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IAR Rube Goldberg Project Report

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ABSTRACT. *This Rube-Goldberg machine links together seven principles of physics over a time span of at least 14 seconds: elastic collision, inelastic collision, torque, conservation of energy, conservation of momentum, projectile motion in two dimensions, and circular motion. The biggest challenge of this machine is that we have to do it on the computer by Blender, thus I need to learn how to use the software to simulate the processes of the machine. After building the machine, I use Tracker to analyze the data from the machine and reveal the physical principles in the machine.*

KEYWORDS*: Physics, Rube Goldberg Machine*

Introduction

My task is to create a Rube Goldberg machine that includes all the topics we learned about Physics. For the coronavirus during the year of 2020, I have to accomplish the machine on the computer through Blender. The biggest constraint I face during my project is the software itself. For one who lacks the experiences of manipulating 3D software, it can be hard for me to achieve the result I expected to have. Also we need include all seven steps in one machine, so it is essential for us to carefully design each of the steps and consider how they can be assembled together. During the process, I encountered many obstacles which had forced me to adjust my plan for several time in order to finalize my work, which cause my final product varied from the one in my initial plan. Also, the task asks me to measure the physical parameters in each process of the Rube Goldberg machine. For the reason that the project was made digitally, so I used Tracker to track the datas of the movements of the balls in the machine and transfer them into proper parameters via calculation.

Method

For the beginning of the project, I need to carefully design the steps so that each of them could run perfectly while they can be linked together as well. At the first time, I use very simple structure to construct the machine. Turned out, the time for each step is too short, so as the total time. As a result, I have to expand every step to make them be able to last longer during the process. When I finished all step and ready for test, I realized a serious problem in my project that the curve I designed for the ball to get to the upper floor is too steep. Consequently, the ball can't get to the top of the curve. By decrease the slope of the curve, the whole process was finally able to go continuously.

After finishing building the objects in the blender, the next step is trying to render the project so it can be transformed into a video for better analysis. To render a clear video with all the step contained inside, I have to carefully place the virtual camera in Blender and arrange the lights in order to make the processes visible. At total, I placed 4 lights from every direction of my machine to increase the light of the video. I changed the color of my object to several different ones in order to distinguish the different part. During the process, I encountered problems like the luminance of the light is too weak and the reflection of the object under the light can be too shiny which can cause the video to be hardly visible. Still, I manage to conquer the obstacles and get a piece of video clip that is able to be analyzed.

I used Tracker—a software on the computer—to accomplish my analysis. I tracked each of the steps of the movement and make graph of the statistics to better show the physical features inside each part of the movement. For making the measurement more easy to analyze, I set the radius of the curve to 1cm.

Blender provides rigid body world in which all the objects are supposed to move according to the physical principles. However, the physical principles in the Blender is simulated by the computer which can be a little different from the real-world's. As a result, some time Tracker can get data that doesn't seem to make sense. I have tried my best to compensate the errors, but there are still some parts that may contain unnatural movements. As to these errors, I will explain them later in the detailed analysis.

Results

Table 1: Outline of Steps in Rube Goldberg Machine

Physical Concept	Description of Step
Inelastic Collision	Collision between the ball 1 and the plane 2; the ball 1 falls down after hitting the chain-ball from plane 1 and drop to the plane 2. After the collision between ball 1 and plane 2, the vertical velocity difference between

	them goes to zero, which means it's a inelastic collision
Elastic Collision	Collision between the ball 1 and the plane 1; the ball 1 slides down the curve and falls to the plane 1. After the collision, the vertical velocity difference between them remain the same, which means it's a elastic collision
Conservation of Energy	Gravitational energy to kinetic energy and thermal energy; To demonstrate conservation of energy, I designed a slope so that the ball 2 can slide down. During sliding on the slope, the ball speeds up and goes down, which means the gravitational energy of the ball 2 converts into the kinetic energy. Also, for the calculation indicates that the energy doesn't convert completely, so some of the gravitational energy may have been converted into thermal energy.

Conservation of Momentum	Momentum of the chain ball fully convert into momentum of ball 2. When the chain ball hit the ball 2, it stops and convert all its momentum into the ball 2 to make the ball 2 start to move. During the process, the momentum changes of the two ball remain the same.
Projectiles in 2-Dimension	The horizontal projectile motion after the ball 1 slide through the curve. The ball 1 moves uniformly along xdirection and accelerate at a constant acceleration along y direction.
Rotation	Ball 1 slides down from the curve. Ball 1 slide down from the curve—which is a quarter circle—from static. The ball rotate around the center of the circle and the supporting force by curve to the ball 1 act as the centripetal force.
Torque	The ball 2 hit a lever which makes the ball 3 move. The torque remains the same on both side of the lever, which cause the ball 3 to move as a result of the ball 2 hitting the lever.

