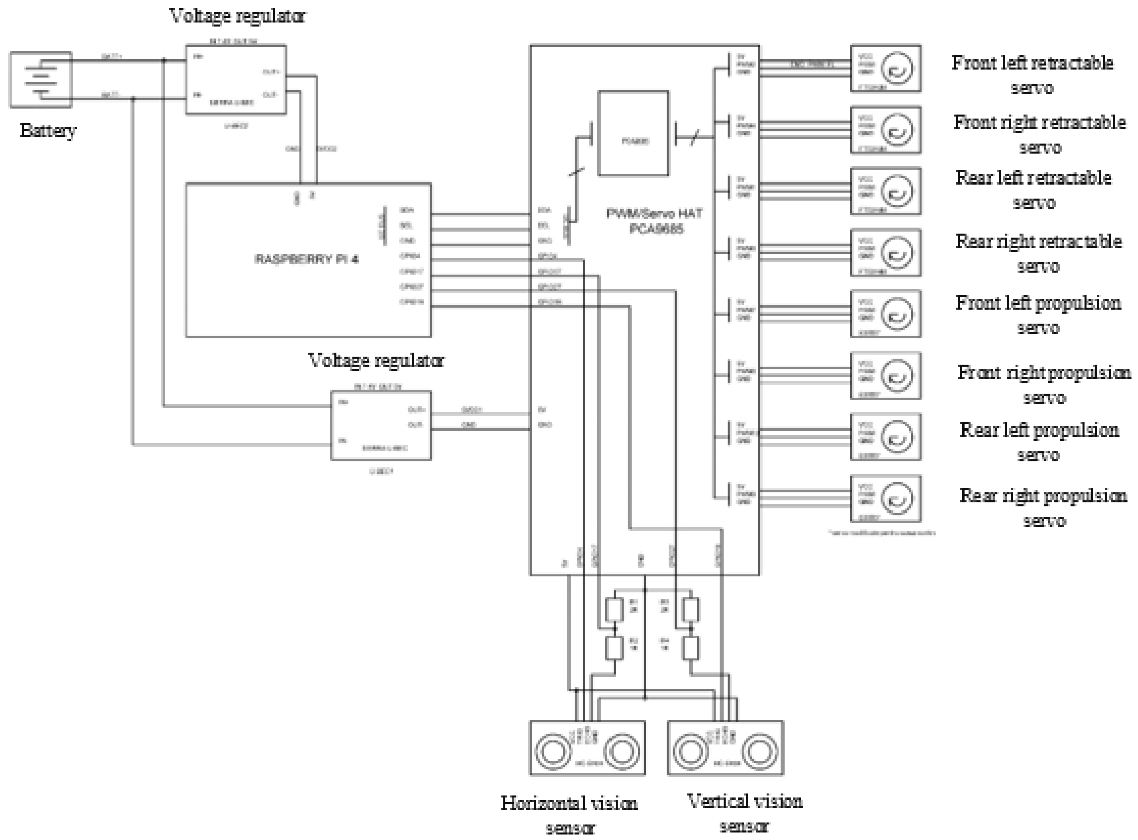

Figure 13. The electrical diagram

Because the servo motor driver works at voltage between 3.3 V and 5 V, the RASPBERRY PI board (RPI) at ~ 5 V, their power source has to be adjusted accordingly, so that the entire ensemble is powered by a primary source. Thus, the use of the Team Corally Sport Racing battery, which provides a voltage of 7.4 V, led to the addition of voltage regulators. Two SIERRA U-BEC regulators were used: one to convert the voltage from the battery to the servo motor driver, and one to convert voltage from the battery to the RASPBERRY PI board, respectively.

Two HC-SR04 ultrasonic sensors were placed on the front side of the ensemble, so that the robot can make autonomous decisions when it comes to ascend an obstacle and descent it. The two sensors have the following functions: the horizontal sensor is the one that triggers the obstacle climbing and crossing maneuvers and the vertical sensor is used for the descent.

V. The Control and Command System

The command-and-control system uses two components: the RASPBERRY PI (the server) and a tablet (the client). Each of these works in different programming languages – Python and Appinventor, respectively. The two communicate via a socket utilizing the TCP protocol, which allows the data transfer between devices with the help of a Wi-Fi network (Fig. 14).

