



Robird autonomous take-off: pneumatic launching system

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BSc Report

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Abstract

This thesis consists on the design, modelling and construction of an autonomous launching system for the Robird. The Robird is a robotic bird that is used for bird control in areas such as airports. A specialized pilot throws the robotic bird manually, but this is not always successful and it leads sometimes to crash. A solution to this problem is a launching mechanism that replaces this way of taking-off. Numerous different launching mechanisms for UAV or RC airplanes are available in the market such as bungee catapults, pneumatic launchers and even magnetic launchers. The system designed is a portable pneumatic launching ramp. A mathematical model describes what is the necessary take-off speed, airflow rate, angle of the ramp and force needed for the bird to take off and reach a certain height. Nevertheless, these models do not predict the lower height achieved by the Robird after performing experiments. The ultimate goal of achieving at least 3 meters in height is achieved by using a larger speed than calculated theoretically.

Acknowledgments

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1 Introduction

1.1 Bird Control

It is estimated that the air traffic will nearly double by 2035, [1] but also number of bird strikes against aircrafts will increase. The modern aircrafts can withstand impacts of small birds with no apparent damage, but larger birds can provoke extensive damage to the engine. Most of the bird strikes are near the ground, close to the airport. [2] There are different short term measures to reduce the amount of collisions such as firing a flare. Clear Flight Solutions is a company specialized in bird control. The company developed several long term bird control strategies. They developed a remotely controlled robotic bird of prey with a realistic appearance and weight, the Robird. This Robird has similar flapping frequency and speed w.r.t the nature counterpart, it can reach speeds up to 60 km/h. The Robird intimidates the other birds as the nature counterpart, the bird population understands that it is a dangerous hunting territory and will leave the area. [3] Currently, CFS is also working in other larger and heavier prototypes the sea gull and a bald eagle. These prototypes are still under development and testing.

Currently the Robird has no automatic take-off mechanism, it is thrown in a straight line. Therefore specialized and trained pilots are needed for such action. The possibilities of a successful take-off is low, because the method is not completely reliable, this can cause the Robird to crash and cause damage to the robot.

The goal of this bachelor assignment is to design and construct a autonomous launching ramp that will successfully launch the Robird into the sky.



Figure 1: Robird [3]

1.2 Robird and aerodynamics

1.2.1 Lift, Drag and Moment

The Robird consists of two wings with a body and a tail, a similar design that of an aircraft. The cross-sectional shape obtained by intersecting a plane in the perpendicular direction of the wing, shown in figure 2 is called an *airfoil*. The most forward point is called the *leading edge* and the most rearward point, the *trailing edge*. The straight line between the leading and trailing edge is called the *chord* given by the letter c . [4] In Figure 3 the airfoil is shown.

Figure 4 shows an inclined airfoil w.r.t the relative wind V_∞ . The free stream velocity or relative wind is the velocity of the wind far upstream. The angle between the chord line and the relative wind is defined as the *angle of attack*, α . There is a total pressure and shear stress distributions over the shape of the airfoil creating a resulting aerodynamic force R . This force can then be resolved into two components, one parallel and one perpendicular. The force parallel to the direction of the relative wind is defined as Drag, D . The aerodynamic force perpendicular direction to the

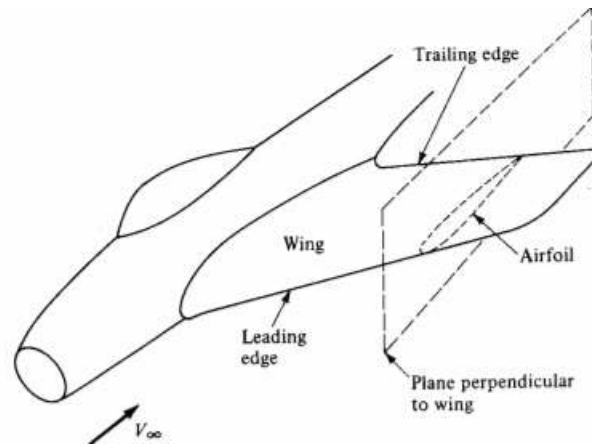


Figure 2: Sketch of an aircraft wing and airfoil [4]

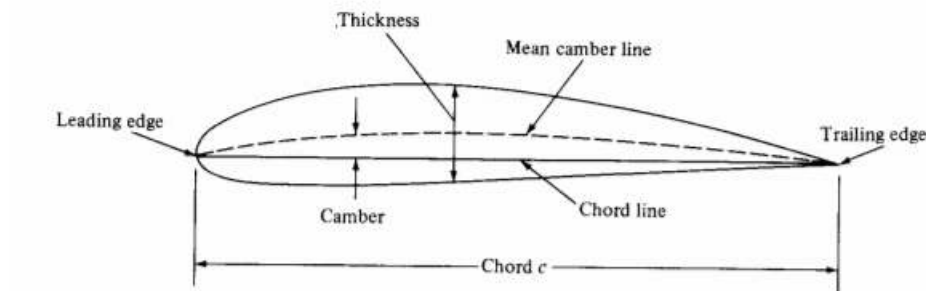


Figure 3: Sketch of an airfoil [4]

relative wind pointing in the upwards direction is defined as lift, L . In addition to the lift and drag, there is also a moment M produced by the surface and stress distributions that causes the wing to rotate. [4]