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I. Descriptions of physical steps

II. Calculation and tracker plots

III. Inelastic collision

IV. Analysis of results

Energy of the ball 1 before collision:

m2 = 50kg

vy = 1m/s

1/2mv2 = 1/2(50)(1)2 = 25J

Final velocity along y direction, the velocity change at plane 2 is negligible.

So the e=0, which means that the collision is an inelastic collision.

1. Elastic collision

Analysis of results

In an elastic collision, energy is conserved, so 1/2mv2=1/2mv2

In addition, momentum (p=mv) is conserved, so mv = mv

m1 = 50kg

Vi,1 = -0.34m/s

Vi,2 = 0.28m/s

*To calculate the conservation of momentum:

p = m1vi,1 = (50)(-0.34) = -17Ns

p = m2vf,2 = (50)(0.28) = 14Ns

*To calculate the conservation of energy:

1/2(50)(-0.34)2=2.89N

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1/2(50)(0.28)2=1.96N

To calculate the coefficient of restitution, we use the following formula: e=-(v2f-v1f)/(v2i-v1i) , where v2 refers to the velocity of ball 1 at y direction, v1 refers to the velocity of plane at y direction which is zero:

e = -(0.28-0)/(-0.35-0) = 0.8**

*The differences in these values will be explored in discussion

**I acknowledge that the coefficient of restitution should be 1 in an elastic collision, the result will be explored in the discussion

Conservation of energy: gravitational energy to kinetic energy and thermal energy

Analysis of results

m2 = 20kg

For the whole process is too long we took the period from 12.542s to 14.542s, which means that the Δt = 2s

To calculate the value of PE that change during the period:

Δy = (-0.51)-(-0.21) = -0.3m

PE = mgh = (20)(9.8)(0.3) = 58.8J

To calculate the value of KE that change during the period

*Δvy = (-0.234)-(0) = -0.234

KE = 1/2mv2 = 1/2(20)(0.234)2 = 0.54J

**TE = PE-KE = 58.26J

*The velocity of the ball 2 at the time of 12.542s is zero, the nonzero data comes from the plot is the result of relatively low precision of Tracker.

**I acknowledge the result seems improper, the result will be explored in the discussion

2. Conservation of momentum

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Analysis of results

*The collision happened during 11.25s to 11.417s

m_c = 20kg; m2 = 20kg

v_c = 0.52m/s

v2 = 0.2m/s

**To calculate the conservation of momentum:

PE = mcvc = (20)(0.52) = 10.4Ns

PE = m2v2 = (20)(0.2) = 4Ns

Because the masses are equivalent, as long as the velocity is equivalent, the momentum should be conserved.

*Collision should happen instantly. However, due to the precision of Tracker, the collision seems to be not happen spontaneously on two balls.

**The differences of these values will be explored in the discussion

3. Projectiles in 2-Dimension

Analysis of results

From the plot, the free fall starts from 4.625s and ends at 5.583s. So the Δt = 0.958s.

To calculate the horizontal velocity and the displacement:

*vx1 = 0.37m/s

x = (-0.12)-(-0.47) = 0.35m

To calculate the vertical velocity and the displacement:

For the velocity of the ball 1 in the y direction, I choose the velocity at the time just before the ball hit the plane, which is at 5.583s and the velocity is -0.34m/s.

vy = -0.34m/s

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y = (0.3)-(0.48) = -0.18m

*The fluctuating numbers are the result of relatively low precision of Tracker

4. Rotations

Analysis of results

As the curve's slope is continuing changing, so the centripetal acceleration and tangential acceleration is not constant. So, I choose one particular time—2.292s—to analyze.

r = 1m

m =50kg

To calculate the centripetal acceleration:

v1 = 0.41m/s

ac = v2/r = 0.17m/s

To calculate the tangential acceleration:

Because the data collected from Tracker is too disordered, I can only estimate the value of tangential acceleration by the velocity before and after 2.292s.

at = (0.425-0.383)/(2.333-2.25) = 0.5m/s2

5. Torque

Analysis of results

m2 = 20kg m3 = 0.5kg

According to the video, the collision happen at 29.250s.

a2 = 0.39m/s2 a3 = -1.72m/s2

To calculate the forces between the lever and each of the ball:

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F2 = m2a2 = (20)(0.39) = 7.8N

F3 = m3a3 = (0.5)(-1.72) = 0.86N

*To calculate the torque:

l2 = 0.125m   l3 = 0.16m

Torque = F2l2 = 0.98N * m

Torque = F3l3 = 0.14N * m

*The torque should be conserved here. The difference of the values will be explored in the discussion.

6. Discussion

Inelastic collision

The inelastic collision in my Rube Goldberg machine is the collision between the ball 1 and plane 2. The ball 1 falls from the upper track to the plane which can be considered as free fall. For the plane is horizontal, the velocity in the x direction can be negligible during the analysis. Just before the collision, the ball 1 has a vertical velocity of 1m/s and thus its KE is 25J. After the collision, the vertical velocity becomes zero, which means that the velocity difference between the tall 2 and the plane in the y direction is zero for the plane is static. The velocity difference changes during the collision, thus the collision is inelastic collision.

