Escape from Colditz Castle

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Introduction

Colditz Castle was a German prison camp during the Second World War. The castle was an ideal prison because it was located on a rocky outcrop, and had walls up to seven feet thick. Because of this, the prison was home to many prisoners who had previously attempted escapes from other POW camps. In 1945, a group of British prisoners led by Bill Goldfinch and Jack Best hatched a plan to escape by building and launching a glider off of the roof of the castle. The photo above (Figure 1) depicts the castle during World War II. The roof where the glider was to be launched is circled in red.

Goldfinch and Best found a book on aircraft design in the prison library, which they used to help them design the glider. The glider was constructed in a hidden attic room from materials they could find in the castle—bed sheets, floorboards, even porridge stolen from the mess hall (Figure 2). The plan was to use a pulley system to launch the glider off of the roof of the castle, and land in a nearby field.

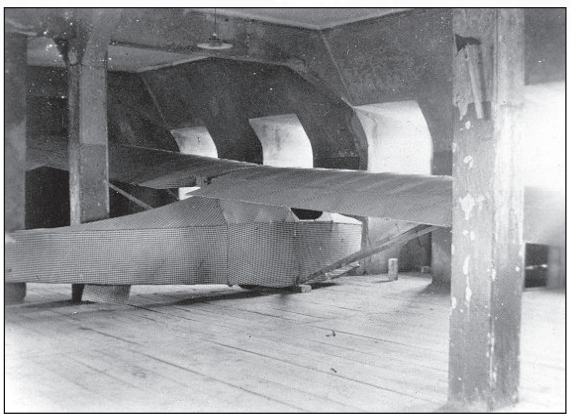


Figure 2. The only known photograph of original glider.

On April 16, 1945, American troops invaded the castle and freed the prisoners; they never had a chance to test their glider. Recently, a group of engineers decided to build a glider using materials that would have been available to the prisoners. Fortunately, Goldfinch had kept the plans, so they were able to reconstruct the glider with the same dimensions as the original. The goal was to test whether or not the prisoner's escape plan was possible.

The prisoner's original plan was to use a pulley system, with a bathtub as a counterweight to accelerate the glider along the roof (Figure 3). The bathtub would then release when it hit the ground, and the glider would continue off the roof, launched horizontally into the air. The prisoners would land in a field on the other side of a stream that ran around the castle grounds.

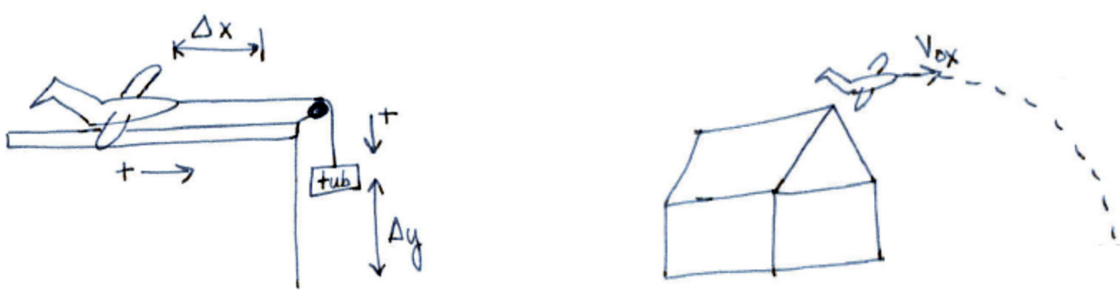


Figure 3. A schematic diagram of the escape plan. The tub would act as a counterweight to drag the glider to the edge of the castle roof (left), and then launch it into the air (right).

Part I – Planning for the Escape

Imagine you are part of the team of engineers who wants to recreate this escape attempt. The first thing the team does is to build a mathematical model to predict the motion of the glider. This includes both the motion before the launch of the glider (when the bathtub is dragging it along the roof), and the motion after the glider has launched in order to predict where it will land.

Questions

1. Look again at the schematic diagram of the escape plan (Figure 3). We want to convert this visual representation into a mathematical model. What fundamental principles of physics will you use to build your model?

2. What additional information do you need to begin building your mathematical model?

3. What assumptions are made in using these mathematical models?

Part II – Is It Even Possible?

One way that mathematical models are used by scientists and engineers is to make predictions about how a system will behave. In the video, the engineers use a simple kinematics model to predict how much the glider would need to accelerate as it is pulled along the runway in order to launch. Based on the aerodynamics of the glider, the engineers calculated it would need to reach a speed of 40 mph to successfully launch into the air.

The roof is 160 feet above the ground, and the runway (built from tables on top of the peak of the roof) was about 60 feet long. The first question the engineers need to figure out is if it is theoretically possible to reach the desired launch speed given the length of the runway and the height of the tower.

Questions

1. Given this information, what must the acceleration of the glider be to reach the launch velocity by the end of the runway? (Convert all values to SI units.)

2. The engineer wants the glider to accelerate at a rate of 1.2g (11.6 m/s^2). How does this compare to your result? Why would the engineer over-estimate the acceleration?