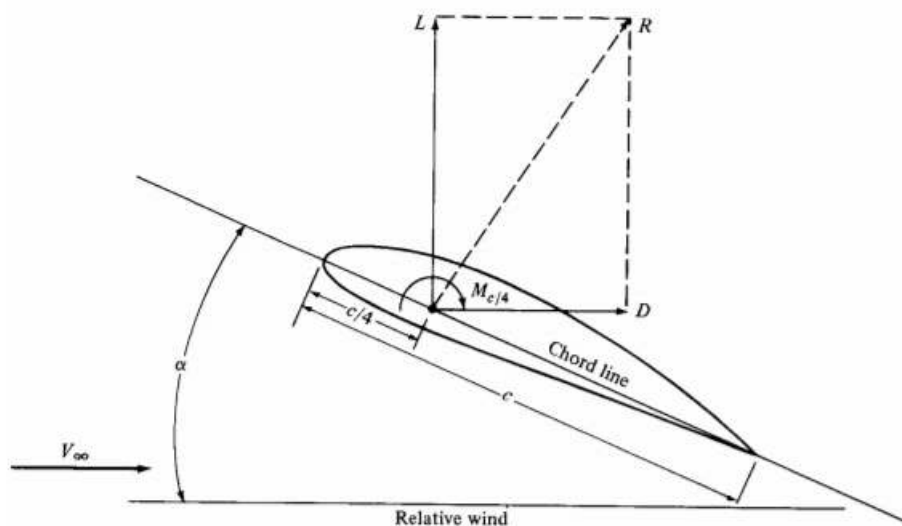


Figure 4: Airfoil at an angle of attack α [4]

1.2.2 Control surfaces

The three basic controls on an airplane, the ailerons, elevator and rudder, are designed to change and control the moments about the x,y and z axes. On the other hand, the spoiler is a device that intends to reduce lift of an airfoil in a controlled way, but also increasing the drag. [4] These control

surfaces are shown in Figure 5.

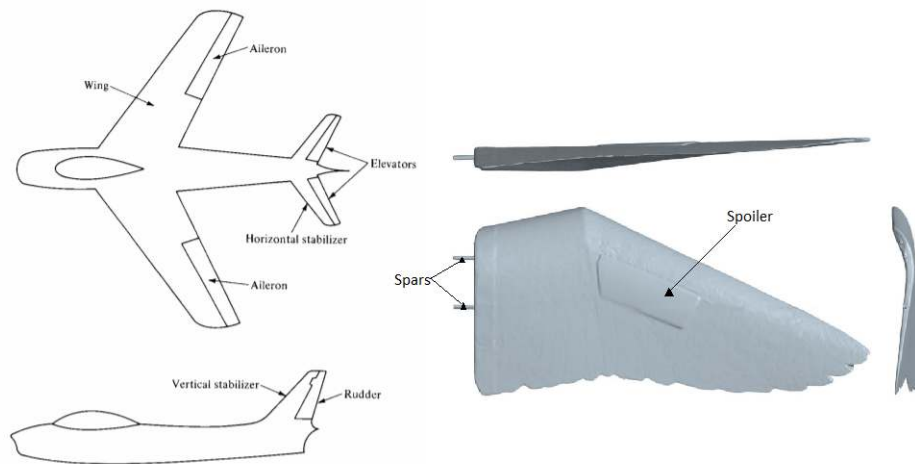


Figure 5: Control surfaces present in an aircraft and the wing of the Robird [4]

1.3 Current launching mechanisms

Nowadays, the Robird is launched by an experience pilot in a straight line and the only possibility to launch the Robird. Nevertheless, a group of high school students designed and developed a launching mechanism for the Robird. In which they used a simple spring mechanism to thrust the Robird into the air, but they did not develop any hooking mechanism for attaching the Robird to the ramp. The launching mechanism is shown in figure 6.



Figure 6: A bungee based Robird launching ramp developed by students

1.4 Requirements and Specifications

The requirements for this design are given by the pilots and technicians of Clear Flight Solutions (CFS) and are listed as follows:

1. **Gliding mode:** The Robird has two flight modes: flapping and gliding mode. In the flapping mode the Robird beats its wings. In contrast, when in gliding mode the wings of the Robird will be locked in a fixed position. The Robird should launch in gliding mode.

2. **Hooking mechanism:** In order to launch the Robird, the Robird itself should be hooked with some mechanism to the launching ramp. Since the wings are fragile and a force on the wings could cause a large moment, it is preferable to attach the Robird to the launching mechanism by the fuselage of the Robird.
3. **Larger prototypes:** It is preferable that the bald eagle and the gull could also use the launching ramp. These other two prototypes are larger and heavier than the Robird.
4. **Fixed parameters:** The launching ramp should have a fixed speed and angle which can be different for each prototype.
5. **Portability:** It should be portable, it should fit in a normal car. After arriving to the desired location, preparing the set-up should take no longer than 5 minutes.
6. **Large wind speeds:** It should work in wind speeds up to 11m/s.
7. **Operational temperature:** It should withstand temperatures ranging from -10 till 40 degrees Celsius.
8. **Weather resistant:** The structure should be resistant to dust and rain.
9. **Weight:** One person should be able to carry the mechanism but 2 people must be able to carry it.
10. **Velocity sensor:** The system should have a feedback mechanism for measuring the launch velocity.
11. **Minimum height:** In order for the Robird to start flapping and not crash after being launch a minimum height that the Robird should reach has been decided by the client. This minimum height is 3 meters with respect to the ground.

1.5 Aims and Approach

In order to design this launching ramp, the aerodynamics of the bird will be considered in gliding mode. The angle of attack, lift, drag and other concepts will be explained in detail in order to understand how does the Robird fly. These parameters have slightly changed due to the different shape of the Robird. Experiments are needed to determine whether this influences in a large amount the aerodynamics of the bird. In the case that the change is large and the calculations differ too much from reality, experiments will be carried in the wind tunnel where the new coefficient of lift, drag etc. will be determined. Furthermore, a mathematical model will be developed to simulate the necessary launching speed, necessary angle and what altitude will the Robird reach after being launched. The Robird must reach a certain altitude before it can start beating its wings and the pilots can take control.

This thesis is structured as follows: In chapter 2, the theory is explained, followed by a description of the device design in chapter 3. In chapter 4, the mathematical model is described, then chapter 5 describes the final product. In chapter 6, the experimental work is described and it's results are presented. The results are discussed in chapter 7 and finally the conclusions are given in chapter 8.

2 Theory

2.1 Aerodynamics fundamental relations

Reynolds number, mach number, lift , drag equations, aerodynamics efficiency

There are certain concepts that are crucial to the understanding of fluid flows, these are the dimensionless numbers. These dimensionless numbers are derived in order to compare different fluid flows around the same object, to compare whether these flows are similar. In our case, the

Reynolds number and the Mach number are important.

