ME3500J
Design and Manufacturing II

Guideline of the Project Report

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Format of the Project Report

1. **Abstract**
2. **Introduction**
3. **Synthesis (Design)**
4. **Fabrication and assembly**
5. **Control of sensors and actuators**
6. **Analysis**
7. **Experiment**
8. **Discussion**
9. **Conclusion**
10. References (~ 10 papers)
11. Appendix

Abstract

A brief summary of your report

A basic structure (~ 200 - 300 words)

- ✓Background (Why do we need to develop these devices)
- ✓Objective (What kind of devices do you develop?)
- ✓Methods (how do you achieve the objective?)
- ✓Main results and conclusions

Background

✓ Background

- Why do we need to develop climbing robots with locking mechanisms?
- Are there unexplored methods for developing those devices?

✓ Objective (What kind of devices do you develop?)

✓ Methods (how do you achieve the objective?)

✓ Main results and conclusions

Objective

- ✓Background (why we need to develop those devices)

- ✓Objective (what kind of devices do you develop?)
  - For example, this project develops an advanced climbing robot with a locking mechanism using XXX.

- ✓Methods (how do you achieve the objective?)

- ✓Main results and conclusions

Methods

- ✓ Background (why we need to develop those devices – e.g., a transformable wheel? Unexplored **methods** for developing those devices?)
- ✓ Objective (What kind of devices do you develop?)
- ✓ Methods (how do you achieve the objective?)

  By using, e.g.,

  - a crank-sliding mechanism with an additional gearbox to increase torque with a small motor
  - a crank-crank mechanism with additional dyads
  - a cam mechanism with a journal bearing for reducing frictional force between cam and follower

  By applying a lightweight design

  - by reducing the number of motors with an intelligent mechanical design – e.g., self-locking
  - by selecting lightweight materials.
- ✓ Main results and conclusions

Main results and conclusions

✓Background (why we need to develop those devices)

✓Objective (What kind of devices do you develop?)

✓Methods (how do you achieve the objective?)

✓Main results and conclusions

Our device weighing XX kg with an expansion to shrinkage ratio of XX can roll at a speed of XX cm/s on the paved road and walk at a speed of YY cm/s on the sand with a transformation time of KK s, theoretically finishing the race within an estimated time of ZZ s on the game track of VM350.

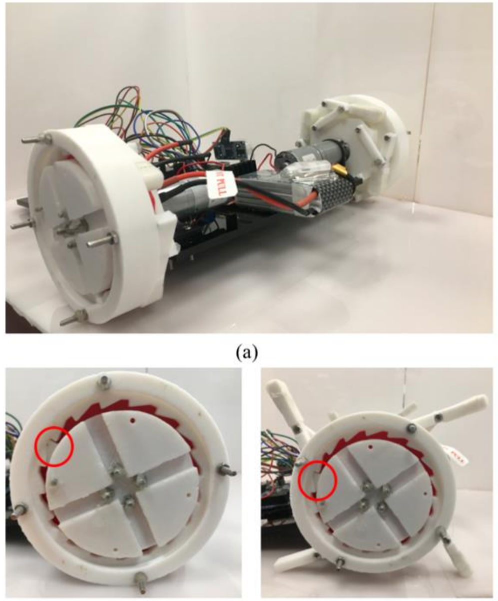
Example

Abstract—In this report, a wheel robot implemented with a ratchet design is presented. Traditional wheels cannot change in size and cannot move on certain type of road conditions such as sand. To overcome these limitations, a wheel robot that can transform autonomously is preferred. The wheel robot discussed in this report utilized four-bar linkage systems and a ratchet design to develop two modes of transformation, in which a shrinking mode enables the wheel robot to pass through terrains with limited height while a stretching mode enables the wheel robot to move on certain terrains that were difficult to overcome by traditional wheels. There are some wheel robots that have been developed to fulfill these tasks. However, almost all the models use more than two motors or use two or more servos, which decreases the reliability of the system. In our wheel robot, each wheel is composed of one ratchet and pawl and four legs, driven by only two DC motors with the help of the ratchet design. The two motors not only drive the transformation mechanism, but they also move the robot forward and backward. Each of the four legs is implemented with a four-bar linkage system. To fit in different conditions and requirements imposed, two wheel robots are manufactured with two types of motors with different torques. Results show that the wheel robot with two motors of no-load rotational speed of 130 rpm (Model A) can lift 339.7 g loading while the model with two 22 rpm motors can lift 2200 g loading (Model B). The diameter of the wheel in the stretching mode is 1.32 times of the shrinking mode. Results also show that the rolling speeds of the shrinking mode and stretching mode on a smooth surface for Model A is 0.67 m/s and 0.09 m/s respectively. On a dynamic surface (sand), the rolling speed of the stretching mode for Model A is 0.38 m/s. As for Model B, the speeds for the shrinking and stretching mode on a smooth surface are 0.10 m/s and 0.16 m/s respectively. On a dynamic surface (sand), the rolling speed of the stretching mode is 0.12 m/s. Conclusively, the wheel robot with a ratchet design can pass through abnormal road conditions and have good reliability.

Objective

Methods

Background



Results and conclusions

Introduction

Nature of problems & Literature review

Contents

- ✓Discuss the nature of problem investigated (one paragraph) and where your device can be used for?

- ✓Discuss the relevant literature (check the literature review table)

- ✓Brief description of your device – methods and results (one paragraph)

Nature of problem

✓Discuss the nature of problem investigated (one paragraph) and where your device can be used for?

subject

i. e.g., **explorer**, **rescue**, or **delivery** robots for both on the paved road and sand (or steps).

ii. Fast-moving on both paved and unpaved road conditions with good stability while moving.

1. A wheel moves fast on the paved road
2. A leg can move relatively fast on the sand

iii. What kinds of explorer, rescue, or delivery robots have been explored? (Literature review)

✓Discuss the relevant literature – e.g., climbing robots with locking mechanisms (check the literature review table)

✓Brief description of your device – methods and results (one paragraph)

Literature review

✓Discuss the nature of problem investigated (one paragraph) and <u>where your device can be used for</u>?

✓Discuss the relevant literature with ~ 10 papers – climbing robots with locking mechanisms (check the literature review table)

No.	Method	Major findings	Unresolved Issues	Refs.
L1	Miura-ori based transformable wheels			[1, XX]
L2	Wheel-leg based transformable wheels	A slider-crank mechanism-based wheel-leg has advantages on ….	Has some limitation on ……	[3,XX]
L3	Others			[5,XX]
L4	Your approach	?	?	Proposed work

✓Brief description of your device – methods and results (one paragraph)

Example

Not clear nature of problems

TRADITIONAL wheels cannot easily change in size and it is difficult for them to overcome some obstacles and accommodate to abnormal road conditions such as sands. The emerging field of smart transformable wheel robots is to solve the problems with the traditional wheels. With a transformable wheel, the robot can accommodate itself to different road conditions. On flat surfaces, the wheels are in shrinking mode where they are identical to the traditional circular wheels. When there are some obstacles on the path, the wheel can be transformed into a stretching mode where there are several "legs" stretching out to overcome the obstacles. Also, this mode enables the wheel robot to move on dynamic surfaces such as sands.

No reference

A lot of different models of transformable wheel robots have been developed to fulfill these tasks. Nevertheless, almost all the models developed so far either use more than two motors or use two motors and two servos, which decreases the stability and reliability of the system. The transformable wheel robot developed by a group from Ohio State University uses a slider crank system and a design of passive leg to solve the problems in the traditional wheel robot [1]. However, they used two additional motors to drive the transforming mechanism besides the two used to move the wheel robot. The transformable wheel robot designed by a group from Seoul National University used a passive mechanism and use only two motors to function the entire wheel robot [2]. Nevertheless, the passive mechanism they used has an issue that the legs will open when "the foot got caught in small crevices in the ground" [2]. Wherever there is an obstacle on the path, the transformation mechanism will be triggered, even at those times unnecessary.

