

Mass Distribution of Moving Robots: an Experiment

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Abstract—When designing a robot, mass distribution should be considered, depending on the task that has to be accomplished.

In our work we examine a robot driving up a ramp. We show that the optimal placement of mass is at the front resulting in the least amount of time needed to reach the top.

Furthermore, we examined different mass distributions on a robot driving along a curved path. For sharp turns the mass should be placed at the inner side of the curve, whereas for a smooth trajectory, the mass should be placed at the outer side.

For both experiments we provide a physical explanation of our results to underpin the experimental data.

I. INTRODUCTION

An important design decision in robotics concerns the weight distribution of the robot. In previous work [4], we synchronized robots using different communication methods. Because of non-deterministic movement we had to use a re-alignment block to re-align the moving robot in each iteration of the experiment. One idea to improve the repeatability of robots trajectories is to optimize its weight distribution.

Work on mass distribution on wheel driven robots is scarce. Hass et al. discuss the impact of weight distribution on walking bipedal robots [3]. They tried to maximize speed and stability of their robot using numerical optimization strategies. The simultaneous optimization of both variables is not possible, but a serial handling allows effective strategies. Furthermore, they studied the differences in speed and stability of robots walking on different ground slopes. At steep inclines a drop in speed as well as stability was noticed.

Other authors discuss the impact of mass distribution on walking robots in detail [1] [2] [5]. However, this work does not apply to robots used in Botball.

Therefore, we conduct two experiments. In the first experiment, a robot drives up a ramp. Using different weight distributions the time needed to reach the top of the ramp varied. In our second experiment the robot drives in circles. Once again we used different weight distributions and got different results.

II. EXPERIMENT A: CLIMBING AN INCLINED PLANE

A. Task

This experiment tests a robots ability to reach the top of a ramp depending on its mass distribution. The ramp is set to one of three slopes. For each slope the robot was tested with three different mass distributions, namely the mass located at the front, at the center, and at the back of the robot.



Fig. 1. Robot with the mass mounted at the front, in the starting position on the ramp. The black line indicates the top of the ramp.

The wooden ramp has a length of 88cm and varying inclinations α_i such that

$$\sin(\alpha_i) = \frac{h_i}{88\text{cm}}$$

where h_i ranges from 12cm to 23.5cm. The robot starts at the very bottom of the ramp, see Fig. 1. The task of climbing the ramp is completed when the robot reaches the black line at the top of the ramp.

B. Materials

The robot consists of a metal base with a controller, a battery, two motors mounted at the front, and a caster wheel attached at the back as depicted in Fig.2. Each motor has a wheel attached to it. The total weight of the robot is 661g.

For detecting the black line a small IR sensor, which is pointing down, is attached at the front.

In the experiment we vary the position of the controller and the battery and measure the weight distribution by weighing

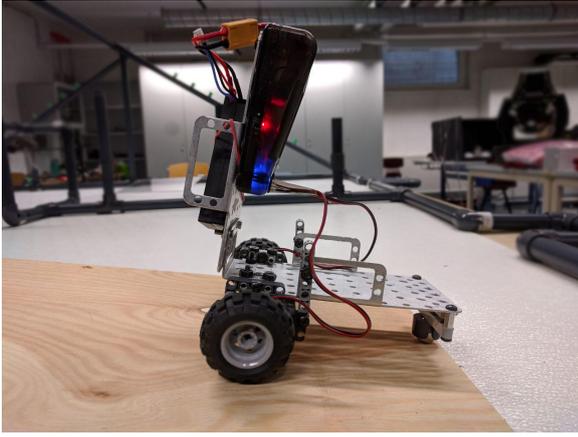


Fig. 2. Structure of the robot in configuration *mass at front*.

TABLE I
WEIGHT DISTRIBUTION OF DIFFERENT SETUPS

	front	center	back
two wheels	606g	352g	213g
caster wheel	55g	306g	447g

TABLE II
TIME NEEDED TO REACH THE TOP OF THE RAMP

	7.77° slope	11.76° slope	15.54° slope
mass at front	4min 18s	4min 19s	4min 24s
mass at center	4min 23s	4min 54s	7min 12s
mass at back	9min 36s	DNF	DNF

the two wheels and the caster wheel with a DC3000M scale, Fidelity Measurement Co. Ltd., Taoyuan City, Taiwan with readability of 0.05g. The baseplate of the robot was horizontal with either its two wheels or its caster wheel on the scale. The different weight distributions can be found in Table I.

C. Implementation

At the start of each try the robot was put at the same position at the bottom of the ramp. The robot was programmed to drive straight ahead until its light sensor detects a black line. The robot also starts a timer when activated and stops it when the line is reached. By implementing this timer the results do not only show if the robot was able to drive up the ramp, but also how long it took to complete the task. At each setup the robot was started ten times, to get more accurate data.

