Wheeled Bouncing Quadruped Robot

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Abstract *– This paper introduces a quadrupedal, jumping robot with four Mecanum wheels. In many cases researchers focus on only one type of movement. In this project, it was decided to extended bio-inspired jumping abilities with Mecanum wheels to reduce power consumption and enable movement in more directions. The robot is meant to operate indoors. However, its behaviour was tested on a number of different grounds. Thanks to cheap 3d parts the robot is convenient to be developed as a student project. The presented robot was designed only as a prototype and therefore a detailed description of possible ways of its improvement is provided.*

Keywords *– Robot, Quadrupedal, Jumping, Mecanum wheels, Omnidirectional*

I. Introduction

The aim of this project was to design and build a jumping robot with four folding legs. During an evaluation of the project, four Mecanum wheels were added to improve movement ability of the robot. Legged robots have advantages in terms of avoiding obstacles over wheeled robots [1]. However, the latter outperforms the former on the flat terrain [2]. Therefore, combining those two methods of locomotion should significantly extend possible areas of operation of the proposed robot.

A. Inspirations

The inspiration for this project came from some existing bouncing robots and some jumping animals. The primary inspiration was a robot presented in [3], which can not only jump but also walk (a movement direction can be set only during walking). However, the driving efficiency was extremely low as most of the bouncing robots had only a single bouncing mechanism. Another example of the robot with multiple ways of movement comes from Boston dynamics and is called Sand Flea. This robot can jump 10m high with a mighty jumping leg as well as moving with four wheels. This height is enough to handle the majority of obstacles [4]. Sand Flea uses a piston powered by CO2 for jumping and is very accurate in adjusting the height of the jump. Hence, to improve the efficiency of moving, for this project, the jumping robot with four Mecanum wheels was designed.

II. Design Process and implementation

A. Evolution of the design

The aim of the project is to design a quadrupedal robot. The initial design (Fig. 1) of the robot consisted of only four jumping legs connected with cylinders meant to be the base of the folding mechanism. The basic jumping structure consists of the motor used for squeezing a spring. When the motor releases the pressure, the spring will transform the elastic potential energy into kinetic energy to complete the bounce action (Fig. 2).

Fig. 1. The most basic model of the robot

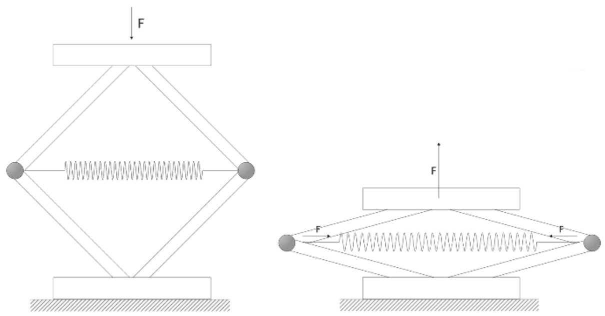

Fig.2. The structure of the jumping mechanism

Continuous use of four legs for jumping will reduce their service life. Use of four legs to change the direction of the robot's movement, it will need more degrees of freedom, which will pose a great challenge to the structural strength of the body. To prolong it and add more directions of movement but without changing the structural strength of the body, four Mecanum wheels were added; two on each side of the robot (Fig.3). To drive them, four Dynamixel RX-28 motors were used.

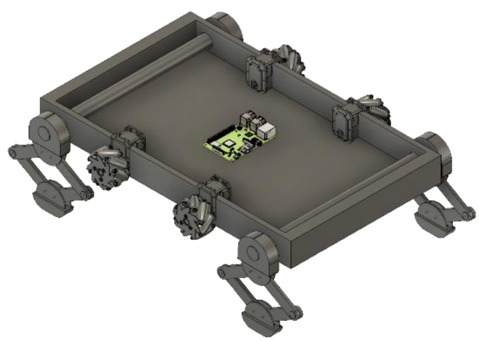

Fig. 3. Version 2 of the robot

Still, the robot was too big and thus too heavy to jump effectively. In order to make it lighter, by using less material, its design was changed, resulting in version 3 presented in Fig. 4. To achieve this goal Mecanum wheels and jumping legs were placed on perpendicular sides of the body. This allowed reducing its size twice. Moreover, additional details were added to the design, i.e. motors, the folding mechanism and the jumping mechanism.