Only two papers

In the transformable wheel robot discussed in this report, a ratchet design is implemented to enable the two motors to manage the transformation mechanism as well as the movement of the whole wheel robot. Also, four triple rocker four-bar linkage systems are utilized to generate desired motion with stability whose details will be discussed in Section II. The wheels of the robot are manufactured by 3-D printing with Acrylonitrile Butadiene Styrene (ABS) and the base board of the robot is made of acrylic. In the stretching mode, the ratchet design enables legs of the wheel robot to rotate along with the inner hub which connected to the DC motor. As the DC motor rotates, the inner hub as well as the legs will rotate so as to move the robot. The stretching mode is prepared for the dynamic surfaces such as sands. When conditions of triggering the transformation mechanism are met (judged by an ultrasonic sensor), the two DC motors will rotate backwards. The shrinking mode enables the wheel robot to pass smoothly and quickly on flat surfaces. With the help of the ratchet design, the inner hub will rotate to transform the four-bar linkage systems to transform the wheels into the shrinking mode. With the implementation of a ratchet design, two modes of the wheel robot that accommodate the robot to different road conditions can be transformed with only two DC motors. Also, two models

Good points

Design

Synthesis

Contents

- ✓ Describe the originality (creativity) of your linkage design compared with other methods published.
  - e.g., A ratchet-pawl mechanism without using additional motors for transformation.
- ✓ Graphical linkage synthesis
  - Two-position or three-position synthesis?
  - Justification of linkage size for both expansion and shrink modes
    - For given heights of the obstacles to climb and the tunnel to pass through, you may justify your linkage size.
  - CAD figures
    - On the linkages
    - On the whole device (if you have)
  - Pictures of your prototypes and components

In this part, we will discuss how we design our transformable robot and what the creative part is. According to the game rules, our device should meet the following requirements: climbing up a barrier with 6 cm height, moving forward on sand and smooth surface, turning left and going through a 9 cm tunnel.

The "close" form of the wheel should be a circle with a radius smaller than 9cm in order to pass through the tunnel smoothly. The "open" form is designed to have a maximum diameter of 13cm so that the hook at the edge of our wheels can easily attach the top of the barrier. Thus, we conduct a two-position synthesis as shown in Fig. 1.

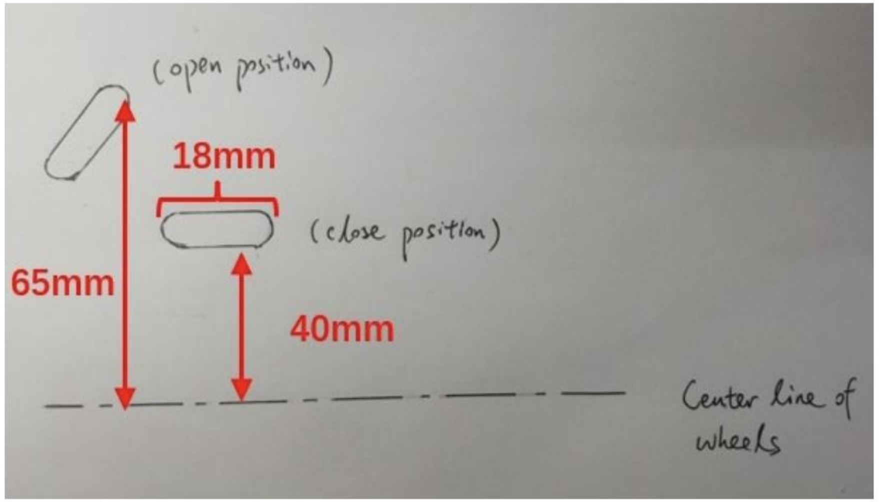


Fig. 1. Two-position synthesis of a single crank of a wheel

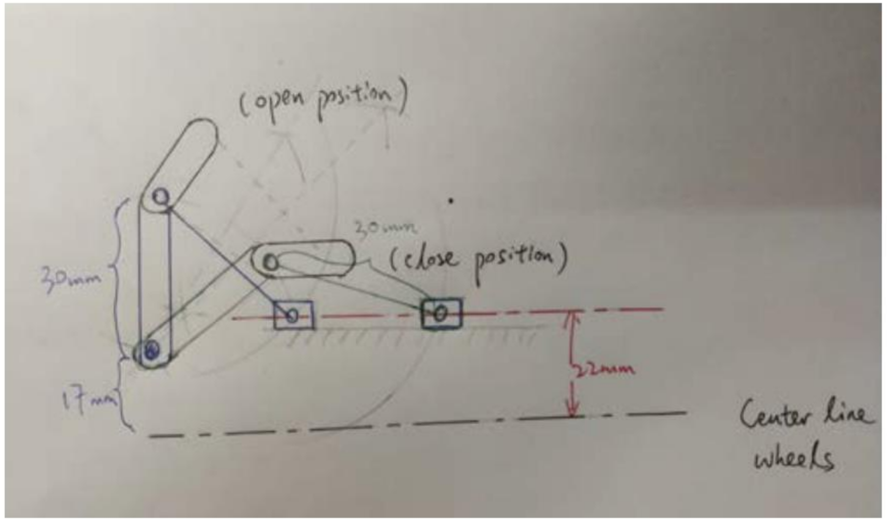


Fig. 2. Dimension of linkages from two-position synthesis

For our design, there is a two-position synthesis, which is as shown below in Fig 3. This is a slider-crank four bar linkage mechanism. The push hoop slides along the column and pushed the coupler inside its push range. When the push hoop pushes the coupler, the crank linked to the coupler rotates about an axis which is fixed at the tip of the column. The length of the coupler is designed to match with the push range so that the crank can rotates exactly 90 degrees and reach a vertical position. In that case, our vehicle can "stand up" and complete the process of transforming.

We used SolidWorks to build the model of our linkage system and simulated the two configurations of transformable wheel. The red petals are the cranks that linked to the coupler while the purple one is the passive leg driven by elastic band which we have already introduced in the creative part. The diameter of the closed-wheel mode of our transforming wheel is 85.12 mm, which is less than 90 mm to ensure the vehicle to run through the tunnel. The radius of the open-wheel mode of the wheel is 85.00 mm, which is more than 60mm to guarantee that the vehicle is able to climb up the terrace.

The linkage size for both expansion and shrink mode are marked and in Fig 3.

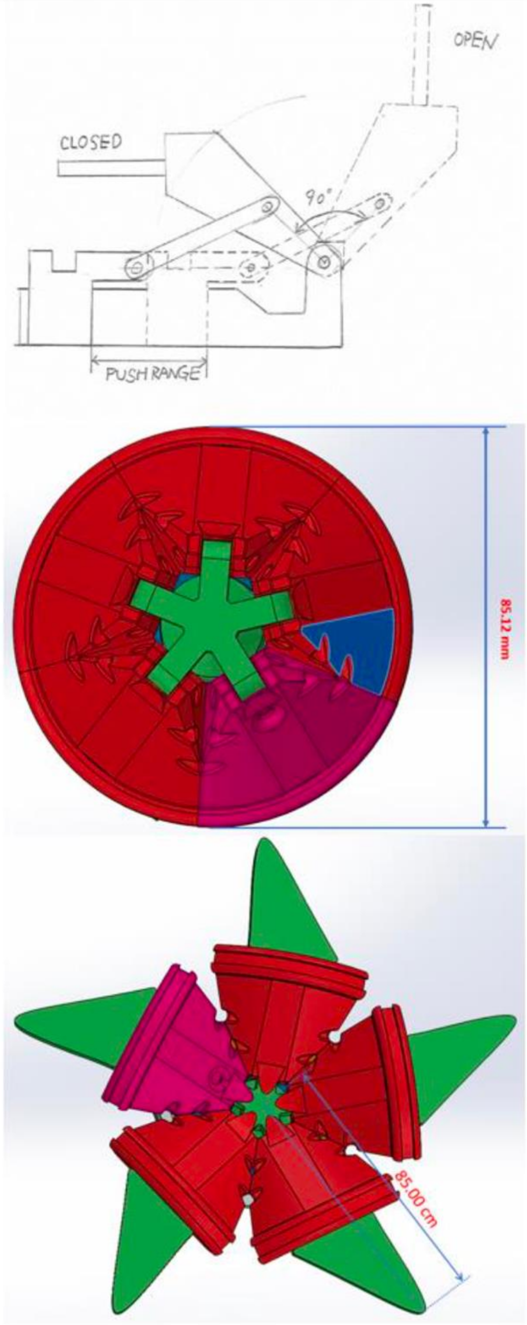


Figure 3. a) The synthesis diagram for designed linkage. b) The closed-wheel mode and its dimension. c)The open-wheel mode and its dimension.