From the video, the velocity of the ball 1 in y direction is indeed zero, for it moves along the plane which is horizontal. However, from Tracker, the value seems to be fluctuating around zero. After examining the whole process, I believe this is caused by the insufficient precision of Tracker and the flaw of auto-tracking. The auto-tracking is functioned by searching for the matched color of the object frame by frame to track an object's movement, which can cause the fluctuating position of the ball for the tracking point can be varied on the ball's surface.

I acknowledge that in an inelastic collision, though KE is not conserved, momentum is. However, according to the video and the analysis, the momentum doesn't conserved. This is because the special features in Blender that can't reflect the texture and the subtle movement physically, which cause the simulation to be a little unrealistic.

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Elastic collision

The elastic collision in my Rube Goldberg machine is the collision between the ball 1 and the plane 1. The ball fall from the curve to the plane 1 which can be considered as free throw. For the plane is horizontal, the velocity in the x direction can be negligible during the analysis. The velocity vs. time graph shows clearly that at 5.8s, the velocity experiences sudden change from negative to positive, which marks the happening of collision. The velocity in y direction before collision is -0.35m/s, which is slightly different from 0.28m/s which is the velocity after the collision.

In an elastic collision, the momentum and energy should be both conserved. However, in my calculation, the values of momentum and KE before and after the collision have differences that can't be negligible. The momentum of the ball 2 before the collision is -17Ns, while the momentum after the collision is 14Ns. Also, KE is 2.89N before and 1.96N after. So we can calculate out the coefficient of restitution which is 0.8. Actually, from the velocity difference before and after the collision, it can be inferred that the momentum and KE can't be conserved for at least on of them due to the transformation of the formula.

The reason that cause this to have is still the fundamental of Blender. Even I have set "bounciness"—the setting that control the elasticity—to maximum, still the collision won't be a perfectly elastic collision and the coefficient of restitution can never reach 1. I contact one of their supporters and he said that the reason of this is that Blender tries to reflect the Physics in the real world where an perfectly elastic collision can rarely happen. So the elastic collision is unable to achieve in Blender and a collision, in which the coefficient of restitution is 0.8, is the most proximate one.

Conservation of energy

The conservation of energy in my Rube Goldberg machine happens during the ball 2 sliding down along the track. During the process, as the ball goes down, the gravitational energy of the ball decreases for, due to my calculation, 58.8J. For the energy must conserve, so the gravitational energy should convert into other types of energy. The first type is kinetic energy, which increases as the ball speeds up during the way down. According to my calculation, the KE for the ball 2 has increased for 0.54J. The second type is thermal energy. The friction between the ball and the slope generates heat while sliding, which generate thermal energy both to the ball and to the slope. The thermal energy increases for 58.26J, which is the difference between the PE and KE.

The extreme difference between the PE and KE seems confusing. These strange values is due to the high friction coefficient of the slope. The friction force exerting on the ball is so big that the ball almost moves uniformly. As a result, the kinetic energy for the ball 2 only increase for little while most of the gravitational energy converts into thermal energy.

Conservation of momentum

The conservation of momentum in my Rube Goldberg machine happens during the chain ball hits the ball 2 and makes the ball 2 to slide down. During the process, the chain ball becomes static after hitting the ball 2 and the ball 2 move from static and slide down the slope. The momentum of two balls should be conserved. For the masses of the two balls are the same—20kg, the velocity of two balls should be same in number but reverse in direction. According to my calculation, the velocity of the chain ball before the collision is 0.52m/s and the momentum is 10.4 Ns, while the velocity of the ball 2 after the collision is 0.2m/s and the momentum is 4Ns.

The momentum doesn't conserve due to the calculation. Through further analysis, I discovered that after the chain ball hit the ball 2, the chain that connect the ball will break apart. I believe that the lost momentum during the collision have contributed to the breaking of chains which costs about 6.4Ns of momentum.

The ball 2 after collision seems to go reversely and drop to the plane 2, this is affected by the breaking of chains which may collide with the ball and make it move, so the movement after the collision can be negligible.

Projectile in 2-dimensions

The projectile in 2-dimensions in my Rube Goldberg machine happens during the ball 1 drop from the curve to the plane 1. Before the collision, we can consider the falling process as free throw. During the free throw, there isn't any force exert on the ball 1 in x direction, so the ball moves uniformly in the horizontal direction. Nevertheless, in y direction, the gravitational force exert on the ball 2 and makes the ball accelerate vertically with an acceleration of 9.8m/s2.

The horizontal displacement during the free throw is 0.35m and the velocity is constantly at 0.37m/s, which can be used to calculate the time duration of the free throw, which is 0.95s. The vertical displacement is -0.18m while the velocity just before the collision is -0.34m/s.