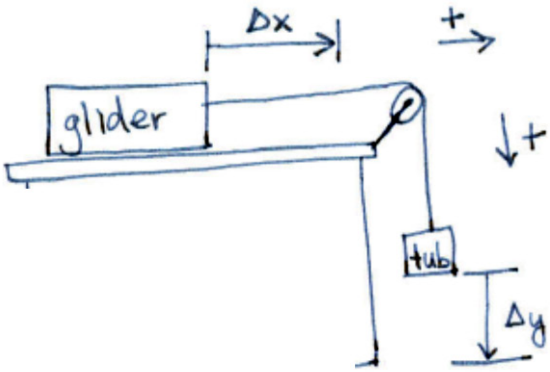
To see if this acceleration can be reached by the actual system, the engineers in the video conduct an experiment using a scale model of the glider system. In the scale model, they launch a piece of wood covered in fabric from a height of about 30 feet, using a bathtub full of water as the counterweight.

The result of this test shows that they did not reach the acceleration they had hoped for. Now the engineers are faced with a problem: they must find a new way to launch the glider so that they can reach the desired speed and acceleration. They are forced to revise both the parameters of the experiment and their mathematical models.

Questions

3. Is it possible for the bathtub to accelerate at $1.2g$? Explain why or why not. If it is not possible, how could you modify the system to generate this acceleration?

4. Why would they use a scaled-down model to test their ideas? What are the benefits of this approach? What are the limitations of this model?



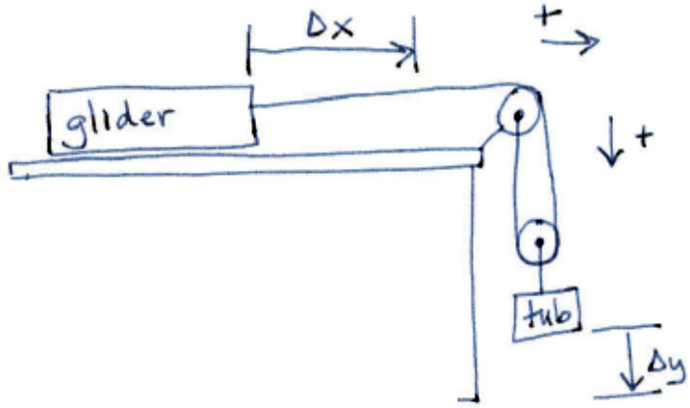


Figure 4: Diagrams of the single and double pulley systems. Note that the distance traveled by the glider and the tub is the same in the single pulley system (left), but in the double pulley system (right) the glider moves twice as far as the tub.

Questions

5. The engineers' solution to this problem was to use a double pulley system (see Figure 4). Using this system, the distance traveled by the bathtub is half the distance traveled by the glider. What does this tell us about the acceleration of the glider relative to the tub?

6. What is the height that the bathtub must fall in order for the glider to reach the desired launch velocity? How does this compare to the height of the castle roof? Will the glider reach 40 mph before launch?

Part III – We Need More Speed!

The engineers find that even with the double pulley system, the glider is not reaching the desired acceleration. Their solution is to reduce the friction on the runway.

Questions

1. What effect will reducing the friction have on the speed and acceleration of the glider? Explain your answer using a free body diagram.

2. Assume that the coefficient of static friction for the glider sliding on wood is 0.4. What tension force must be applied to overcome the static friction?

3. Once the glider starts moving, the coefficient of friction drops to 0.2. What tension force must be applied to the wood to reach the desired acceleration?

4. What mass of bathtub does this correspond to? (Hint: first draw a free body diagram of the tub and write Newton's Second Law.)

5. A typical bathtub has a volume of 0.16 m^3. The density of water is 1000 kg/m^3 and for concrete can range from 2400 kg/m^3 to 3500 kg/m^3. Assume the mass of the empty tub is 100 kg. Can the tub filled with water produce the required tension? Use the above information to justify your answer.

6. The engineer then reduces the amount of friction in the system by covering the runway with sheets of metal. Wood on metal has a coefficient of static friction of about 0.2, and a coefficient of kinetic friction that is close to zero. Will this solve the problem? Justify your answer using calculations and/or free body diagrams.

Part IV – Success?

After revising their launch plan several times, the engineers are read for launch! Due to safety reasons, they do not fly the glider themselves, but decide to test the glider with a radio control system and a dummy which simulates the weight of a person. The launch day is quite windy, and it looks like a storm is rolling in. They are delayed by a problem with a motor in the radio control system, but finally they are ready for launch. In the end, the glider launches with a speed of 36 mph, which is less than they had hoped for, likely due to the windy day. Will the glider make it across the river to safety? We will now model the glider as a projectile in two-dimensional motion.

Questions

1. Assuming the glider acts like a simple projectile in free fall, how long will it take to reach the ground? Recall that the tower is 160 feet above the ground.

2. Assuming the glider acts like a simple projectile in free fall, where will it land?

3. In the real test, the glider landed in a field about 984 feet (300 m) from the castle wall. How does that compare to the distance you just calculated? What could account for any difference? How can you modify your model to account for these differences?

The glider does not act like a simple projectile in free fall because there are other forces acting on the system: drag, lift, and the force of the wind, in addition to gravity. These other forces will impact the acceleration of the glider in both the horizontal and vertical directions.

Questions

4. Draw a free body diagram of the glider while it is in flight.

5. If we assume the glider is actually in the air for 20 seconds, calculate the horizontal and vertical components of the acceleration.

6. Based on the acceleration you just calculated, find the magnitude of the lift force.

7. This glider has a lift-to-drag ratio of 12:1. Use this fact to calculate the magnitude of the drag force.

8. Finally, calculate the force of the wind acting on the glider. Did you draw it in the correct direction in your free body diagram?

9. What are the limitations of this mathematical model? How could we improve the model to better describe the path of the glider?