D. Results

In Table II the results of the experiment are shown. The time values show the average of ten repetitions of each sub-experiment. Sub-experiments where the robot did not complete the task are marked with DNF.

The sub-experiments where the mass is located at the front give the best results. Remarkably the time dependence regarding the slope of the ramp is insignificant, when the mass

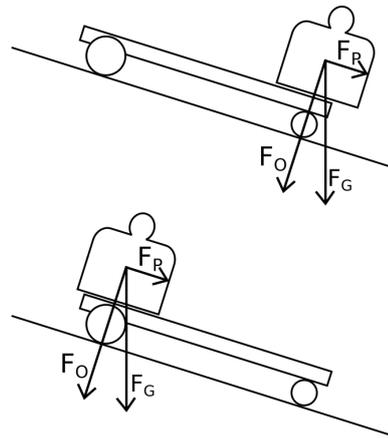


Fig. 3. The gravitational force can be split into two components F_P and F_O . All three vectors remain constant regardless of where the mass is placed.



Fig. 4. Deformation of Tires. The left wheel carries only the weight of the metal base plate. The right wheel carries an additional mass, resulting in a bigger area touching the ground.

is located in front of the robot, ranging from 4min 18s to 4min 24s. This is in contrast to other mass distributions.

In the sub-experiment where the mass was mounted at the center, the robot still was able to complete the task on every slope. The table shows that the time the robot needs is significantly higher than in the first sub-experiment, with a time of 7min and 12s at the highest ramp.

In the last sub-experiment the mass is located at the back. This makes it impossible for the robot to reach the top on the medium and the high slope. Even though the robot is able to complete the task on the lowest slide, it needs an average of 9min 36s.

E. Physical Explanation

The different performance of robots going up a ramp can be explained by different weight on the motor driven wheels, see Table I. The gravitational force F_G acting on the robot's mass can be split into two components: one force F_O orthogonal to the ramp and one force F_P parallel to the ramp. As Figure 3 depicts the component F_P does not change when moving the mass back and forth. However, the component F_O acts stronger or weaker on the driving wheels. As a result, the friction of the wheels changes due to deformation of the tires, see Figure 4. When going up a ramp, higher friction on the front wheels results in higher speed.

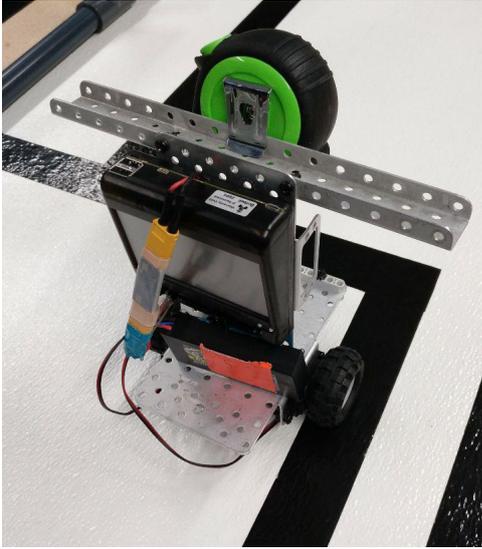


Fig. 5. Structure of the robot when the mass is attached in the center.

III. EXPERIMENT B: DRIVING A CURVE

A. Task

This experiment shows the impact of mass distribution when a robot drives on a curved path. As a representation of a curved path we choose a circle. In this experiment, the robot drives along a clockwise circle as well as an anti-clockwise circle on a flat paper surface. For the sub-experiments the mass is mounted at the center, on the left side and on the right side of the robot.

B. Materials

The robot comprises a metal base plate with two motors that operate two wheels mounted at the front and a caster wheel attached at the back. On the base plate another metal plate is mounted pointing upward. Its purpose is to hold a metal channel that carries a mass of 382.35g, see Figure 5.

For the first sub-experiment the mass is attached at the center of the metal channel. For the second one it is placed 8cm to the left and for the third it is placed 8cm to the right.

C. Implementation

As a way to measure the motion of the robot, the output data of the integrated gyroscope is continuously recorded. The gyroscope shows in which direction the robot is pointing during the experiment. We only measured the axis measuring rotation to the left and the right. The other two axis can be ignored since from the perspective of the sensor they don't change.

In each sub-experiment the robot is placed on the paper surface, where it drives a circle while reading the data from the sensor. This measurement happens 3500 times in about 21 seconds which is the time required for three full circles.