However, we can see that the vertical velocity of the ball is much less than the ideal value which should be (0.95)(9.8) = 9.31m/s, so as the displacement. The reason of this has been introduced previously that Blender aims to reflect the real physics world, where rarely has any places where the air resistance can be negligible. So the simulation in Blender include air resistance which cause the acceleration to be lower than expected.

Rotation

The rotation in my Rube Goldberg machine is the ball 1 moves along the curve. The ball 1 moves from static on the top of the curve and slide down the curve with an acceleration. The curve is a quarter circle which makes the rotation a circular rotation. For the rotational speed isn't constant, I pick out one set of data to analysis.

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For the centripetal acceleration, I use the formula ac = mv2/r to calculate. At the time I pick out—2.292s, the velocity of the ball is 0.41m/s, which leads to the result of centripetal acceleration—0.17m/s.

For the tangential acceleration, I tried to use Tracker to directly track the values. However, in a circular rotation, Tracker seem to have trouble generating the valid data that can be used in my analysis. As a result, I can only use the speed of the ball 1 before and after the particular time to estimate the tangential acceleration, which is 0.5m/s2. Though the value may be not so accurate, this seems the only way to calculate the tangential acceleration.

The curve is a quarter circle, which means that the ball 1 only participate in a quarter of a complete rotation. After the ball goes out of the curve, its direction of velocity is horizontal and it can conduct the following motion of free throw.

Torque

The torque in my Rube Goldberg machine happens when the ball 2 hits the lever, making the static ball 3 to move. The ball 2 slides down through the slope and gains an initial velocity. When the ball 2 hits the lever, the lever rotate and exert force on the ball 3 to make it move. To analyze the torque of the lever, the force that the ball 2 exerts on the lever and the force lever exerts on the ball 3. To calculate that, I track the acceleration of the two balls and pick out the accelerations of both balls at the time of collision—29.25s. The acceleration for the ball 2 is 0.39m/s2 and the acceleration for the ball 3 is -1.72m/s2. So, both of the forces can be known: 7.8N and 0.86N. Then, combined with the length of the lever on each side, the torque can be calculated.

For the conservation of torque, the values of torque calculated through both sides should be the same. However, the torque is not conserved, with a difference of 0.84N*m. The reason for the difference is that the precision of the data from Tracker inn insufficient. The actual time of the collision is earlier than the time we used to calculate, but the scale division is too large that the exact data from the point of collision can’t be collected. Thus, the values are not so precise.

Conclusion

In order to build the machine that met all the constraints, I made the first craft of the machine. I used to think that making the first plan is the most difficult thing, and all I need to do after making the plan is just following it. However, when I try to convert my plan into the real machine, it is difficult then I have expected. I kept finding new problems and have to fix them time by time. I have made tens of modifications to my original plan which is now completely different from my machine. Every adjustment I made and every obstacle I encountered have never been thought by me. From this time, I realize that the plan that made in my mind doesn’t always can be so perfectly executed. I need to out the plan into practice so that I can discover the flaws in my ideas instead of working by only mere thinking.

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Also, I find out that during an experiment, there are always many interference factors to prevent you from getting the ideal data. The air resistance, the friction, the insufficient precision of the measurement, which can all cause the errors that don't consistent with the principle. Nevertheless, these errors should be considered as one part of the experiment because they are inevitable. Few experiment can produce ideal data and I should include those flawed data in the report with proper explanation, but not to falsify the data to the ideal circumstances. The authenticity of the report are extremely important for the experiment and the errors help me to develop other possibilities.

References

[1] Zhang yinman. Sports injuries and preventive measures in police unarmed defense and control training. public security education, no. 7, pp. 36-40, 2016.

[2] Wei Jie. On unarmed defense control training in police colleges. Contemporary Sports Science and Technology, vol. 6, no. 16, pp. 15-15, 2016.

[3] Liu Tao, Mou Xiaodong, Leng Qiyan, et al. Investigation on an outbreak of human brucellosis in Yantai City, Shandong Province. Chinese Journal of Local Epidemiology, vol. 38, no. 4, pp. 310-312, 2019.

[4] Luo Liang. Discussion on the Characteristics of Taijiquan Skill to Improve Police's Unarmed Defense and Control Ability. Science Mass (Science Education), vol. 000, no. 3, pp. 164-164,180, 2015.