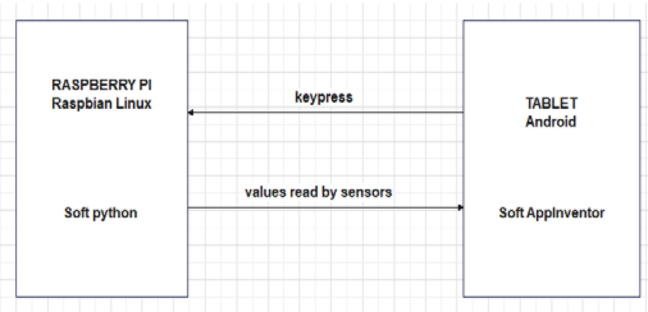

Figure 14. The logic of data transmission

The main program contains a code portion that determines the server (RASPBERRY PI) to „listen” the socket and wait for the connection with the client (the tablet). After the server has accepted the client, four threads will begin. These threads, once initiated, will loop separately from the rest of the program.

According to Fig. 15, the four threads are: READER, for reading the information from the sensors, SENDER, for transmitting the values from the sensors and displaying them on the tablet, RECEIVER – for receiving the data from the tablet, so that it can be checked if the user interacted with the interface in any way and MOVEMENTS, which deals with the robot's movements and indicates the fact that locomotion can be initiated manually (via key press) or automatically (via the two sensors that set off the scaling, crossing and descending from the obstacle).

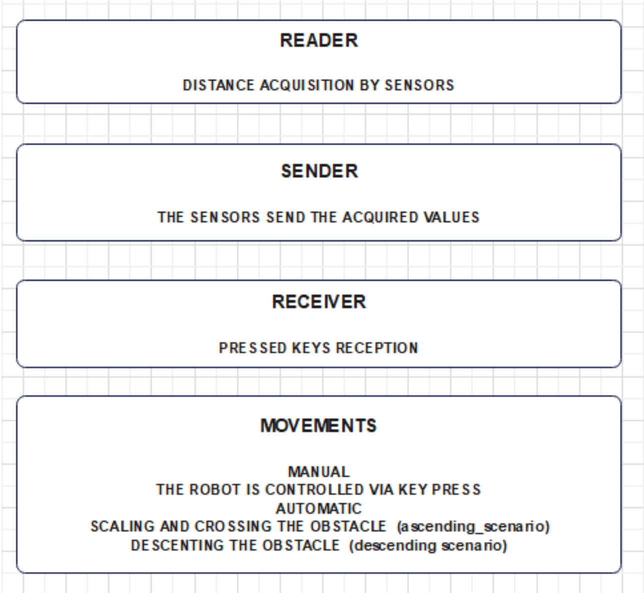

Figure 15. The RASPBERRY PI threads

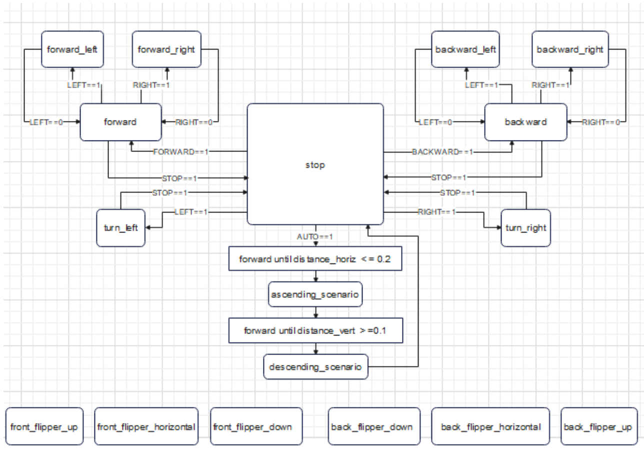

Figure 16. The robot's possible movements

In order for the programming of the source code to be more modular, the MOVEMENTS thread separates the code into code portions that define the robot's modes and facilitates the transition from one mode to another.

Thus, Fig. 16 shows which are the robot's possible modes, taking into consideration its mode from the moment of interrogation. For instance, if it is necessary for the robot to cross from the FORWARD mode to the BACKWARD mode, then it will be needed for it to cross the STOP mode first.

Regarding the movement of the retractable arms, these can be found in the scheme independent from the platform's locomotion movements, as they can be accessed in any mode.

VI. System Subject to Test Procedures

At the moment of the initial performance test, the robot was not equipped with the two threaded rods, next to the distance and rigidity bushings, but they were added later. The reason why the threaded rods were added is that, while in pause mode, the platform's retractable arms were not perfectly aligned, being slightly tilted outwards. This

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problem was solved by adding the rods into its own bushing.

Another problem from the initial testing was that, as the robot moved, the drive wheel would block the movement by coming in contact with the retractable servo motor engagement wheel. Thus, we added four distance bushings, as the wheel interference can affect the performance and reliability of the robot.

The final robot is shown in Fig. 17, where it is being tested while scaling and descending a stair obstacle of 500 × 500 × 60 [mm × mm × mm].