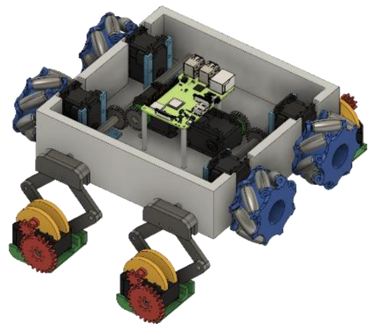

Fig. 4. Version 3 of the robot

The version's 3 legs were printed as a prototype and tested. The outcome was that the leg cannot jump. It was due to the fact that the motor was placed at the bottom of the leg and the center of gravity was too low. For this reason, legs were redesigned resulting in the origin of the fourth and final version of the robot's design (Fig. 5). Finally, the motor was placed at the top of the leg, a holder for the power bank was added and because it was found that one motor is not sufficient enough in folding two legs the second one was added to the folding mechanism. Furthermore, the structure of the Mecanum wheels was redesigned to make them much stronger.

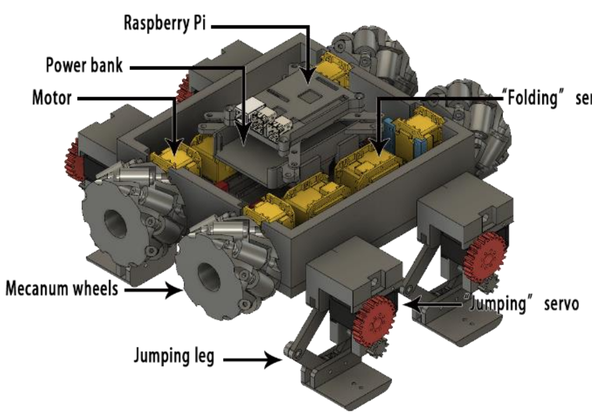

Fig. 5. The final version of the robot

B. Hardware

The robot is built of 3d printed elements (the base, legs, the jumping mechanism, Mecanum wheels, power bank's and Raspberry Pi's holders), two metal cylinders (being part of the folding mechanism), 12 Dynamixel motors, the Raspberry Pi and the power bank. The outline of the hardware connections used in this project is shown in Fig. 6.

a) Mecanum Wheels

In this project, Mecanum wheels were used due to their omnidirectional properties and ability to operate in narrow spaces [5]. The Mecanum wheels (Fig. 7) were designed based on sketches and images found in [5] and then 3d printed. They consist of 8 congruent rolls placed symmetrically around the wheel body. The face of each roll is part of a surface of revolution R whose axis b is skew to the wheel axis a. "b" is the axis of small roll and is skew to the wheel axis "a". The angle θ between a and b is ±45 °.

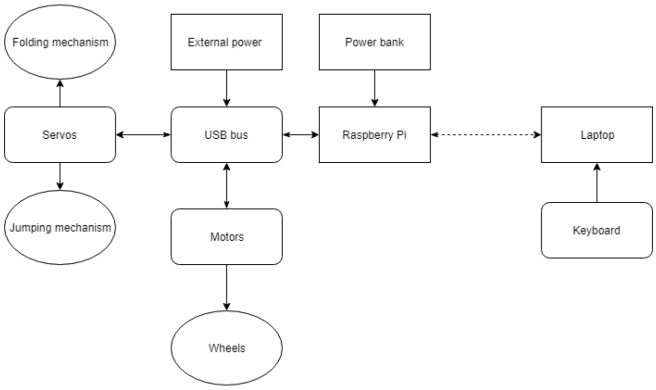

Fig. 6. Outline of hardware connections

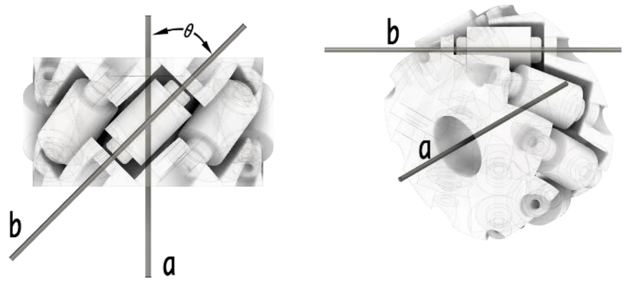

Fig. 7. Mecanum wheels structure

b) Jumping mechanism

To enable jumping it was necessary to design a force accumulating and releasing mechanism (its visualisation is presented in Fig. 8). Before jump the big gear is rotated to the starting position, i.e. position in which the first tooth is just near the small gear); the line connecting cylinder is loose. Jumping process is divided into two phases. The first phase is the process of accumulating force of a spring. The big gear rotates anti-clockwise and thus the line wraps around the cylinder tightening itself. As a result, the top and bottom parts are forced towards each other extending the spring. The second phase is the process of releasing the force accumulated in the spring. Once the big gear rotates further than the last tooth (the releasing position), the small gear is no longer blocked and the whole force of the spring is released at once vigorously pushing both parts of the leg away. The next jump is executed in the opposite direction.