The Reynolds number is the ratio of inertial forces to viscous forces, it helps to predict whether the flows will be turbulent or laminar. [5] The Reynolds number is given by:

$$Re = \frac{\rho_{\infty} V L}{\mu_{\infty}} \quad (1)$$

Where ρ is the density of the surrounding air, V is the relative velocity, L is the characteristic length(for airfoils is the chord length) and μ is the dynamic viscosity. On the other hand the Mach number is the ratio between the relative velocity and the speed of sound. The Mach number is given by:

$$M = \frac{V}{c} \quad (2)$$

Where V is the relative velocity and c the speed of sound. Lift(L) and Drag(D) are two aerodynamics forces which depend of the Mach and Reynolds numbers, these are given by: [5]

$$L = \frac{1}{2} \rho_{\infty} S C_L \quad (3)$$

$$D = \frac{1}{2} \rho_{\infty} S C_D \quad (4)$$

Where ρ_{∞} is the density far away from the object, S is the area of the wing, C_L is the coefficient of lift and C_D is the coefficient of drag.

The coefficient of lift and drag of the wing and the body were calculated by S.Hartman in his master thesis. In his thesis, the coefficient of lift and drag of the wing and the body (together) is calculated experimentally by using the wind tunnel at the University of Twente. He calculated these coefficients in function of the Reynolds number, root section and angle of attack. Also, the Robird version used in his paper is different than the version currently used by CFS. [6] The values C_D and C_L serve as an approximation for this model. Nevertheless, the Robird expected to be used in the experiments is a paperboard body and tail made by us with a pair of old wings from an older version of a Robird attached to it. It seems likely that the coefficient of lift is much lower and the coefficient of drag much higher compared to the values found by S.Hartman. Therefore lower values of the lift coefficient and higher values of the drag coefficient have been used with up to a 30% difference w.r.t. the original value. Furthermore, when the Robird is in gliding mode the wings are locked at a negative angle of -3 degrees with respect to the body. This is an important consideration for the model.

Types of drag

There are different contributions to the total drag when measuring the drag on a (lifting) body in an airstream. The effects of viscosity on the body results in two different types of drag and another type of drag is produced due to lift. [5]

- **Pressure drag** is the component of the drag caused by the separation of the boundary layer from a surface. This causes a wake and this depends on the shape of the object.
- **Skin friction drag** is the drag caused by the viscosity of the air and the resulting friction against the surface of the body. This drag can be found by integrating the shear stress over the whole body.
- **Lift induced drag** is a component of the drag produced by the passage of a wing through air. The air flowing below the wing tends to go upwards due to the pressure on top is lower than the pressure below. Thus, at the tip of the wings the air tends to go in the upwards direction. Also the streamlines over the top surface tend to go to the root, and the streamlines below tend to go to the tip. This causes a circulatory motion that trails downstream at the end of the wings. A trailing vortex is created at each wing tip. Figure 7 shows this phenomenon.

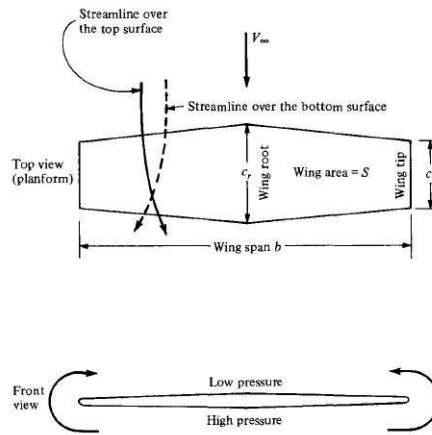


Figure 7: Finite wing showing the 3D aerodynamics effects [5]

2.2 Existing launching mechanisms

The different launching mechanisms that are used in RC airplanes and drones were researched. There are four main possibilities:

- Hand launch: is the most common mechanism used in R.C. planes. The plane should be pointing towards the wind and give it a firm push. This is also the current launching mechanism for the Robird.
- Bungee launch: a long elastic chord is pinned into the ground in one end. The aircraft has a hook in the bottom of the fuselage and the other end of the chord is attached to it, where there is also a small parachute. The chord is extended up to a certain length and then the aircraft is released, once the chord is loose it will slowly fall due to the parachute attached to it. See figure 8 a.
- Bungee catapult: this is a complete system that consists on having a platform where the aircraft is positioned. This platform is attached to a bungee cable which can be stretched up to a certain amount. There are many different models developed, such as X8 Catapult Bungee Rail Launcher see figure 8 b [7].
- Winch launching: similar to bungee launching, the aircraft is hooked by a long line. Nevertheless, this long line is reeled by a powerful winch.
- Pneumatic launch: mainly used for the launch of UAV's, this is based on a piston moving due to air pressure. It can be used for large and heavy drones due to the large power it can have. An example of this can be seen on figure 9 developed by UAV Factory Ltd [8].

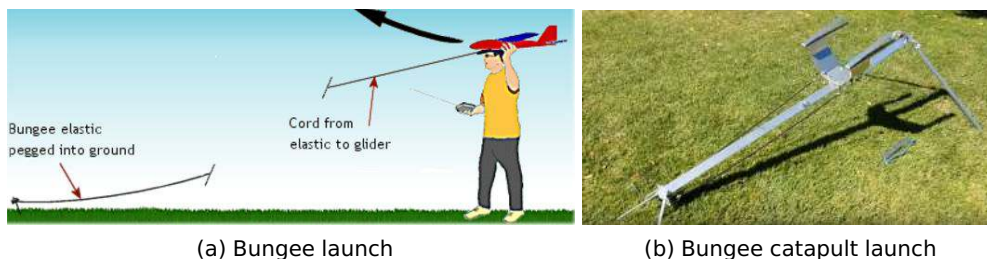


Figure 8: Two different bungee launch mechanisms in which figure a uses the force given by human strength and figure b uses an electrical winch to stretch the bungee. [7] [9]

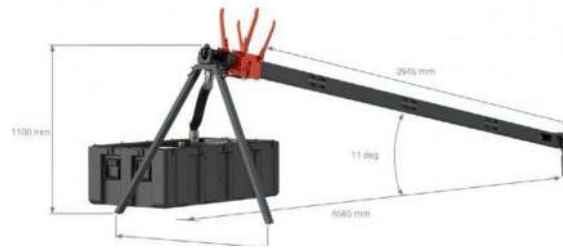


Figure 9: A Pneumatic UAV launcher that uses compressed air from an air tank to move a piston inside the air cylinder which in turn moves the UAV [8]

3 Concept design

The concept design was ideated depending on the different aspects that were considered important for this project. In this section an explanation of the choices made is shown.