Manufacturing

Fabrication and assembly

Contents

- ✓Selection of materials with sound justification
  - Part materials, motors, and sensors.
    - Rank materials candidates using the Ashby chart – choose high stiffness to density ratio.
    - Can lower the overall mass by % if we choose XX material compared with YY material.
- ✓Selection of manufacturing methods with sound justification
  - Can improve dimensional accuracy by XX % compared with YY method.
  - Can lower the manufacturing cost by XX % compared with YY method.
- ✓Describe the procedure of manufacturing
- ✓Describe the procedure of assembly of components, motors, sensors, etc.

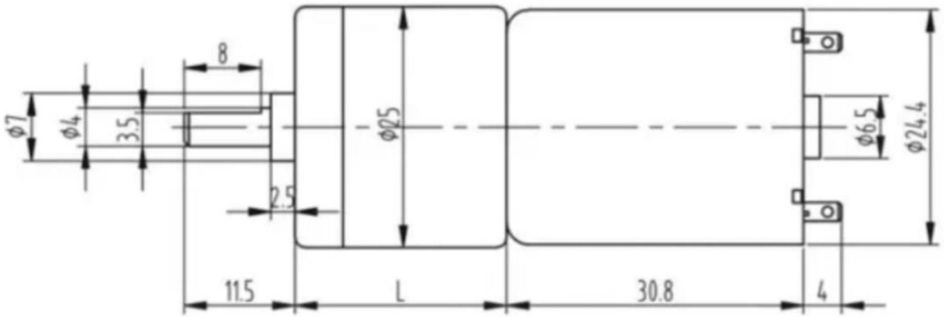


Table 1.
Electro-mechanical properties of 370 gear motor

Motor type	JGA25-370-171K	L=25mm	Weight=89g
	No load	Nominal	Stall
Speed(rpm)	35	27	
Current(A)	0.07	0.3	1.8
Torque(kg*cm)		3.3	9.2

1. **Size:** The diameter of the motor 24.4mm is smaller than half of the small wheel's diameter 35mm. The length of the motor is 66.7mm which is smaller than half of the base boards' width. So, the size of the motor is acceptable.
   Output: This motor is capable to climbing up the stairs and go through the sand.

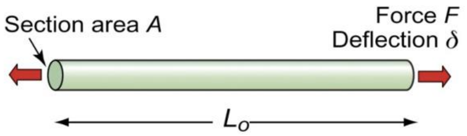
How?

I would say "we prove this in the analysis section later.

Recall – VM250

✓ **Function**

- Tie rod



✓ **Constraints**

- Length L is specified (geometric constraint)
- The rod must support tensile load F without displacing too much, meaning that axial stiffness is specified as k (functional constraint).

✓ **Objective**

- Minimize the mass m of the tie.