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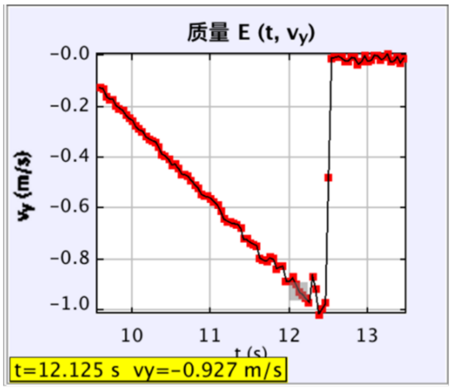

Fig.1.1, velocity in the y direction vs. time for the ball 1

t (s)	y (m)	vy (m/s)
11.625	-0.694	-0.794
11.667	-0.727	-0.802
11.708	-0.761	-0.804
11.750	-0.795	-0.791
11.792	-0.827	-0.797
11.833	-0.861	-0.835
11.875	-0.896	-0.827
11.917	-0.930	-0.824
11.958	-0.965	-0.886
12.000	-1.004	-0.884
12.042	-1.039	-0.869
12.083	-1.076	-0.893
12.125	-1.113	-0.927
12.167	-1.153	-0.936
12.208	-1.191	-0.951
12.250	-1.233	-0.967
12.292	-1.272	-0.864
12.333	-1.305	-0.913
12.375	-1.348	-1.013
12.417	-1.389	-0.991
12.458	-1.430	-0.971
12.500	-1.470	-0.480
12.542	-1.470	-9.049...
12.583	-1.471	-4.965...
12.625	-1.471	-3.139...
12.667	-1.471	-7.415...

Fig.1.2, tie and corresponding y coordinates and velocity

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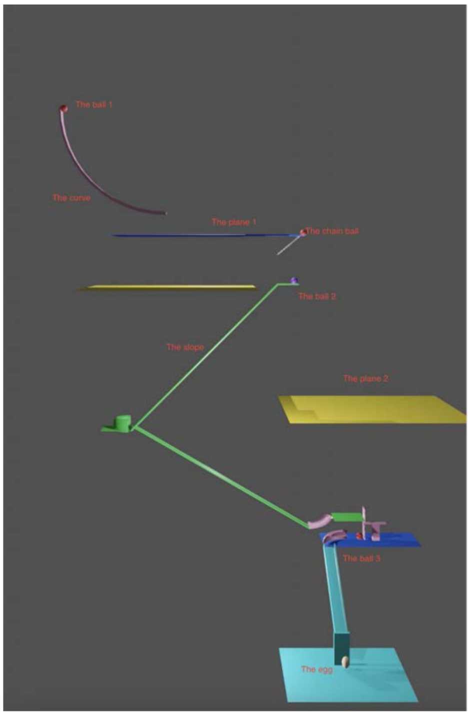

Fig, design of my Rube Goldberg machine

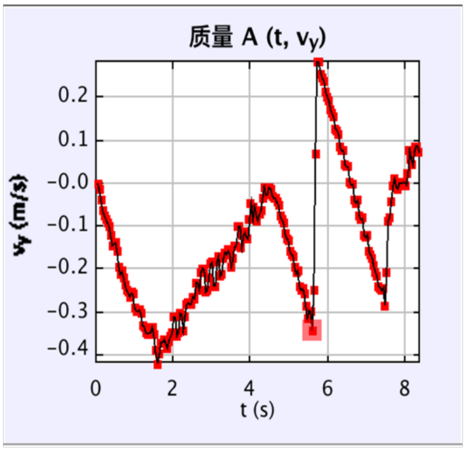

Fig.2.1, velocity in the y direction vs. time for the ball 1

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t (s)	y (m)	vy (m/s)
5.292	0.384	−0.247
5.333	0.374	−0.245
5.375	0.363	−0.255
5.417	0.353	−0.285
5.458	0.340	−0.315
5.500	0.326	−0.297
5.542	0.315	−0.298
5.583	0.301	−0.342
5.625	0.286	−0.249
5.667	0.281	6.862E−2
5.708	0.292	0.286
5.750	0.305	0.283
5.792	0.316	0.256
5.833	0.326	0.246
5.875	0.336	0.239