3.1 Comparison of different launching mechanisms

The literature research showed different methods to launch the robotic bird: using the bungee method, a pneumatic system or even springs. These different methods are compared in many aspects and given one to five points, where 5 is the best and 1 is the lowest. It is assigned a weight from 1 to 3 to each of these aspects depending on the importance of it and the opinion of the client. Throughout the report the same type of weight table is shown, with the same scoring system. This comparison can be seen in table 1

Table 1: Different launching systems comparison

	Weight	Bungee with electrical winch	Pneumatic piston	Springs
Weight	3	5	4	4
Cost	1	5	3	5
Size, foldability	3	5	3	2
Easy to mount	3	4	4	4
Durability	3	2	5	3
Consistency	3	2	4	2
Automotion	3	5	5	1
Safety	2	3	4	3
Total		27	30	24
Total with weight		80	86	59

Weight

The weight of the system is an important aspect because one person should be able to carry it or a maximum of 2. Therefore we compared the different launching ramps in base of their materials needed and their respective weight. The one that scored the best is the bungee with electrical winch combination, since the bungees are lightweight and the the electrical winch weights less than a large air tank. However, the pneumatic system needs to have an air tank which can weight up to 10 kg but the total weight of the system is slightly more than bungees. On the other hand, the springs are also lightweight but heavier than the bungees.

Cost

The cost is an aspect that needs to be taken into consideration, since the system should be economically viable. Nevertheless, the cost is not a decisive factor because high quality is required

according to the client in order to avoid accidents with the expensive robotic birds.

Size, foldability

The launching ramp should be able to fit in a normal car, therefore whether the system has a small size or it can be folded has a large impact on the design choice.

Easy to mount

The system should be set up in a short period of time, to have a fast assembly is crucial. The assembly time compared to the hand launch should be similar. If the assembly time is large, the pilot prefers to launch the bird by hand.

Durability and maintenance

The system's durability is tested on the number of throws the system can handle without any maintenance needed. The system should also be prepared for different climates and temperatures, since there are projects in relatively "cold" countries such as Canada and others with higher temperatures.

Consistency

The consistency, the number of times the system works without failure is crucial for this project. Since the Robirds are expensive robots, the ramp should not fail after a large amount of throws. For instance the bungee cables loses its strength over time due to repeated uses, making it less consistent than a pneumatic system.

Automotion

One important aspect is that the human intervention in the system should be minimal. Therefore the possibility to have a fully automated system in the future is critical. For instance a pneumatic system can be fully automated by having electric valves/regulators and by pressing a button the bird can be launched. The same goes for a bungee with an electrical winch.

Safety

These launching ramps are moving at very high speeds, from 5 to 15 m/s, the risk to cause an injury should be kept minimal. For instance, if a bungee cable is not fixed properly it can cause severe injuries to any person standing nearby.

3.2 A pneumatic Robird launcher

The design chosen is a combination of an air cylinder connected to the rails with a cable, a cart which carries the Robird and a damper. The concept is designed in SolidWorks and it can be seen in Figure 10.

The piston moves due to the air pressure and flow at high speeds, which in turn moves the cart. This system is of similar to what is used for UAV launchers nowadays. [8]



Figure 10: Pneumatic Robird Launcher

The cylinder is 3.5 meters long and it can be tilted to a maximum of 16.5 degrees. The reason to this maximum angle is because, if the angle is increased the Robird will stall after launch and this can be catastrophic. In this situation right after launch, the Robird will already have 1 meter in altitude, thus only needing 2 more meters to reach the height required by Clear Flight Solutions.

3.3 Pneumatic Robird Launcher: specifications(materials used etc.)

Air cylinder

The tube where the compressed air is passing through can be made of different materials: PVC-U pressure rated, copper, aluminium and stainless steel. The material chosen is PVC-U pressure rated since it is the lightest, cheapest and readily available. This can be seen in table 4

On the other hand, the piston needs to be a strong, light and temperature resistant material. The most important aspect is that it can withstand a large range of temperatures since the air cylinder will rise in temperature due to friction and large pressures. Three different materials were compared: Delrin, aluminium and perspex. The material chosen is Delrin because it has high strength and stiffness, it is light and can withstand high temperatures up to 175 degrees Celsius. [10] Aluminium is also a good option, but it does add unnecessary extra costs and weight to the structure. Perspex is a type of plastic that is softer than Delrin but also cannot withstand high temperatures, around 110 degrees Celsius the materials softens. [11] The comparison can be seen in table 5

Rails and cart

Several different rails and carts are available in the market. The deciding factors are the weight, strength, friction between wheels and the rails, also if it is possible to align two different pieces together and the availability of it. In Appendix C table 7 shows the comparison between different types of rails.

There are two types of rails that were immediately considered those were : camera rails and robotic rails. These rails were disregarded as possible options because of their excessive cost. Also, since some other parts of the system were delayed due to problems with the provider, the availability became the most important factor because we did not have much time left to finish the project. Therefore the best option was the door rails.