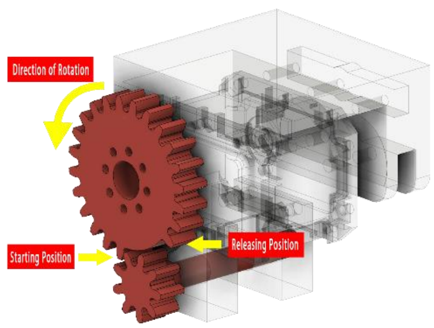

Fig. 8. The visualisation of the mechanism releasing spring's power

c) Dynamixel motors

The Dynamixel is a smart actuator system with high performance which was developed to be the exclusive connecting joints on a robot or mechanical structure. It can be programmed, and actuators status can be read and monitored through a data packet stream [6]. In this case, 12 MX-28 Dynamixel motors were used. Four of them were used to spin four Mecanum wheels, other eight were used as servos; four of which to squeeze springs (in the jumping mechanism) and the other four were used to rotate two cylinders which execute leg folding.

d) RaspberryPi and power bank

The Raspberry Pi is a small and powerful computer, and the power bank is enough source of power for it. The Raspberry Pi was used to control the robot, especially for the purpose of communication with Dynamixel motors. To this end, it was connected via a USB bus to all motors and wirelessly sends and receives data from the operator.

C. Used materials

a) PLA

For most of 3d printed parts, PLA (Polylactic Acid) filament was used. It is one of two the most commonly used. The second is ABS. The better material would be ABS because it is stronger, more flexible and durable. Moreover, PLA is denser; the robot is heavier because of this [7]. However, PLA was the only possible choice and was found to be strong enough in the described application.

b) FLEX 45

To 3d print rolls of Mecanum wheels, it was necessary to find more suitable filament. The most intuitive is rubber, which is an organic material and cannot become fluid. Consequently, it cannot be 3d printed [8]. However, there are a few rubber-like 3d filaments. The most common is thermoplastic elastomer (TPE) although it is too soft for Mecanum wheels. Thus, FLEX 45, which is similar in feel but more rigid, was used. FLEX 45 is very strong and flexible 3d printing filament that simulates rubber.

c) Aluminium

The 3d printed cylinder connecting legs was not strong enough and broke during tests. For this reason, it was replaced with the aluminium one which is much stronger and can withstand greater forces during landing.

D. Software

The Robot Operating System is “an open-source, meta-operating system for” robots [9]. It was built to enable collaboration between different groups working on robotics software. It helps in creating robot applications by providing libraries, tools, which are used for operating code across multiple computers, and services (e.g. hardware abstraction and message passing between processes). [9], [10]

A distributed system is the system, in which components located at networked computers communicate and coordinate actions only by passing messages [11]. In this project, ROS-based communication between nodes is the base of the functioning of the designed system, which consists of a few different nodes distributed on different platforms. On the laptop, there is a node collecting and analysing input from the keyboard (operator’s commands) and publishing them in ROS topics. The Raspberry Pi has a node communicating directly with motors. The laptop’s node was written in Python. As shown in Fig. 9, commands collected by the laptop node (written by the project’s authors in Python) are published in ROS topics (individual for each motor), which are subscribed, transformed and then published in motors-readable format by Dynamixel_node. Messages for motors consist of data about speed and direction of rotation while messages for servos consist of data about the speed of rotation and the final angel.

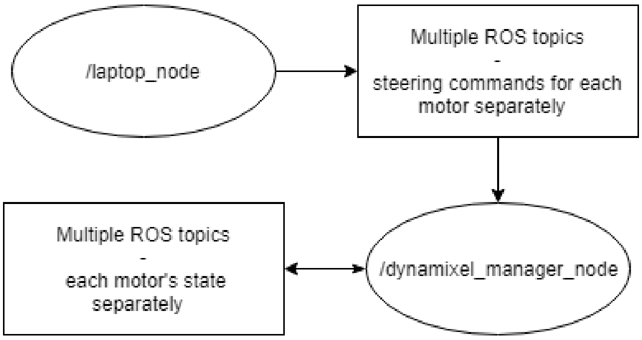

Fig. 9. Simplified ROS rqt_graph

III. Experiments

A. Tensile tests

A tensile test is one of the most common and crucial engineering tests. Its aim is to determine the strength of the material and its maximum elongation. A tensile test is conducted by applying a pulling force to a material and measures its response to the stress [12]. The performance of springs concerning the force of tension and displacement of stretching was evaluated on a tensile testing machine. In Fig. 10 results of the tensile test with the indicated force for the anticipated displacement are shown.