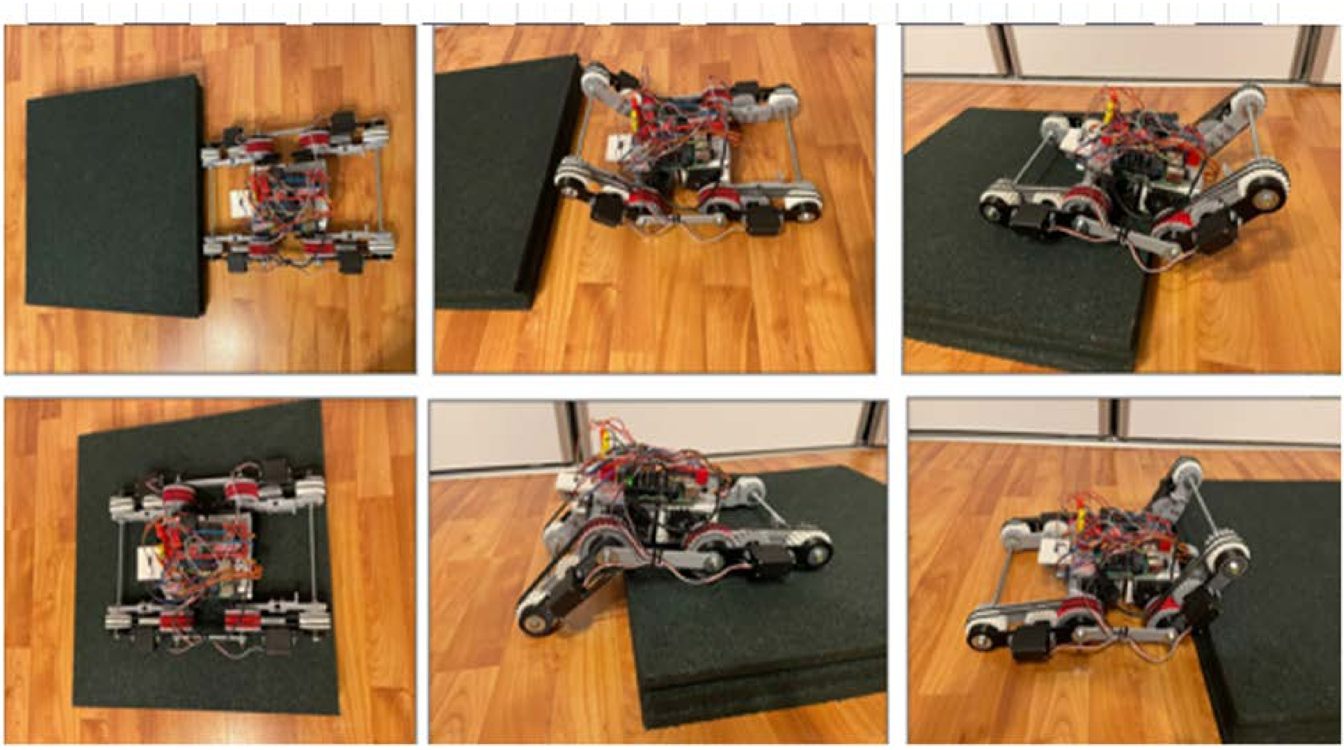

Figure 17. Testing the robot while scaling an obstacle

VII. Conclusion

The final testing of the robot's performances in its final form, with the necessary improvements, proves that the robot has the necessary abilities to perform the tasks it is given. Specifically, it can perform all the maneuvers that are necessary for it to turn, scale and descend from obstacles, keeping its stability.

Even though the robot performs the tasks it was designed for, it is important that the testing continues so that we can have the certainty that it can function effectively in various conditions and environments. Moreover, we can also take into consideration improving the robot's abilities so that it can perform its tasks more efficiently or take on new, more complex tasks.

There are multiple possibilities for the creation of the mobile platform, both for the hardware and the software component. On the hardware level, the two elements that hold the propulsion servo motors could have been replaced by a single element and, thus, leaving the screws out as well, the servo motors would have had a more secure grip. Moreover, another hardware improvement focuses on the way in which the tracks behave during turns.

In regards to the software, the platform could have been capable of making autonomous decisions based on the information collected from the environment, if it would have contained machine learning algorithms, such as supervised and unsupervised learning, decision and planning algorithms and if it would have been equipped with a camera. Thus, once the robot would have detected the presence of an obstacle of any kind, it would have made the autonomous decision to scale it or maneuver around it, according to the obstacle's nature and the robot's programmed risk tolerance.

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