Damper

The damper is one of the most important aspects of the system, since it damps a large amount of force. There are several different types of dampers: pneumatic dampers, hydraulic dampers, simple springs and high impact foams. Table 6 at the Appendix C shows the comparison between the different options. The pneumatic or hydraulic damper is not easily available, also adds significant weight to the system and it is expensive. The winning option is the high impact foam because it is light, cheap, there is high availability and its durability is also high. Wolters Europe provided us with some free samples of high impact foams such as EPP, EPS, HIPS and Neopor. [12] Also they provided these materials with different densities. Neopor is the better foam because after getting hit, it reshapes back to the first position, compared to the other foams that don't. Also the foams provided could withstand very large forces, larger than the ones needed in our project.

Robird attaching mechanism

The Robird attaching mechanism is the mechanism where the robotic bird is attached to the cart. There are two main attaching mechanisms that were considered:

- A simple hook on the body of the Robird connected to the cart. Figure 30 a, shows the hook mechanism installed in the Robird.
- A mechanism where the wings are placed in a V-shaped aluminium frame. Figure 30b shows this hooking mechanism used in RC airplanes. [13] This option was disregarded after taking with the pilots of CFS because of the large amount of force given to the wings, which may break them.

4 Mathematical modeling

The mathematical modelling of the entire system has been divided in three main parts: the air cylinder, the motion of the Robird while on the ramp and the motion of the Robird right after take-off. From these mathematical models the goal is to determine the required force, velocity and acceleration for the Robird to reach the minimum height needed for launch.

4.1 Pneumatics: air cylinder

A pneumatic system is a gas-based system in which an enclosed fluid can be used for producing rotatory or linear motion or apply a force. [14]

The pneumatic circuit used in the launching ramp consists of an air tank, a regulator, one valve and an air cylinder. An air tank is a reservoir of compressed air, this compressed air is produced by a compressor. The main function of a regulator is to reduce the input pressure of a fluid to a desired value at its output. An air cylinder is a basic actuator which consists of a piston of radius R , moving in a bore. A schematic of this can be seen in Figure 11. The piston is connected to a rod or cable of radius r . The force applied by the piston depends of the pressure applied to it and the area.

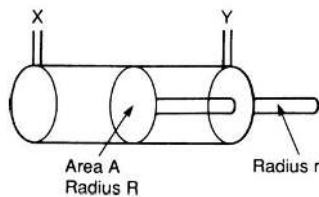


Figure 11: A graphical depiction of a simple air cylinder that shows the workings of the system [14]

$$F_p = P\pi R^2 \quad (5)$$

On the other hand, for the maximum retract force the area of the cable is taken into account.

$$F_r = P\pi(R^2 - r^2) \quad (6)$$

The velocity of the movement of this piston depends on volume of flow delivered to it. Suppose a cylinder of area A has moved a distance d , this requires a volume V of fluid:

$$V = Ad \quad (7)$$

If the piston moves at velocity v , then it moves a distance d over the time t

$$v = \frac{d}{t} \quad (8)$$

Therefore the flow rate, V_f is given by:

$$V_f = \frac{Ad}{t} = Av \quad (9)$$

Where A is the area of the piston and v the velocity of the piston. It should be noted that the fluid pressure has not influence on the piston speed. For instance, doubling the piston area while keeping the same flow rate and pressure, gives half the speed but doubles the maximum force. Figure 12 shows the theoretical flow rate for an area of $A = 0.00078m^2$.

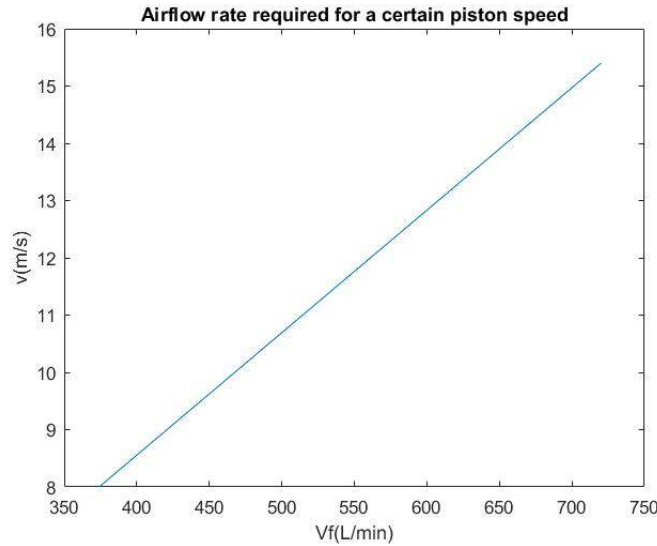


Figure 12: The airflow required can go up to 700 L/min to get a speed of 15 m/s

The flow rate is an important aspect to know because each regulator has a maximum flow rate that it can withstand. Thus a regulator that can hold up to at least 700L/min needs to be chosen. More information about the pneumatic system chosen can be found in Appendix D.1.

4.2 During launch

During launch the Robird is attached to a cart, therefore it experiences a Normal force with the ground, drag due to the aerodynamic forces, the weight of the system itself and a force that propels the cart. The goal of this model is to determine the required force needed for the cart to move and its acceleration. A Free Body Diagram can be seen in Figure 13. An assumption is that the force, F , will remain constant during lunch, since this simplifies the calculations. The Newton-Euler equations are:

Table 2: Coefficient of drag an area for each part of the Robird

	S	Cd
Wing and body	0.18	0.33
Tail	0.05	0.004

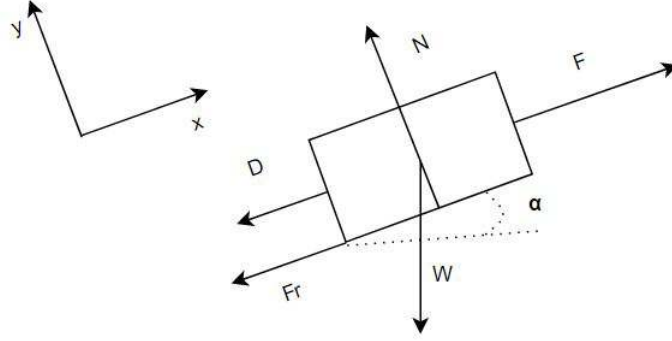


Figure 13: Free Body Diagram of the Robird during launch

$$\begin{cases} F - D - F_r - W \sin \alpha = m\ddot{x} \\ N - W \cos \alpha = 0 \end{cases} \quad (10)$$

Where the general formulation of D is given by equation 4, the drag produced by the wing, body and tail should be taken into account. F_r is the frictional force of the cart wheels with the surface, N is the normal force due to the ground, W is the weight of the system, m the mass of the system and x is the position of the system. Therefore D and F_r are:

$$D = \frac{1}{2} \rho_{\infty} (S_w C_{Dw} + S_t C_{Dt}) \dot{x}^2 \quad (11)$$

$$F_r = \mu N \quad (12)$$

S_w and C_{Dw} are the area and coefficient of drag of the wing and body respectively. S_t and C_{Dt} are the area and coefficient of drag of the tail and μ is the dynamic coefficient of friction.