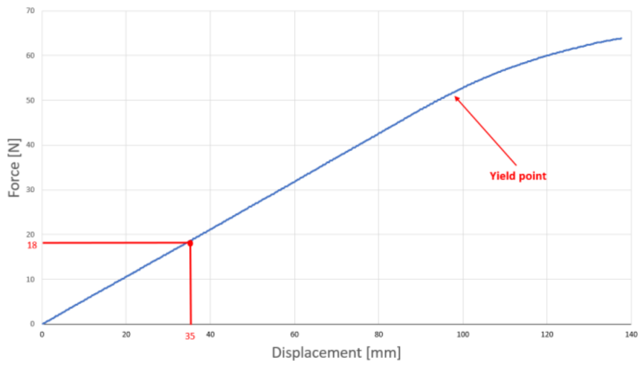

Fig. 10. The graph showing the displacement of the spring

This data proves that the spring can hold a large force up to approximately 50N before plastically deforming and later fracturing. Such a force is achieved for the displacement of about 95mm. Taking into consideration that the anticipated displacement achieved in the robot’s leg is of only about 35mm, the tensile test’s result means that the spring is more than sufficient for use on each leg for jumping of the robot.

B. FEA

Finite element analysis (FEA) is used to predict the strength of components by simulating how a product reacts to real-world forces, vibration, heat, fluid flow and other physical effects [13]. Hence, in order to evaluate whether the wheels and leg components break, FEA was performed.

FEA for wheels were executed for force corresponding to the estimated weight of the robot (i.e. 2.5kg). In Fig. 11a it can be seen that the initial design of the wheel was hardly enough for the proposed robot (safety factor is 1.8), thus improvement of the structure was executed resulting in much better design (Fig. 11b). The safety factor of the latter is the maximum available, i.e. 15.

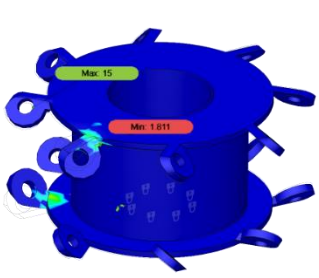

Fig. 11a. FEA test of initial version of the wheel

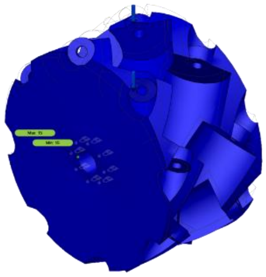

Fig. 11b. FEA test of final version of the wheel

A force used for FEA of legs was calculated based on tensile results, 18N were divided by two because the force is equally distributed over both arms of legs. As can be seen in Fig. 12a, the first version of the leg was not strong enough (the safety factor is just over 1.3) and therefore it was redesigned. Although the final version of the leg is also not very strong (the safety factor just over 3 – Fig. 12b) it was found to be strong enough even when the second spring was added.

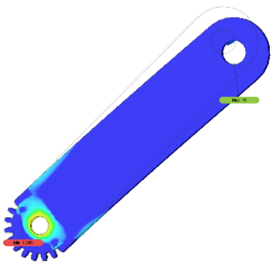

Fig. 12a. FEA test of initial version of the leg

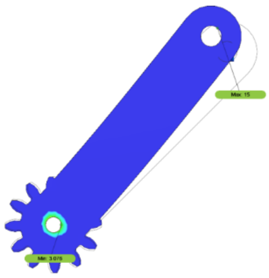

Fig. 12b. FEA test of final version of the leg

C. *Height of a jump tests*

a) Mathematical theory

The force (F = 18N) achieved in the tensile test was used to calculated predicted height of a jump. Firstly, the elastic potential energy of the spring (PE_S) was calculated

$$PE_S = \frac{kx^2}{2} = \frac{Fx}{2} \tag{1}$$

Secondly, the elastic potential energy is converted into gravitational potential energy (PE_g), kinetic energy (E_k) and internal energy (Wf – work done by friction)