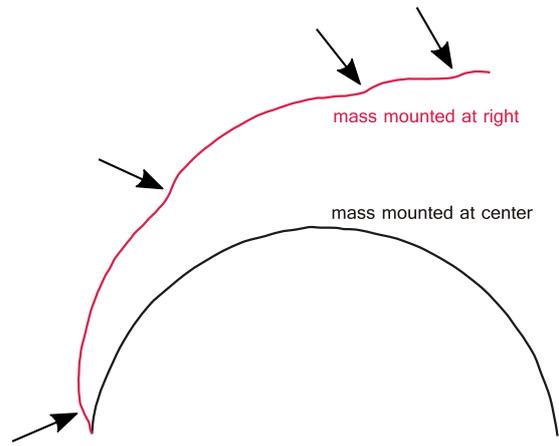


Fig. 6. Sketch of the trajectories with two different mass configurations. Arrows indicate skidding of the wheels.

TABLE III
CLOCKWISE CIRCLE: OUTPUT OF GYROSCOPE IN A.U.

	mass left	mass center	mass right
Gyroscope minimum	-9.4	-7.2	-6.6
Gyroscope maximum	325.8	367.9	365.3
Gyroscope average	272.6	295.17	296.38
Gyroscope standard deviation	25.73	27.59	30.76

TABLE IV
ANTICLOCKWISE CIRCLE: OUTPUT OF GYROSCOPE IN A.U.

	mass left	mass center	mass right
Gyroscope minimum	-394.6	-369.6	-355.7
Gyroscope maximum	33.2	53.1	15.2
Gyroscope average	-323.85	-294.88	-285.77
Gyroscope standard deviation	31.36	32.06	29.4

D. Skidding of wheels

We tested our experiment using too much weight. Since we attached a pen to the robot drawing a trajectory on the paper surface we could easily observe skidding of the wheels. This happened when the robot drove clockwise and the weight was mounted at the right. The resulting sketch of the pen marks can be seen in Figure 6. Skidding is indicated by slight rotation to the left, away from the trajectory of the robot when the mass was mounted at the center. The places where skidding occurred are indicated by arrows.

E. Results

After adjusting the weight we performed the experiment again. This time no skidding could be observed. The results of the gyroscope for clockwise movement can be found in Table III and for the anticlockwise movement in Table IV.

Positive output of the gyroscope indicates clockwise rotation, while negative indicates anticlockwise rotation.

If the objective of the moving object is to make a U-turn it is best to place the mass on the inner side of the trajectory. This

can be seen in Table III as well as Table IV, lines "Gyroscope average". Values further away from zero indicate sharper turns, or rather circles with smaller diameter.

The standard deviation of the output indicates the irregularity of the robot's rotation. In Table III the most regular rotation was recorded when the mass was located at the left, while the most irregular rotation was recorded when the mass was at the right.

However, the most irregular rotation in the anti-clockwise experiment (Table IV) was recorded when the mass was mounted at the center. This could have multiple causes: inaccurate motors, sensors and placement of weight as well as asymmetric construction of the robot.

F. Physical Explanation

The robot moves along a sharper turn if the weight is placed on the same side as the robot is turning to. See Table III and Table IV, lines "Gyroscope average".

There are two physical phenomena acting on a robot driving a circle. The centrifugal force acts on the robot in radial direction. However, this force is weak in the given scenario: a robot with mass $m = 0.661\text{kg}$ driving on a circular trajectory with radius $r = 0.2\text{m}$ taking $t = 7\text{s}$ per revolution has a velocity of

$$v = \frac{2\pi r}{t} = 0.18\text{m/s}.$$

The centrifugal force F_Z is

$$F_Z = m \frac{v^2}{r} = 0.1\text{N}.$$

Far more important is once again different friction of the wheels. If the mass is mounted on the inner side, the gravitational force applies more weight to the inner wheel than to the outer one. The flexible tire of the inner wheel indents more, see Figure 4. Consequently there is more friction resulting in a sharper turn. In contrary, mounting the mass at the outer side results in wider turns due to higher friction of the outer wheel.

The reason for negative values in Table III, line "Gyroscope minimum" is counter movement after stopping. The same is true for line "Gyroscope maximum" in Table IV. Here the values are positive since the counter movement is rotation to the right.

IV. CONCLUSION

Typically, robots are designed to perform more than one specific task. To achieve these tasks, some components must be mounted on specific locations. All other components should be mounted close to the center, due to the fact that robots usually move forward *and* backward and therefore no direction should be favored. In addition, the robot is less likely to fall over in comparison to the mass being mounted at one side.

In Botball, grapplers, which can move up and down, are almost always needed. These grapplers can be used to dynamically vary the mass distribution. In our experiment we found out that it is easier to drive up ramps with the grapples pointing to the front.

If a sharp turn is required, the mass of the robotic arm should be pointing to the inside of the curve. On the opposite, repeatability of the robot's trajectory improves with a robotic arm pointing to the outside of the curve. However, if too much weight is put on the inside wheels, skidding may occur.

Because of the additional complexity involved in moving grapplers according to turning directions we doubt that the increase in agility justifies the effort.

For robots without grapplers the same principles apply, hence these robots should be build symmetrically to not favor either direction.

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