The wing and the body of the Robird have been tested in the wind tunnel for different Reynolds numbers and angles, obtaining the coefficient of lift and drag. [6] The coefficient of drag obtained due to experiments in the wind tunnel of the Robird does take into account the lift induced drag too. A higher coefficient of drag is taken from the master thesis, because in reality our Robird has more drag due to using older parts and also the small hook on the body also has a small influence. On the other hand, the tail of the Robird was not tested in the wind tunnel, thus the coefficient of drag has been approximated using an assumption that it is a flat plate. Thus, the tail is assumed to be a non-lifting surface for simplicity. The values can be seen in table 2. The calculation of the coefficient of drag for the tail is given in the Appendix B. Then we find that

$$N = W \cos \alpha \quad (13)$$

And the force needed is:

$$F = \frac{1}{2} \rho_{\infty} (S_w C_{Dw} + S_t C_{Dt}) \dot{x}^2 + \mu W \cos \alpha + W \sin \alpha + m\ddot{x} \quad (14)$$

The acceleration $\ddot{x}$ is given by:

$$\ddot{x} = \frac{V_{\text{final}}^2 - V_{\text{initial}}^2}{2L_r} \quad (15)$$

Where L_r is the length of the ramp. The case with the largest force is treated as the minimum necessary force that the system should reach. The largest force is given by the largest velocity, this velocity is $15 \frac{m}{s}$. Thus, by using equation 14 the force is found to be 71 N and the acceleration in this case is $32.1 \frac{m}{s^2}$.

4.3 After take-off

The situation described in this section is the motion of the Robird after it takes-off the launching ramp. In this situation it is assumed that the angle of the Robird remains constant during the flight, since it is of interest only the trajectory of the Robird until it reaches the point of maximum height. The motion of the Robird after it reached the maximum height is not of interest here because the pilots at CFS would already turn on the flapping mode and the Robird would start to fly. Taking into consideration the aerodynamic forces, the weight and an initial speed and angle a Free Body Diagram is depicted in Figure 14. The Newton-Euler equation follows:

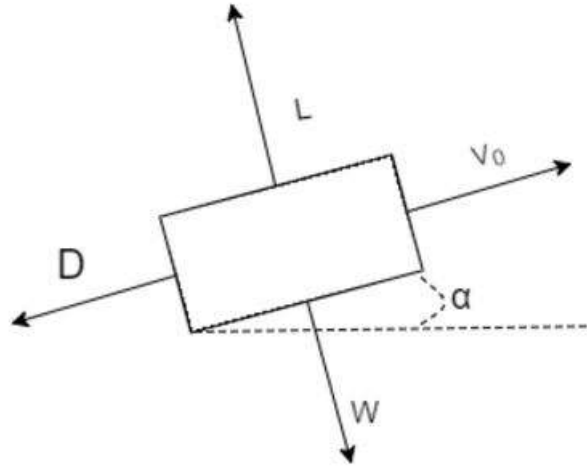


Figure 14: Free Body Diagram of the Robird with an angle α due to the inclination of the ramp. Where L is the lift, D the drag, W the weight and v_0 the initial velocity

$$\begin{cases} -D - W \sin \alpha = m\ddot{x} \\ L - W \cos \alpha = m\ddot{y} \end{cases} \quad (16)$$

The lift and drag forces are given by equations 3 and 4.

The equation in the x and y direction are solved:

$$\begin{cases} \ddot{x} = -\frac{1}{2m}\rho_{\infty}(S_w C_{Dw} + S_t C_{Dt})\dot{x}^2 - g \sin \alpha \\ \ddot{y} = \frac{1}{2m}\rho_{\infty}S_w C_{L}\dot{x}^2 - g \cos \alpha \end{cases} \quad (17)$$

These are non-linear coupled second order differential equations. These equations cannot be solved analytically in this form. Therefore these equations are solved numerically using MATLAB. In order for MATLAB to start solving the equations it is first needed to reduce the second order differential equations to first order by defining:

$$\begin{cases} x = Y_1 \\ \dot{x} = Y_2 \\ y = Y_3 \\ \dot{y} = Y_4 \end{cases} \quad (18)$$

First the equations in 18 are differentiated with respect to time. Then, the equations in 17 are substituted into these differentiated equations. This gives a set of first order differential equations making it possible for MATLAB to process the equations:

$$\begin{cases} \frac{dY_1}{dt} = Y_2 \\ \frac{dY_2}{dt} = aY_2^2 - b \\ \frac{dY_3}{dt} = Y_4 \\ \frac{dY_4}{dt} = cY_2^2 - d \end{cases} \quad (19)$$

Where $a = -\frac{1}{2m}\rho_{\infty}(S_w C_{Dw} + S_t C_{Dt})$, $b = g \sin \alpha$, $c = \frac{1}{2m}\rho_{\infty} S C_L$ and $d = g \cos \alpha$.

The MATLAB code used to find the numerical solution is shown in the Appendix A. The parameters such as initial angle and velocity are changed several times, giving different differential equations and solutions.