✓ **Free variables**

- Cross-section area A
- Choice of material

$$k = \frac{EA}{L}$$

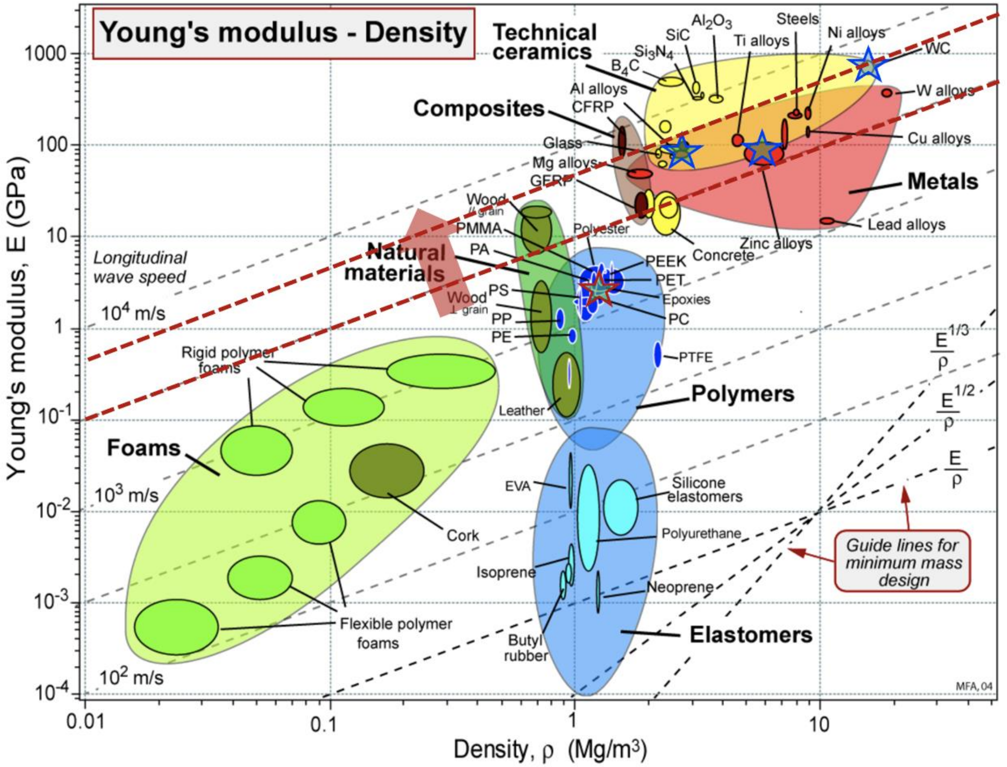
$$m = AL\rho$$

Geometric constraint

$$m = (k)(L^2)\left(\frac{\rho}{E}\right)$$

Functional constraint

Material properties



Therefore, maximize

$$M_{t2} = \frac{E}{\rho}$$

Answer- WC

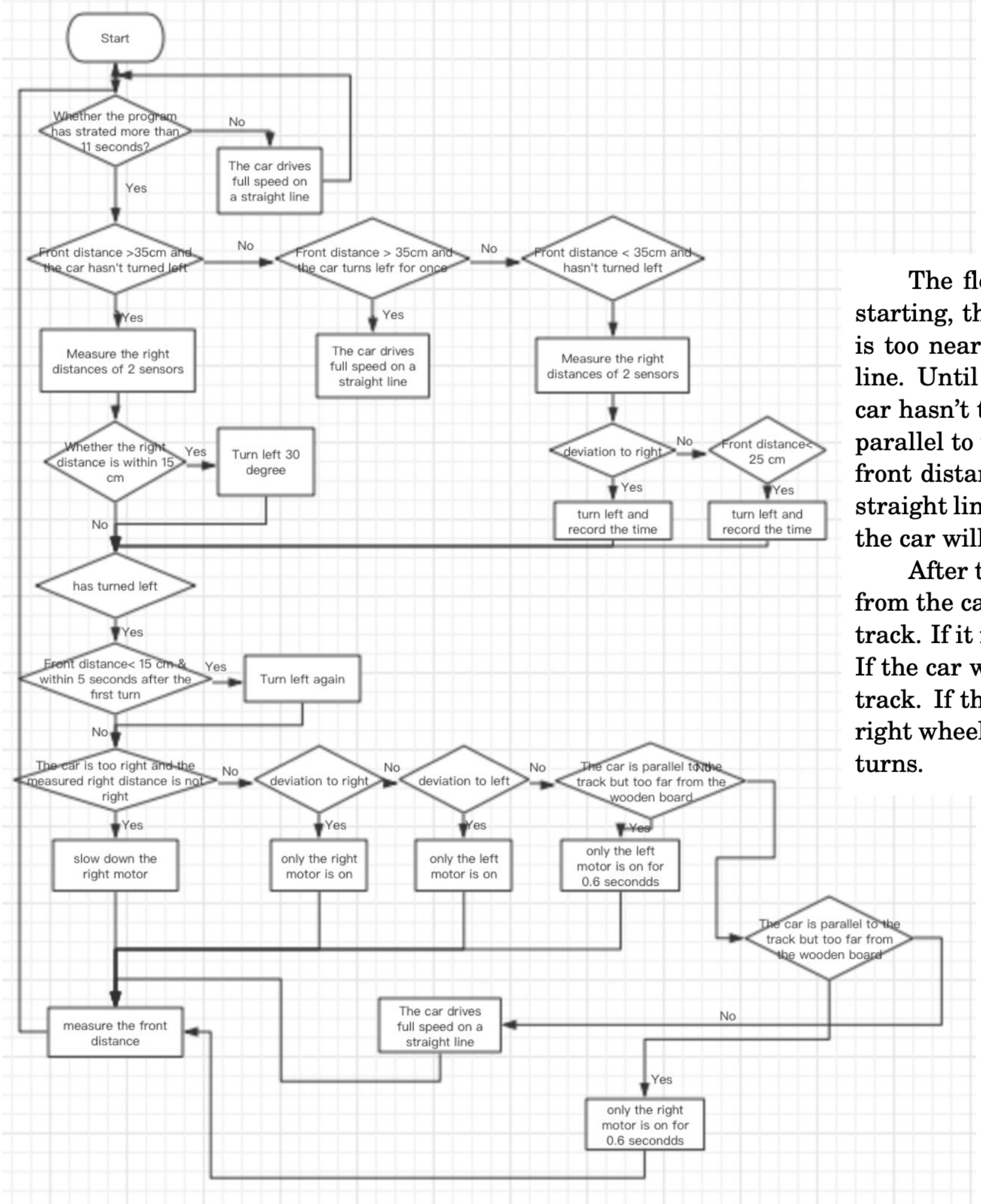
Control

Sensors and actuators

Contents

✓Describe the algorithm with

- a flowchart and
- a circuit diagram

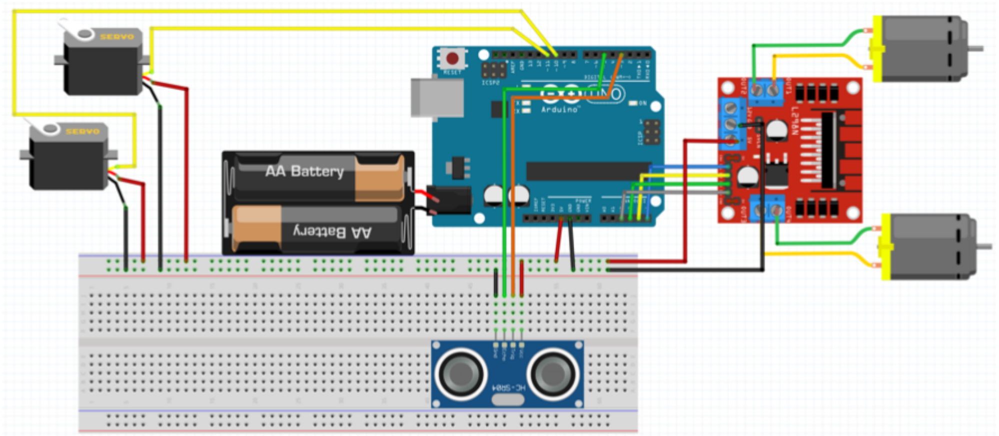


The flow chart below shows how our code works. After testing, we found that after 11 seconds from starting, the car will definitely climb up the sand box. The car runs on a straight line. After that, if the car is too near the wood board on the right side, the car will turn left for 30 degree and then run on straight line. Until the distance between the front of the car and the wood board is 35 cm, after finding out that the car hasn't turned left, the ultrasonic sensors on the right will measure 2 different distances. If the car is not parallel to the track and has a deviation to the right, the car will immediately turn left. Otherwise, when the front distance reaches 25 cm, the car will turn left. If the car has already turned left, the car will run on a straight line. Also, if the car has turned left for once and within 5 seconds, the front distance is less than 15cm, the car will turn left again.

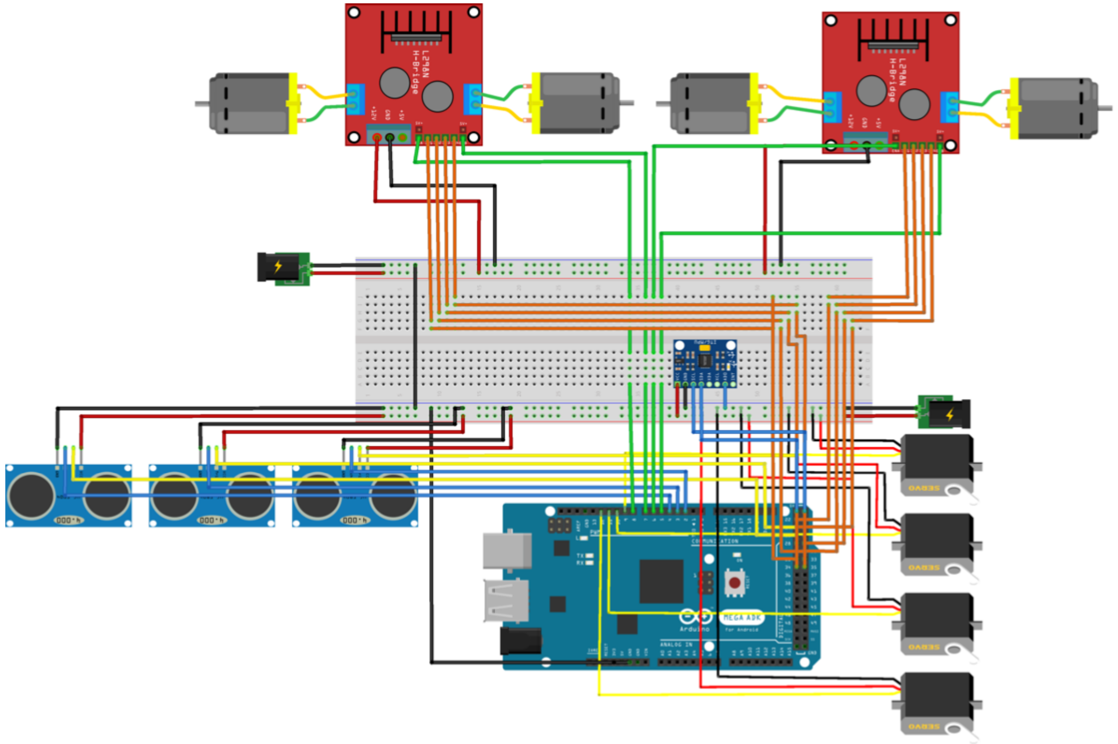
After the car turns left, the two ultrasonic sensors on the right edge of the car will measure two distances from the car to the wood board. Based on the two distances, we can find out whether the car is parallel to the track. If it is not parallel to the track and it will come closer to the wood board, only the right motor will work. If the car will get farther from the wood board, only the left motor will work, so the car can be parallel to the track. If the car is parrallel to the track, but the distance between the car and the wood board is too far, the right wheel will be locked and only the left wheel turns. If it is too near to the wood board, only the right wheel turns.

The target motion of the robot in this project is climbing up and down the step, which does not require much resources in terms of sensing. Therefore, the optimized design is adopting only one sensor at the front, instead of two sensors with one on the side, due to the stability of the robot's orientation.

The circuit diagram of the automatic mobile robot is shown in Fig. 10. The Arduino UNO board receives signals from the front ultrasonic sensor and controls the two DC motors and two servo motors accordingly. The whole system is powered by a 12 V battery.



Another point to note is that we created a negative feedback in the program requiring the device to move in a straight line. The circuit is shown in Figure 12, which can be used as a reference to rebuild the device.



Analysis

Contents

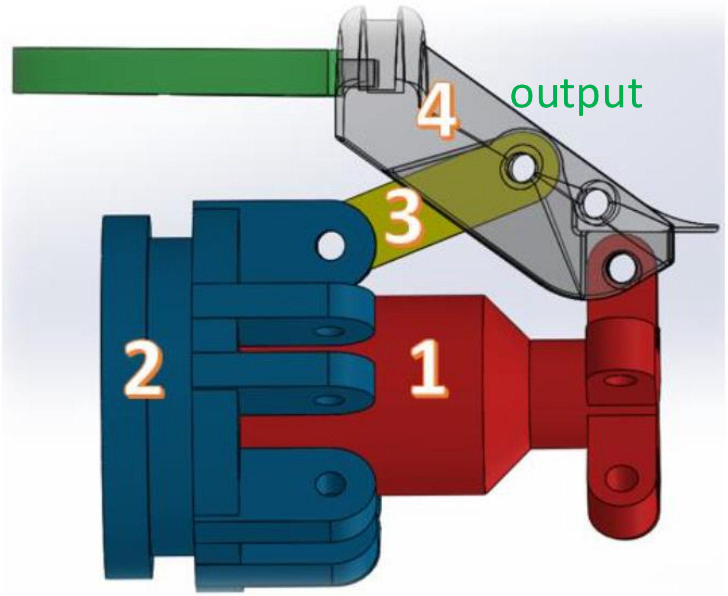
- ✓ Classification of the designed linkage
  - DOF
  - e.g., Crank-slider, crank-crank, etc.
  - Grashof condition
    - A crank-slider may not have a Grashof condition.
- ✓ Position analysis for transformation (with graphs from MATLAB results)
  - When generating the plots, do not forget the dimension on the x- and y- axes.
- ✓ Force analysis with **free body diagrams** (with graphs from MATLAB results)
  - Required input torque to lift the weight of the device
    - Justification of the selection of motors
    - Design and analysis of external gearboxes, if added
  - Friction force
  - Rolling Speeds (Climbing speed)
  - Check the safety factors of the assembled components with the force analysis.