Fig.2.2, time and corresponding y coordinates and velocity

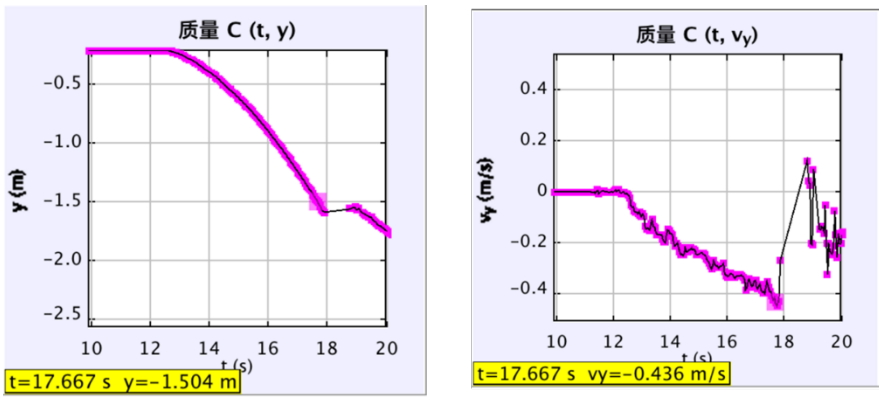

Fig.3.2, position in the y direction vs. time

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t (s)	y (m)	vy (m/s)
12.333	−0.209	-6.459E-4
12.375	−0.209	-8.923E-3
12.417	−0.209	-4.695E-3
12.458	−0.209	-8.324E-3
12.500	−0.210	-1.371E-2
12.542	−0.210	-2.132E-2
12.583	−0.212	-5.286E-2
12.625	−0.215	-5.953E-2
12.667	−0.217	-5.794E-2
12.708	−0.220	-7.327E-2
12.750	−0.223	-7.886E-2
12.792	−0.226	-8.069E-2
12.833	−0.230	-8.429E-2
12.875	−0.233	-7.848E-2
12.917	−0.236	-9.080E-2
12.958	−0.241	-9.706E-2
13.000	−0.244	-8.448E-2
13.042	−0.248	-9.650E-2
13.083	−0.252	−0.134
13.125	−0.259	−0.148
13.167	−0.265	−0.142
13.208	−0.271	−0.143
13.250	−0.276	−0.151
13.292	−0.283	−0.123
13.333	−0.287	−0.110
13.375	−0.293	−0.135
13.417	−0.298	−0.138
13.458	−0.304	−0.154
13.500	−0.311	−0.168
13.542	−0.318	−0.170
13.583	−0.325	−0.167
13.625	−0.332	−0.168
13.667	−0.339	−0.170
13.708	−0.346	−0.183
13.750	−0.354	−0.196
13.792	−0.362	−0.199
13.833	−0.371	−0.176
13.875	−0.377	−0.148
13.917	−0.383	−0.152
13.958	−0.390	−0.163
14.000	−0.397	−0.162
14.042	−0.403	−0.169
14.083	−0.411	−0.192
14.125	−0.419	−0.213
14.167	−0.428	−0.208
14.208	−0.437	−0.200
14.250	−0.445	−0.214
14.292	−0.454	−0.233
14.333	−0.465	−0.247
14.375	−0.475	−0.244
14.417	−0.485	−0.249
14.458	−0.496	−0.240
14.500	−0.505	−0.219
14.542	−0.514	−0.237
14.583	−0.525	−0.234
14.625	−0.534	−0.226

Fig.3.3, time and corresponding y coordinates and velocity

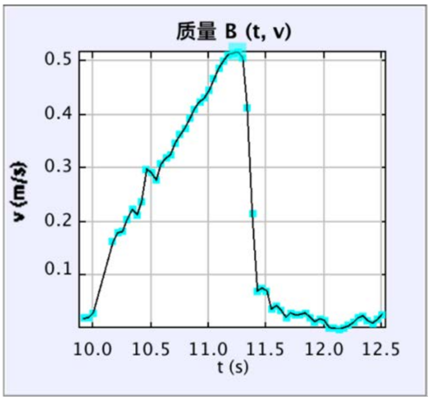

Fig.4.1, velocity vs. time for the chain ball

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t (s)	v (m/s)
10.250	0.185
10.292	0.205
10.333	0.223
10.375	0.215
10.417	0.238
10.458	0.299
10.500	0.292
10.542	0.278
10.583	0.308
10.625	0.319
10.667	0.326
10.708	0.349
10.750	0.364
10.792	0.376
10.833	0.394
10.875	0.412
10.917	0.425
10.958	0.431
11.000	0.446
11.042	0.468
11.083	0.487
11.125	0.502
11.167	0.513
11.208	0.516
11.250	0.519
11.292	0.507
11.333	0.414
11.375	0.215
11.417	7.116E-2
11.458	7.689E-2
11.500	7.137E-2
11.542	3.790E-2
11.583	4.446E-2

t (s)	vy (m/s)
11.083	-1.868E-4
11.125	1.756E-5
11.167	8.350E-5
11.208	-7.718E-4
11.250	-1.039E-3
11.292	-1.901E-4
11.333	-4.053E-3
11.375	2.774E-3
11.417	7.197E-3
11.458	-6.764E-3
11.500	-3.233E-3
11.542	3.153E-3
11.583	3.097E-3
11.625	3.364E-3
11.667	-4.022E-4
11.708	1.690E-4
11.750	2.520E-4
11.792	-1.755E-3
11.833	-1.079E-3
11.875	7.927E-4
11.917	1.177E-3
11.958	-1.394E-3
12.000	2.187E-3
12.042	8.445E-3
12.083	3.902E-4
12.125	6.881E-3
12.167	7.372E-3
12.208	-3.399E-3
12.250	-4.279E-3

Fig.4.3, time and corresponding velocity for the chain ball

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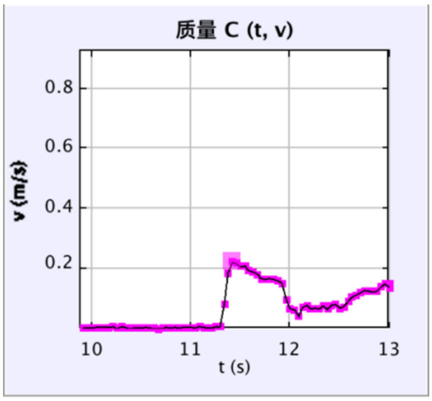