Since the axis is slightly rotated, a rotation matrix is used to reverse the axis to the general position:

$$\begin{cases} x' = x \cos \alpha - y \sin \alpha \\ y' = x \sin \alpha + y \cos \alpha \end{cases} \quad (20)$$

The results from MATLAB greatly vary when the initial conditions are changed. As expected the angle and initial velocity have a large influence on the maximum altitude the Robird reaches. A plot of the solutions is shown in figures 15, 16, 17 and 18:

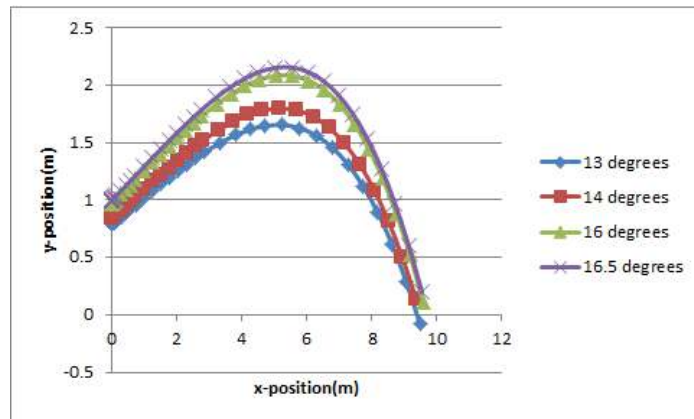


Figure 15: Trajectory of the robird after launch with an initial velocity of $11 \frac{m}{s}$

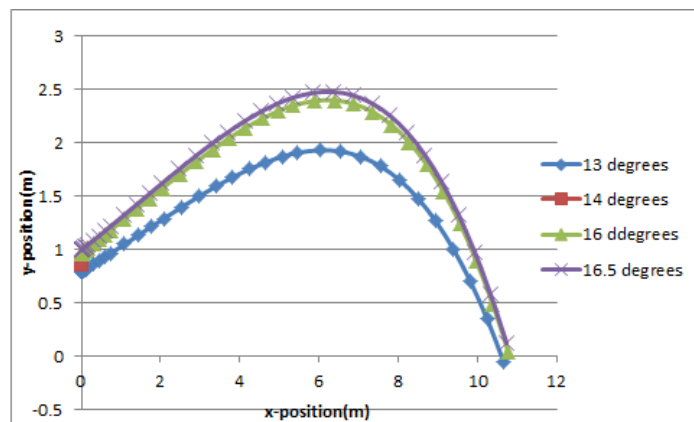


Figure 16: Trajectory of the robird after launch with an initial velocity of $11.75 \frac{m}{s}$

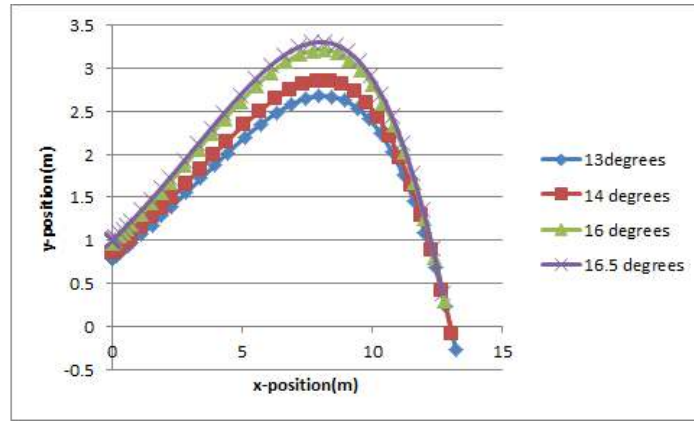


Figure 17: Trajectory of the robird after launch with an initial velocity of $13.2 \frac{m}{s}$

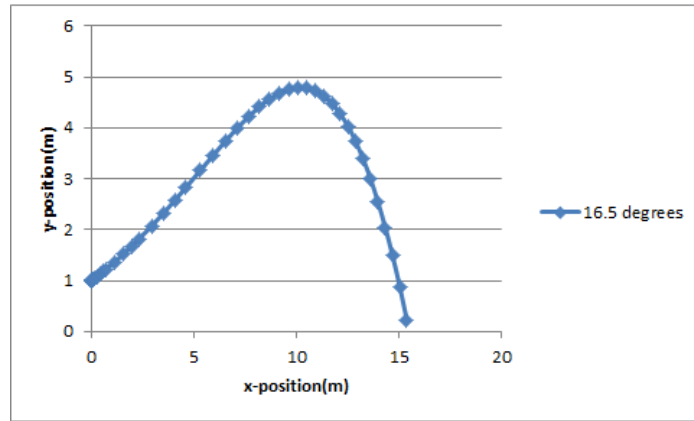


Figure 18: Trajectory of the robird after launch with an initial velocity of $15 \frac{m}{s}$

One should notice that a slight change in the coefficient of lift has large consequences in the final trajectory. The experiments to determine the Robird's trajectory are carried between $2 * 10^5 < Re < 3 * 10^5$. Nevertheless, the maximum Re tested by S.Hartman in the wind tunnel was $Re = 1.57 * 10^5$, thus this adds more uncertainty about the validity of the values chosen for C_L and C_D in this model. The values for C_D are given in Table 2 and $C_L = 0.5$. The most important requirement is to reach a height of 3 meters. When analyzing the results, this height is reached when the angle of the ramp is of 16.5 degrees and exiting velocity of 13.2 m/s.

5 Final Design

After deciding the dimensions and materials of the complete system, the launching ramp was constructed. Figure 19 shows the final design of the launching ramp. The details of the construction can be seen in Appendix D. The system consists of a 3.5 meter long pressure rated PVC which is separated in four parts, three pieces of 1 meter and one piece of 0.5 meters. On top of it the rails were installed with a small cart which carries the Robird. The cart has two blocks that hold the wings and a small connection where the hook is attached. This can be seen in Figure 20. The Robird itself has a hook connected to it that can be seen in Figure 22. This cart is pulled by a cable that is connected via a pulley to the piston as can be seen in Figure 21. For the last and mid platforms legs are attached via a hinge. The length of the legs can be changed by putting a pin in one of the several holes the legs have. The angle of the ramp can be changed by changing the length of the legs. The speed of the system can be changed by changing the pressure output from the air tank. The total weight of the system is 14.830 kg without taking into account the air tank. A more detailed description of the weight of each part can be seen in table 8 under appendix D. The

final velocity reached by the cart with the Robird is $15 \frac{m}{s}$. Furthermore, many different pictures of parts of the system can also be found under Appendix D.