For the DOF of the linkage, as is shown in figure x, we can get:

$$L=4,\ J_1=4,\ J_2=J_m=0$$

$$DOF=3*(4-1)-2*4=1$$

For the transforming part, it is a RRRP slider-crank linkage.



input

Sider – crank
(input) (output)

As is shown in Fig 9, the unknown parameter for the process of transformation is the θ_3 and the position of the slider d under the condition that we have already known the input angle θ_2.

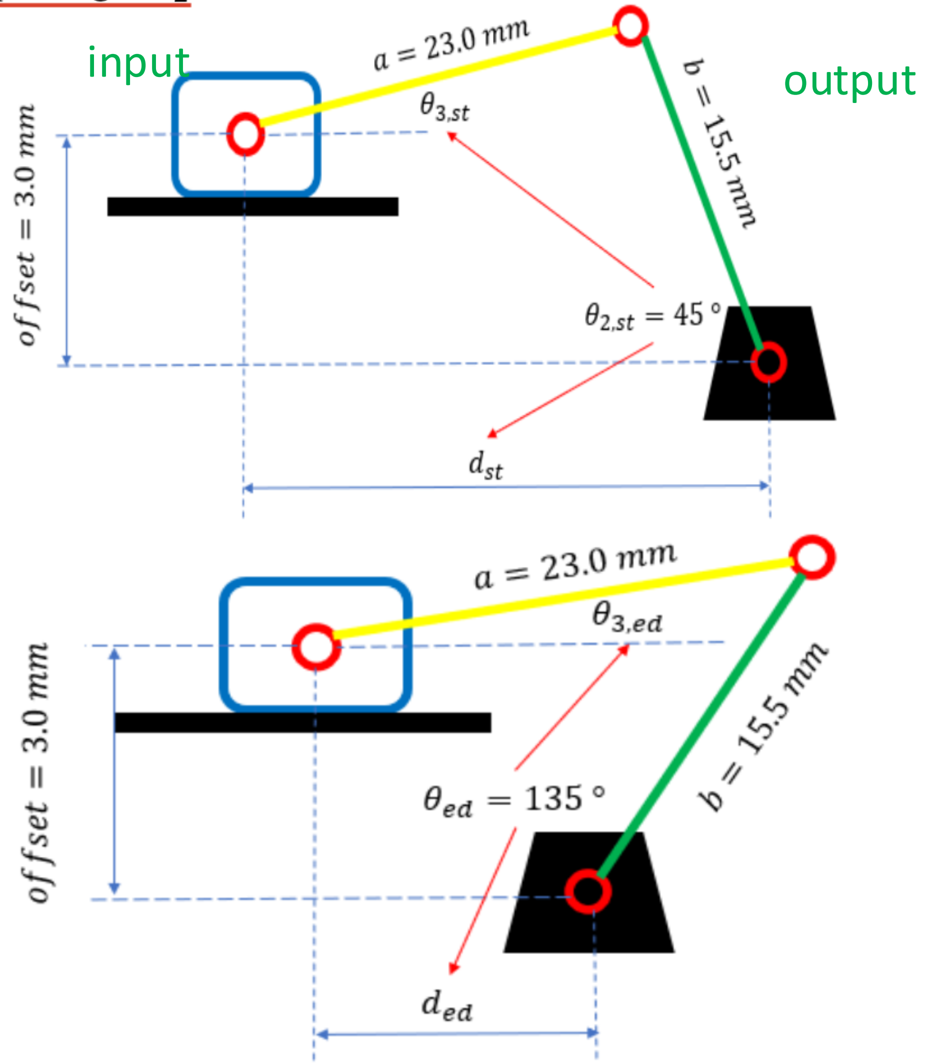


Figure 9. The position analysis for transformation.

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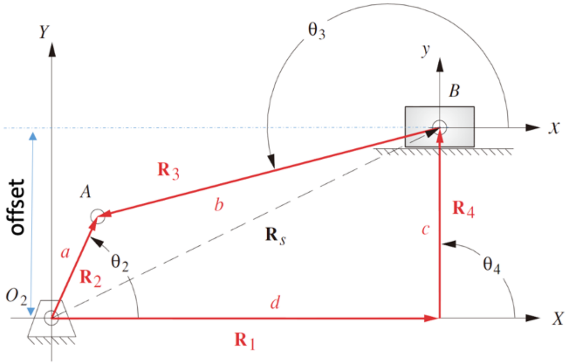
Indentify your mechanism (inpu-output) correctly.

Recall

Fourbar slider-crank linkage

✓Vector loop approach



Input: a slider position d

Q. What are the unknown variables to find?

θ_2 and θ_3

$$\mathbf{R}_2 - \mathbf{R}_3 - \mathbf{R}_4 - \mathbf{R}_1 = 0$$

$$ae^{j\theta_2} - be^{j\theta_3} - ce^{j\theta_4} - de^{j\theta_1} = 0$$

$$a(\cos\theta_2 + j\sin\theta_2) - b(\cos\theta_3 + j\sin\theta_3) - c(\cos\theta_4 + j\sin\theta_4) - d(\cos\theta_1 + j\sin\theta_1) = 0$$

First, we can draw free body diagrams for both expanding and shrinking processes. The linkage is subjected to three forces basically: the friction force with the ground, the normal force for supporting and the pushing force from the pushing hoop. Both free body diagrams are shown in Fig 11.

good

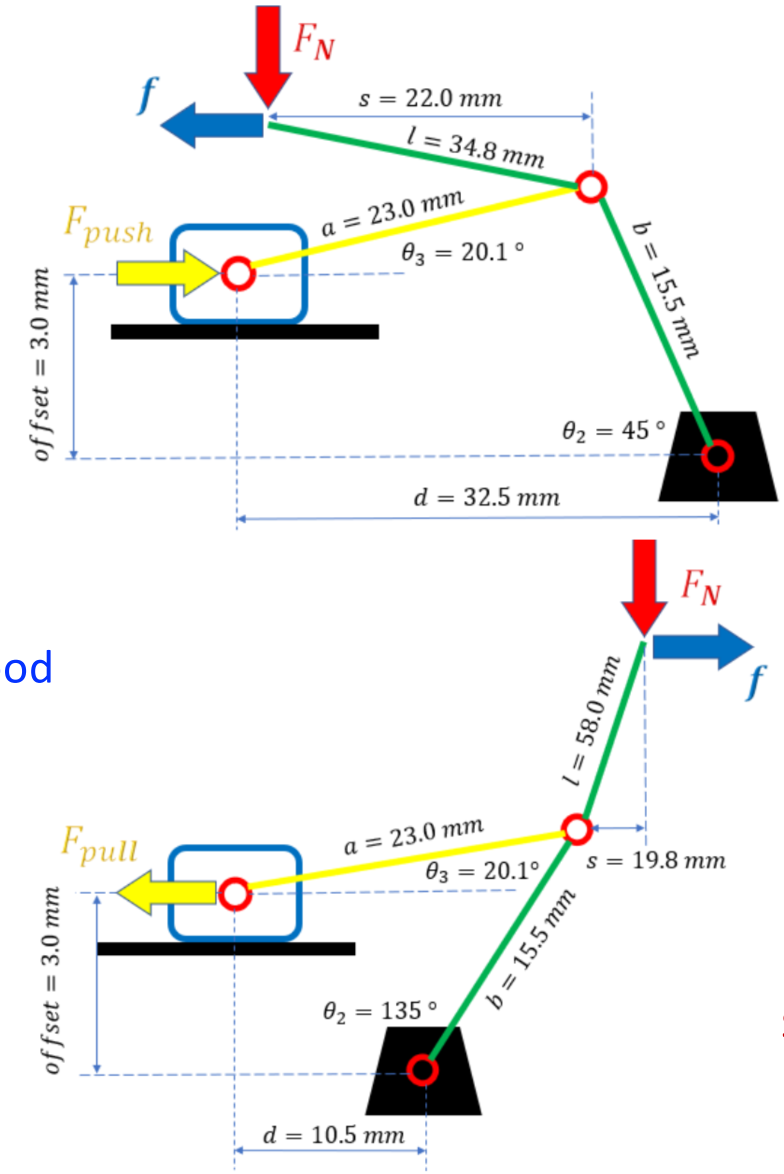


Figure 11. Free body diagram for expanding and shrinking.