Fig.4.4, time and corresponding velocity for the ball 2

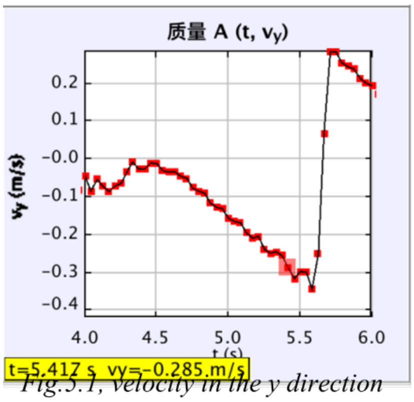

Fig.5.1, velocity in the y direction vs. time for the ball 1

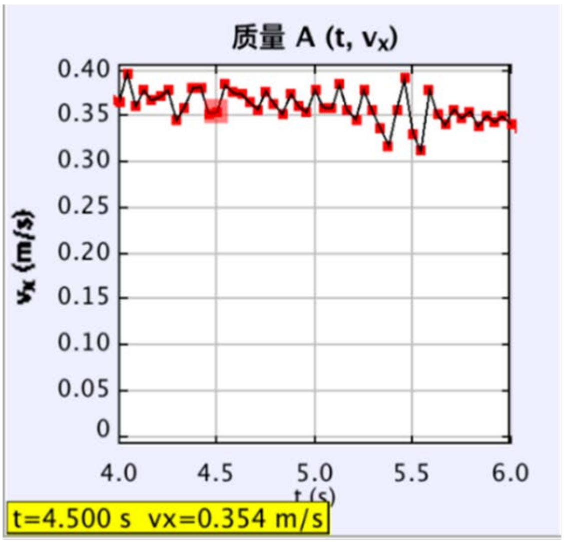

Fig.5.2, velocity in the x direction vs. time for the chain bank

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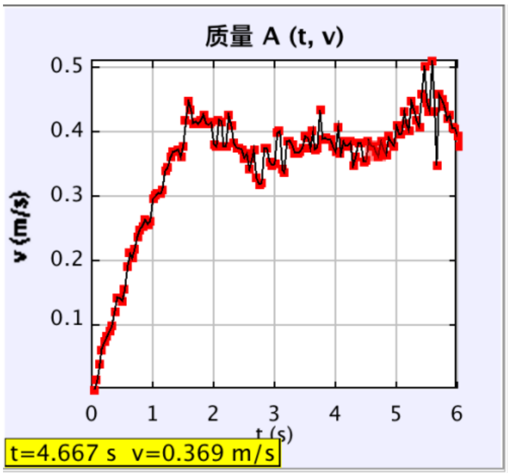
t (s)	y (m)	vy (m/s)
4.292	0.482	-3.355...
4.333	0.481	-7.350...
4.375	0.482	-2.519...
4.417	0.479	-2.645...
4.458	0.480	-9.139...
4.500	0.478	-1.157...
4.542	0.479	-2.860...
4.583	0.476	-3.318...
4.625	0.476	-3.376...
4.667	0.473	-4.354...
4.708	0.472	-5.098...
4.750	0.469	-7.527...
4.792	0.466	-8.378...
4.833	0.462	-8.934...
4.875	0.459	-0.116
4.917	0.452	-0.127
4.958	0.448	-0.131
5.000	0.441	-0.156
5.042	0.435	-0.164
5.083	0.428	-0.168
5.125	0.421	-0.194
5.167	0.411	-0.208
5.208	0.404	-0.204
5.250	0.394	-0.238
5.292	0.384	-0.247
5.333	0.374	-0.245
5.375	0.363	-0.255
5.417	0.353	-0.285
5.458	0.340	-0.315
5.500	0.326	-0.297
5.542	0.315	-0.298
5.583	0.301	-0.342
5.625	0.286	-0.249
5.667	0.281	6.862E-2
5.708	0.292	0.286

Fig.5.3, time and corresponding y coordinates and velocity

t (s)	x (m)	vx (m/s)
4.292	-0.591	0.346
4.333	-0.576	0.360
4.375	-0.561	0.381
4.417	-0.544	0.382
4.458	-0.529	0.353
4.500	-0.514	0.354
4.542	-0.500	0.385
4.583	-0.482	0.376
4.625	-0.468	0.375
4.667	-0.451	0.366
4.708	-0.438	0.358
4.750	-0.421	0.378
4.792	-0.406	0.364
4.833	-0.391	0.353
4.875	-0.377	0.375
4.917	-0.360	0.362
4.958	-0.347	0.355
5.000	-0.330	0.379
5.042	-0.315	0.361
5.083	-0.300	0.359
5.125	-0.285	0.385
5.167	-0.268	0.357
5.208	-0.255	0.347
5.250	-0.239	0.379
5.292	-0.224	0.357
5.333	-0.209	0.338
5.375	-0.196	0.318
5.417	-0.183	0.358
5.458	-0.166	0.392
5.500	-0.150	0.332
5.542	-0.138	0.313
5.583	-0.124	0.379
5.625	-0.107	0.353
5.667	-9.46...	0.341
5.708	-7.81...	0.358