$$PE_g = mgh \tag{2}$$

$$PEs = PEg + E_k + Wf \tag{3}$$

Finally, the speed of the robot in the highest point is equal to zero, hence $E_k = 0$.To calculate predicted height of a jump (h_{max}) the no-friction ($Wf = 0$) situation was considered. Hence,

$$h_{max} = \frac{PE_S}{mg} = \frac{Fx}{2mg} \tag{4}$$

While, the mass (m) of the robot is 2.78kg and the displacement of the spring (x) is 0.035m then predicted height of a jump is

$$h_{max} = 0.09m \tag{5}$$

b) Execution

The height of a jump was tested with the real robot. To perform the test, a ruler was placed near the jumping robot. To capture the exact height of a jump, it was recorded in slow motion. In Fig. 13 it can be seen that the measured height of a jump is approximately 6cm. It is smaller by third than calculated because of friction between elements of the robot.

IV. CONCLUSION

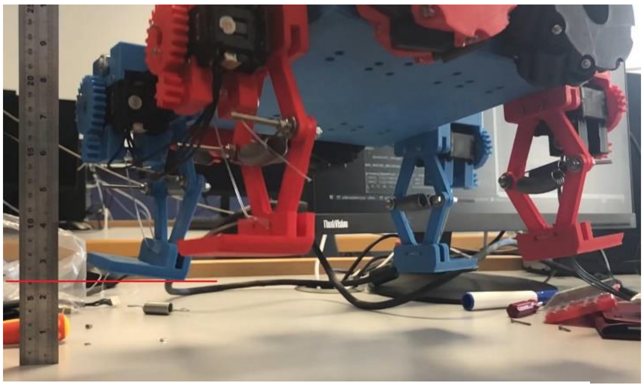

Fig. 13. The result of the height of a jump experiment

Considering all the executed tests, the created system fulfils requirements stated at the beginning to a large degree. The robot can drive on multiple grounds in all directions typical to Mecanum wheels. Folding mechanism is fully functional on various grounds. The only part of the project requiring significant improvements is the jumping mechanism. Currently, the robot can jump to a relatively small height and therefore the length of a jump is very short and its direction cannot be controlled. To fully meet the requirements a few improvements are essential.

A. *Ways of improvement*

In order to improve the robot's behaviour, it is necessary to add a few improvements. The most crucial is the improvement of the leg structure. The current leg bends significantly during jumping and therefore it is not possible to use stronger springs. For this reason, the new design of the leg is proposed. As can be seen in Fig. 14, the second pair of arms were added as well as leg's material was changed to be metal. Legs should ne also extended adding more space for springs. Those improvements will enable to use stronger (or more) springs and thus jump higher.

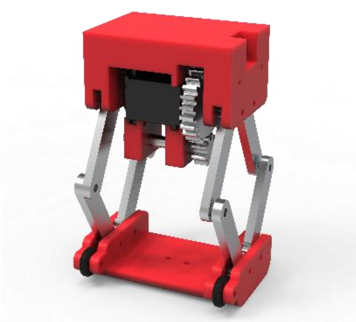

Fig. 14. Visualisation of the proposed evaluation of the leg

Secondly, the presented robot is too heavy to jump efficiently. One reason for this are too heavy and at the same time too weak motors, they are not sufficient enough to load more springs. Therefore, the use of smaller and more powerful motors should be considered. Additionally, because of the used power-release mechanism, the new motor should be of continuous rotation type. Then it will be possible to reverse gear ratio and use motors' power more efficiently.

Once the height of a jump is improved it will be possible to control the direction of jumps. Thanks to folding structure it will be possible to change legs angle before a jump and therefore jump not only upward but also forward. Before landing (i.e. during flight time) the position of the legs should be changed again to prevent the robot from falling.

Making the robot autonomous is also a possible way of expanding this project. To this end, a few sensors should be added. The most basic should be an ultrasonic sensor, enabling the robot to detect obstacles. However, more sophisticated sensor, i.e. LIDAR should be considered, enabling the robot to simultaneously map the environment and localise itself. Adding a camera would also be beneficial because of allowing the operator to control the robot's behaviour from the remote distance. All the proposed sensors can communicate using ROS what makes them very convenient in implementation.

Appendix

Appendix 1 - GitHub Repository
https://github.com/MichalBogoryja/JumpingRobot_ROCO507.git

Appendix 2 – Videos of the project evaluation and final results
https://www.youtube.com/playlist?list=PLvzAnZwwUsSJ6Qc2-6mDjJ0A4z9WqbkL7

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