Then we can use the vector method to calculate the minimum torque we need for the expanding process:

??

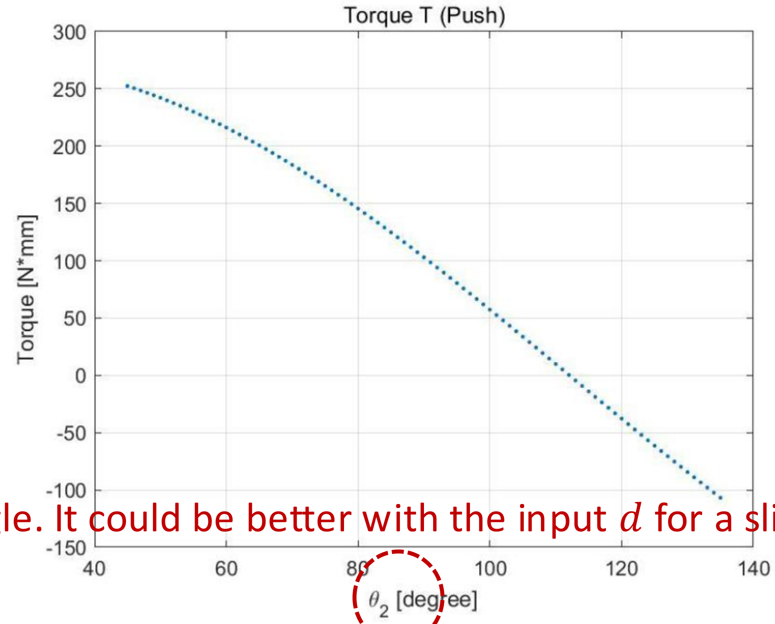
Not clearly defind A

$$A = \begin{pmatrix} 15.5 * cos\theta_2 \\ 15.5 * sin\theta_2 \\ 0 \end{pmatrix}; B = \begin{pmatrix} 15.5 * cos\theta_2 + 34.8 * \cos(\theta_2 + 5.82°) \\ 15.5 * sin\theta_2 + 34.8 * \sin(\theta_2 + 5.82°) \\ 0 \end{pmatrix}; F = \begin{pmatrix} 2.4 \\ -4.9 \\ 0 \end{pmatrix};$$

$$T = r \times F = \begin{bmatrix} i & j & k \\ B_x & B_y & 0 \\ f & -F & 0 \end{bmatrix} = \begin{pmatrix} 0 \\ 0 \\ -4.9 * [15.5 * cos\theta_2 + 34.8 * \cos(\theta_2 + 5.82°)] \\ -2.4 * [15.5 * sin\theta_2 + 34.8 * \sin(\theta_2 + 5.82°)] \end{pmatrix}$$

$The\ required\ torque\ T$
$= 4.9 * [15.5 * cos\theta_2 + 34.8 * \cos(\theta_2 + 5.82°)] + 2.4 * [15.5 * sin\theta_2 + 34.8 * \sin(\theta_2 + 5.82°)]\ (N * mm)$

We calculated and plotted the diagram using MATLAB. We get the following plot of T v.s. θ_2. By reading the diagram, we can figure out that the torque$T$ varies from 250 N*mm to (-100) N*mm where the minus sign means the opposite direction and there is no need to push. We can see that the maximum torque we need is 250 N*mm in pushing process. The plot is shown in Fig 12.



Still θ_2 is not the input angle. It could be better with the input d for a slider-crank linkage.

Figure 12. The plot for the torque and input angle for force analysis in expanding process.

At last we use the same method to calculate the minimum torque we need for the shrinking process:

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$$A = \begin{pmatrix} 15.5 * cos\theta_2 \\ 15.5 * sin\theta_2 \\ 0 \end{pmatrix}; B = \begin{pmatrix} 15.5 * cos\theta_2 + 58 * \cos(\theta_2 - 29.13°) \\ 15.5 * sin\theta_2 + 58 * \sin(\theta_2 - 29.13°) \\ 0 \end{pmatrix}; F = \begin{pmatrix} -2.4 \\ -4.9 \\ 0 \end{pmatrix};$$

Not clearly defind A

$$T = r \times F = \begin{bmatrix} i & j & k \\ B_x & B_y & 0 \\ -f & -F & 0 \end{bmatrix} = \begin{pmatrix} 0 \\ 0 \\ -4.9 * [15.5 * cos\theta_2 + 58 * \cos(\theta_2 - 29.13°)] \\ +2.4 * [15.5 * sin\theta_2 + 58 * \sin(\theta_2 - 29.13°)] \end{pmatrix};$$

$$\text{The required torque } T = 4.9 * [15.5 * cos\theta_2 + 58 * \cos(\theta_2 - 29.13°)] - 2.4 * [15.5 * sin\theta_2 + 58 * \sin(\theta_2 - 29.13°)]\ (N * mm)$$

We calculated and plotted the diagram using MATLAB. We get the following plot of T v.s. θ_2. By reading the diagram, we can figure out that the torque$T$ varies from 260 N*mm to (-300) N*mm where the minus sign means the opposite direction and there is no need to pull. We can see that the maximum torque we need is 260 N*mm in pulling process. The plot is shown in Fig 13.

Comparing the two maximum torque that we have calculated above, we can draw the conclusion that in order to meet the demands of both pulling and pushing, the minimum torque we require is 260 N*mm. Therefore, it is appropriate for us to choose a servo that can provide a torque of 3.5 kg*cm (343 N*mm).

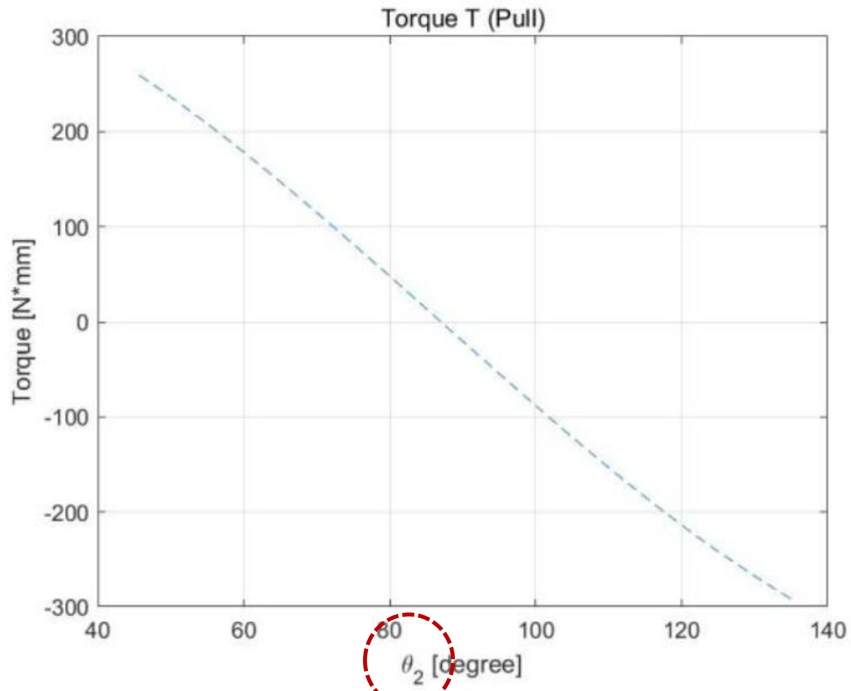

Figure 13. The plot for the torque and input angle for force analysis in shrinking process.

Still θ_2 is not the input angle. It could be better with the input d for a slider-crank linkage.

6.4 Rolling Speed Analysis

Our wheel is designed to transform to expansion mode only on sand, and to shrink mode only on the smooth surface. We can calculate the theoretical speed with the formula

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$$n = \frac{v}{2\pi r}$$

for the closed wheel, and

May be too ideal without considering loaded torque T.

$$n = \frac{v}{3 \times \sqrt{3} r}$$

for the open wheel, if we approximate the perimeter of the open wheel to be that of a triangle with the same configuration.