Fig.5.4, time and corresponding x coordinates and velocity



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t (s)	v (m/s)
1.542	0.417
1.583	0.447
1.625	0.434
1.667	0.414
1.708	0.416
1.750	0.412
1.792	0.418
1.833	0.427
1.875	0.414
1.917	0.411
1.958	0.415
2.000	0.381
2.042	0.377
2.083	0.418
2.125	0.416
2.167	0.377
2.208	0.378
2.250	0.425
2.292	0.411
2.333	0.383
2.375	0.376
2.417	0.375
2.458	0.373
2.500	0.360
2.542	0.366
2.583	0.342
2.625	0.357
2.667	0.372
2.708	0.328
2.750	0.319
2.792	0.320
2.833	0.374
2.875	0.374
2.917	0.354
2.958	0.349

Fig.6.2, time and corresponding velocity

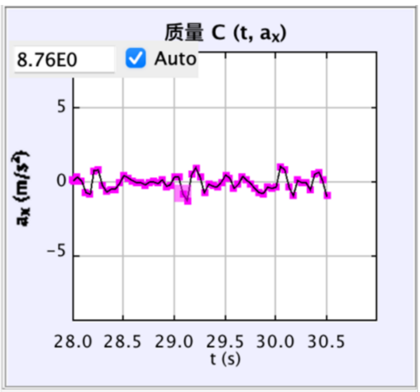

Fig.7.1, acceleration in the x direction vs. time for the ball 2

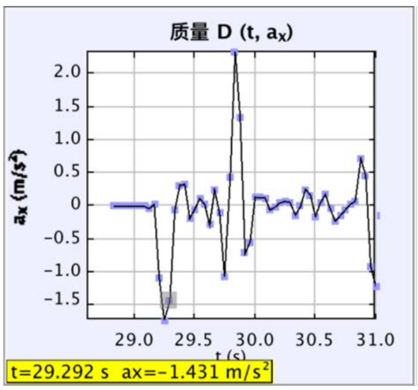

Fig.7.2, acceleration in the x direction vs. time for the ball 3

t (s)	ax (m/s²)
28.292	-0.226
28.333	-0.625
28.375	-0.460
28.417	-0.437
28.458	-4.227E-2
28.500	0.460
28.542	0.305
28.583	0.133
28.625	7.309E-3
28.667	-3.376E-2
28.708	-0.152
28.750	2.550E-2
28.792	4.632E-2
28.833	-4.117E-2
28.875	0.160
28.917	-0.251
28.958	-0.172
29.000	0.346
29.042	0.377
29.083	-0.800
29.125	-1.215
29.167	0.533
29.208	0.980
29.250	0.385
29.292	-0.686
29.333	-0.124
29.375	-0.242
29.417	-0.288
29.458	3.325E-2
29.500	0.519

Fig.7.3, time and corresponding acceleration in the x direction for the ball 2

t (s)	ax (m/s²)
29.083	0.000
29.125	-4.117E-2
29.167	3.230E-2
29.208	-1.084
29.250	-1.718
29.292	-1.431
29.333	-5.591E-2
29.375	0.321
29.417	0.328
29.458	-0.191
29.500	-5.064E-2
29.542	0.117
29.583	2.918E-2
29.625	-0.280
29.667	0.239
29.708	-0.100
29.750	-1.064
[illegible]	[illegible]

Fig.7.4, time and corresponding acceleration in the x direction for the ball 3

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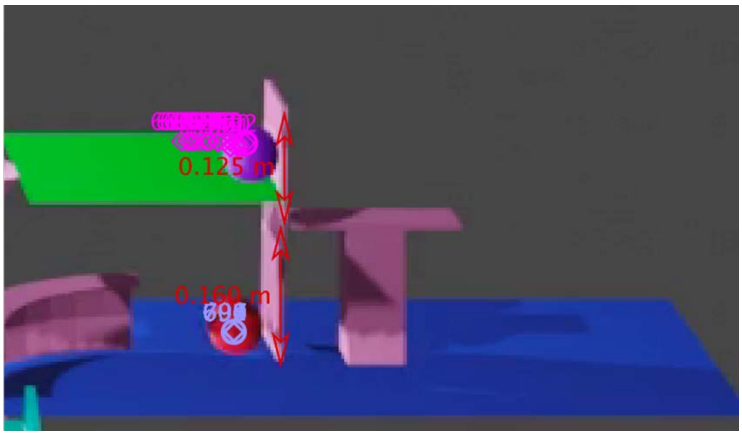

Fig.7.5, the displacement of two part of the lever