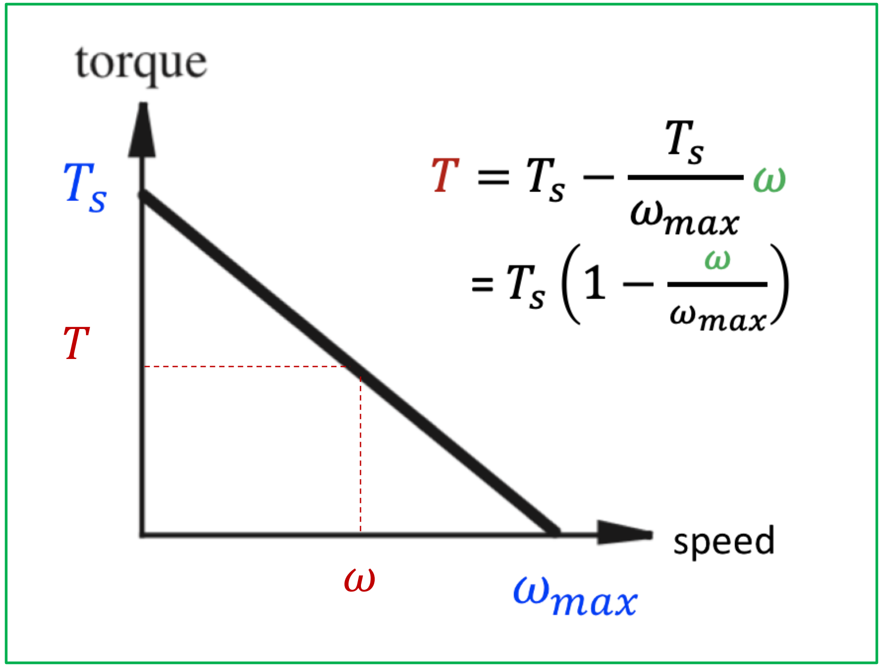
Since we don't know the performance of the motor under different load, we will use the rated speed (30rpm) for the motor, and the theoretical values of the wheel (d=177.7mm at expansion and 88.33mm at shrinkage), we obtain

$$v_{closed} = \pi \times 0.08833 \times 30 \times \frac{1}{60} = 0.139[m/s]$$

$$v_{open} = 3 \times \sqrt{3} \times \frac{0.1777}{2} \times 30 \times \frac{1}{60} = 0.231[m/s]$$

See the following part for more details.

Recall



May obtain loaded ω for the loaded T
from a free-body diagram of the driving mode.

System	Static friction μ_s	Kinetic friction μ_k
Rubber on dry concrete	1.0	0.7
Rubber on wet concrete	0.7	0.5
Wood on wood	0.5	0.3
Waxed wood on wet snow	0.14	0.1
Metal on wood	0.5	0.3
Steel on steel (dry)	0.6	0.3
Steel on steel (oiled)	0.05	0.03
Teflon on steel	0.04	0.04
Bone lubricated by synovial fluid	0.016	0.015
Shoes on wood	0.9	0.7
Shoes on ice	0.1	0.05
Ice on ice	0.1	0.03
Steel on ice	0.4	0.02

Tread Material	Floor Material	Coefficient of Rolling Friction (inches @ 3mph)
Forged Steel	Steel	0.019
Cast Iron	Steel	0.021
Hard Rubber	Steel	0.303
Polyurethane	Steel	0.030 - 0.057*
Cast Nylon	Steel	0.027
Phenolic	Steel	0.026

*Polyurethane has a range of coefficient values depending on the specific poly material selected.

Assumptions

Total Load: 1200 lbs.
Floor Material: Steel
Wheel Speed: 3 mph

Experiment

Contents

- ✓Demonstration of climbing capacity
  - Measure the rolling speed, compare it with the analysis, and discuss the mismatch.
- ✓Demonstration of locking capacity without a power source.

7.1 Demonstration of Load Carrying Capacity

To measure the maximum carrying capacity, we put weights on the car and tested whether it can climb onto the sandbox. A 500g load was added after each successful test. When the weights reached 2.5 kg, visible deformation of the base occurred, but the motors were still able to lift the car; when the weights reached 3.0kg, the motor was overloaded and the wheels failed.

See the attached video clip for the whole test.

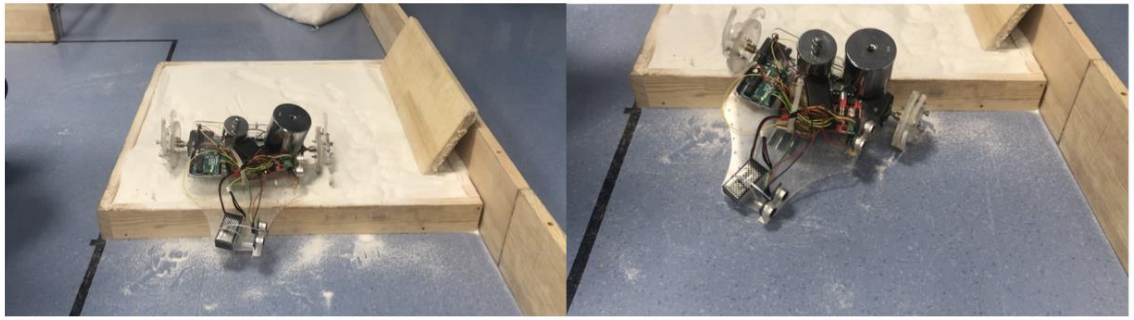


Figure 22: The performance with 2.5kg load (left) and 3.0kg load (right).

Since the weight of the car itself is 1.4kg, the total maximum load adds up to

$$M_{max} = 1.4kg + 2.5kg = 3.9kg$$

With the same calculation method as stated in Analysis part, we obtain the maximum torque

$$T_{max} = rFsin(\theta) = 3.084N \cdot m = 31.47kg \cdot cm$$

This is a slight mismatch with our analysis, which states that the rated load of one motor is 15kg-cm. The error is

$$T_{err} = \frac{(31.47 - 30)}{2 \times 15} \times 100\% = 4.9\%$$

We think this error is acceptable. The error might came from:

1. The supporting force of the ground, which wasn't taken into account in analysis
2. The mismatch of the actual load with the rated load of our motors.

7.2 Demonstration of Climbing Onto the Sand Box and Running Through the Tunnel

Our wheel was able to transform when it met obstacles, and shrink when it came back to smooth ground. Below are the pictures of game day performance. See the attached video clip for more details.

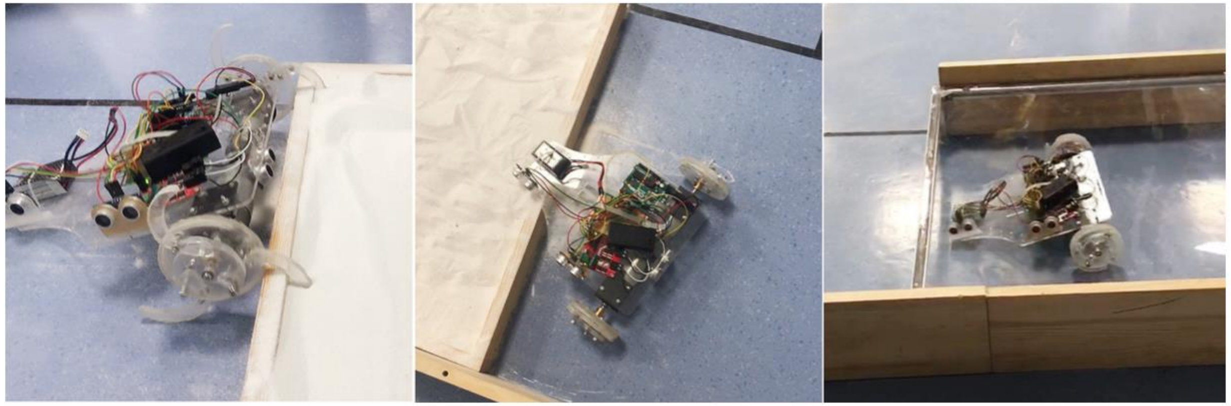


Figure 23: Gameday performance: climbing onto the sand (left), climbing off (middle), and running through the tunnel (right).

7.3 Ability of Transformation

We used a 0.02mm-precision caliper to measure the diameter of the closed wheel, and a 1mm-precision ruler for the radius of the open wheel. The theoretical value is calculated from CAD dimensions. The results are as follows.

	Actual dimension [mm]	Theoretical value [mm]	Error
Expansion	179.0	177.7	0.73%
Shrinkage	88.60	88.33	0.31%

Table 2: The dimensions of the wheel.

The precision of our wheel is high, since the error of laser cutting is usually less than $\pm 0.2mm$. Except for that, we think the error might came from:

1. the thickness of hot-melt glue on the outer surface of the wheel;
2. measuring errors.

7.4 Demonstration of Rolling on Sand and Smooth Surface[1]

To measure the speed of the car, we did 5 tests and calculated the average value. The results are listed below. The results of the previous analysis are used to calculate the rotation speed.

Then, we compare the rotation speed with the rated speed of the motor, which is 30 RPM. Three significant digits are kept for all the calculations.

7.4.1 Speed on Smooth Surface

	speed [m/s]	speed [rpm]	deviation from theoretical value
Trial 1	0.121	26.1	
Trial 2	0.121	26.1	
Trial 3	0.121	26.1	
Trial 4	0.105	22.6	abnormal data
Trial 5	0.121	26.1	
Average	0.121	26.1	13.0%

Table 3: the speed on smooth surface.

The error could only come from the mismatch of the rated rotation speed and the actual speed of the motor, which is due to the load. A 10 percent mismatch is acceptable.

[1]See the attached video clip for demonstration.

7.4.2 Speed on Sand

	speed [m/s]	speed [rpm]	deviation from theoretical value
Trial 1	0.103	13.1	
Trial 2	0.130	16.7	
Trial 3	0.125	16.1	
Trial 4	0.133	17.1	
Trial 5	0.138	17.8	
Average	0.126	16.3	45.8%

Table 4: the speed on sand.

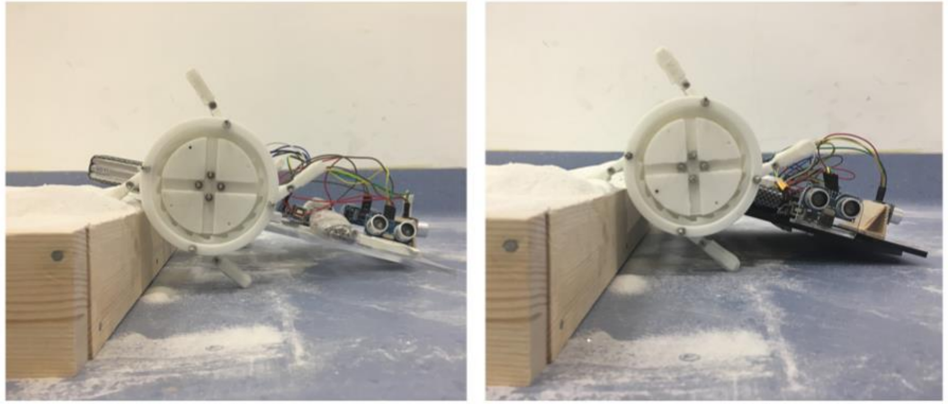
We see a serious speed mismatch here. To eliminate the effect of the motor, we will calculate the deviation again, with the actual motor speed (26.1rpm) obtained in the previous part:

$$n_{err} = \frac{16.3 - 26.1}{26.1} \times 100\% = 37.5\%$$

The reason for the difference between the real value and the theoretical result is that we cannot calculate the resistance in the sand. Under the load in the sand, the rotation speed of the motor will decrease. The higher the resistance, the lower the speed will be. The speed given by the manufacturer is measured under no load. The reason that the speed in the sand is lower than the one on the smooth surface is because the wheel will experience more resistance in the sand. Also, the torsion spring helps close the trigger leg, thus reducing the radius of the wheel. The result we calculate matches our expectations.

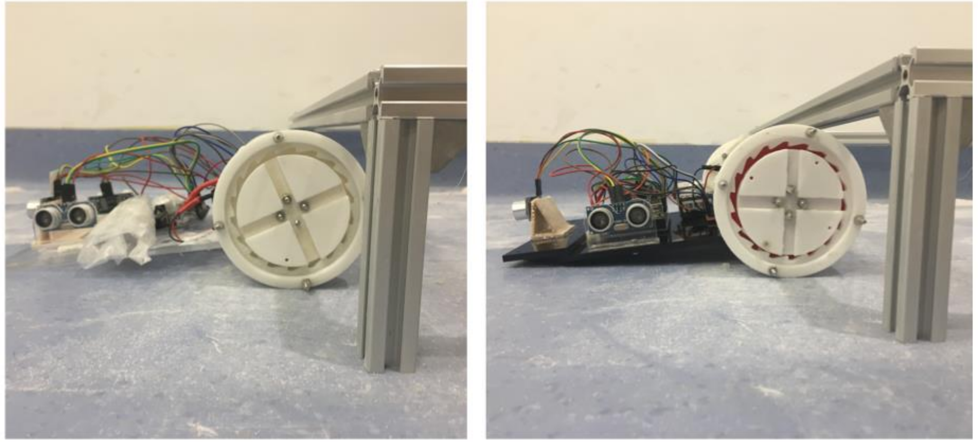
B. *Adaptability to Multiple Surroundings*

The wheel robots are able to adapt to different kinds of surroundings. They can climb up a 6-cm-high step in stretching mode as shown in Fig. 25, and go through a 10-cm-high tunnel in shrinking mode as shown in Fig. 26.



(a) (b)

Fig. 25. Experiments of climbing a 6-cm-high step. (a) Model A. (b) Model B



(a) (b)

Fig. 26. Experiments of going through a 10-cm-high tunnel. (a) Model A. (b) Model B.

(Further) Discussion

Contents

- ✓Discuss agreement or disagreement between your **analysis** and **experiments**.
- ✓Discuss the **intellectual merit** of your work.
- ✓Discuss the theoretical and practical implications (**broader impact**) of your work.

Conclusion

Contents

- ✓A summary of objectives and methods
- ✓Short narrative vital findings with a bulleted list
- ✓Generalized ideas
    - o The conclusion must be drawn from the results and discussion.

Others

References & Appendix

Contents

- ✓References ~ 10 papers
  - Use the IEEE format
- ✓Appendix
  - Contribution of each team member (with pictures of each member)
    - Use IEEE format on the author's pictures.
  - Gantt chart
  - Budget table and justification. (Is your spending under the budget?)
  - Raspberry Pi programming code
  - Others

Grading Sheet for Project Report

Group #________________

Grading Policy: The median grade should be between 75 and 85.

1.	Abstract (~200-300 words) - Background (why we need to develop these devices?) - Objective (what kind of devices do you develop?)) - Methods (how do you achieve the objective?) - Main results and conclusions	5	
2	Introduction - Discuss the nature of problem investigated and where your device can be used for. - Discuss the relevant literature with ~ 10 papers. - Brief description of your device – methods and results (one paragraph)	10	
3	Synthesis (Design) - Describe your **originality** (**creativity**) of your linkage design (and locking design) compared with other designs published. - Graphical linkage synthesis o Two position or three position synthesis? o CAD figures ▪ On the linkages ▪ On the whole device (if you have) o Pictures of your prototypes and components	8	
4	Fabrication and assembly (**Manufacturing**) - Selection of materials with sound justification o Part materials, motors, and sensors. - Describe the procedure of manufacturing. - Describe the procedure of assembly of components, motors, sensors, etc.	7	
5	Control of sensors and actuators - Describe the algorithm with a flowchart and a circuit diagram	5	
6	Analysis - Classification of the designed linkage o DOF o Crank-slider, crank-crank, etc. o Grashof condition - Position analysis for transformation (with graphs[1] from MATLAB results) - Force analysis with a **Free Body Diagram** (with graphs from MATLAB results) o Required input torque to lift the weight of the device ▪ Justification of the selection of motors ▪ Design and analysis of external gearboxes if added o Check the safety factors of the assembled components with the force analysis. - Climbing speed analysis o For different radial spring forces.	15	
7	Experiment (with figures) - Demonstration of load carrying capacity o Measure the rolling speed and compare it with the analysis. - Demonstration of locking capacity without power source. o Show it with the analysis.	10	
8	(Further) Discussion - Discuss agreement or disagreement between your analyses and experiments. - Discuss the intellectual merit of your work. - Discuss theoretical and practical implication (broader impact) of your work.	5	
9	Conclusion - Brief summary of objectives and methods - Short narrative key findings with a bulleted list - Generalized ideas o Conclusion must be drawn from results and discussion.	5	
10	References ~ 10 papers - Use the IEEE format	2	
11	Appendix - Contribution of each team members (with pictures of each member) o Use IEEE format on the author pictures. - Gantt chart - Budget table and justification. (Is your spending under the budget?) - Raspberry PI programming code - Others	3	
12	Peer evaluation	5	
13	Gameday performance	20	
	Total	**100**	