Figure 19: Complete pneumatic launching ramp, with a total weight of 23.840 including the air tank.



Figure 20: Robird on the cart ready to be launched

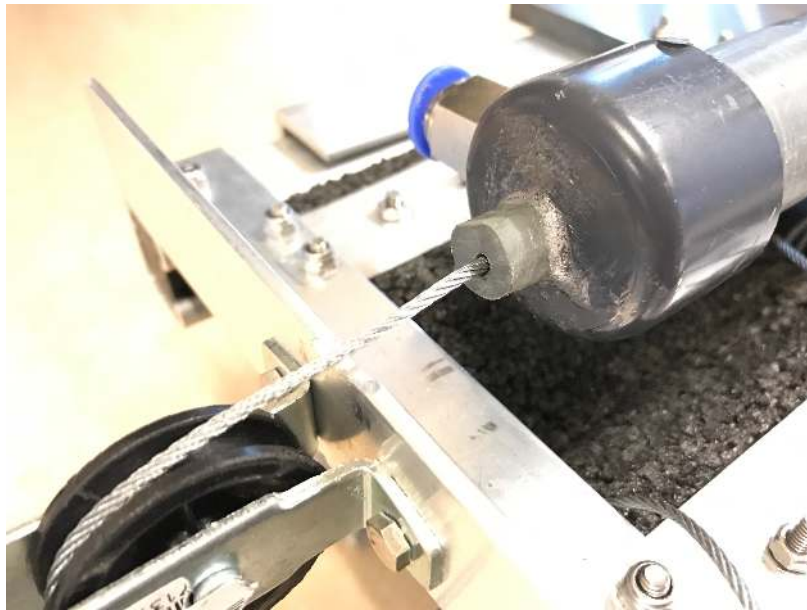


Figure 21: Connection of the piston to the cart via the pulley. Note that the hole where the cable passes through causes air leakage.



Figure 22: Hooking mechanism attached to the Robird.

6 Experiments

6.1 Robird hand launch

The Robird is launched by hand at a certain angle and speed while in flapping mode, which allows it to fly instead of crashing into the ground. The goal is to find what is the velocity and angle at which it is launch. These values serve as an approximation for what at least the launching ramp should achieve.

This experiment consists on determining the angle, velocity and acceleration of the Robird when is launched by hand, using a software called tracker. The **set-up** of the experiment consists of:

- Nikon D5200 (camera with high frame rates)
- Tripod



Figure 23: Measurement of the angle and velocity during hand launch

- Pilots to fly the Robird
- Measuring tape
- Wind meter
- 0.5 wood sticks
- Laptop with Tracker

The experiments were carried in a RC airplane club in Nijverdal. The first step was to determine the wind speed of the area where the test was carried. This wind-speed was $3 \frac{m}{s}$ which was very high for a normal flight day.

The second step was to put the 0.5 m long sticks 0.5 m apart from each other in a straight line, which is used later as a reference to measure the distance travelled by the Robird. The camera was placed in front of the sticks with the least possible angle with respect to the ground. The pilot was at the side of the sticks aiming in the direction of the sticks. Then the hand launch was filmed with the high speed camera. This can be seen in figure 23 a.

Postprocessing and results

Tracker was used to determine (using every frame available) the velocity, acceleration and angle in which the Robird was launch. See figure 23 b. This consisted in giving an initial frame of reference which was given when the pilot was about to throw the Robird. Also Tracker requires a measured reference, for this the 0.5 meter sticks were used. Then frame by frame the new position of the Robird was given. Thus the position, velocity, acceleration and angle could be determined. Also, the wind-speed should be taken into account since when doing calculations the relative velocity with respect to the wing is necessary to determine Lift and Drag.

6.2 Pneumatic system

The pneumatic system is an integral part of the entire system because it determines the speed at which the Robird will take-off. Therefore two different experiments are carried in order to determine whether the air cylinder delivers enough force to move the system and also the necessary speed for the Robird to take-off.

6.2.1 Delivered Force by the air cylinder

The goal of this experiment is to determine whether the pneumatic system delivers the necessary force for the cart and the Robird to start moving. Therefore using equation 6 it is possible to

Table 3: Comparison between the theoretical and experimental pressures needed to move a certain amount of kilograms

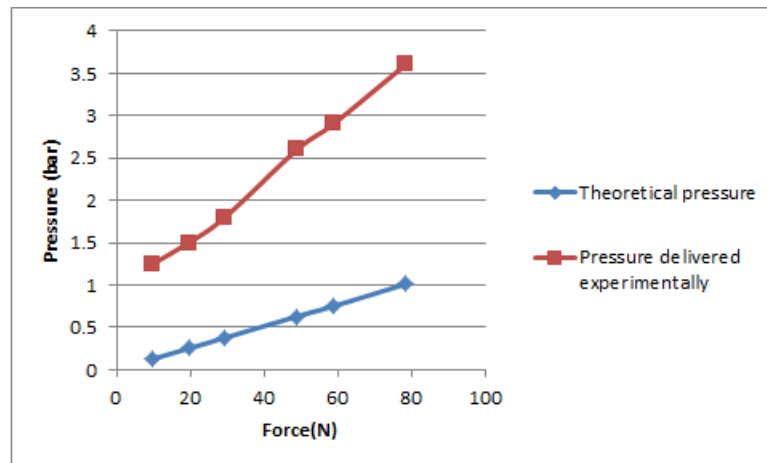


Figure 24: Comparison between the theoretical and experimental pressures needed for the air cylinder to apply a certain amount of force

determine the pressure necessary to reach a certain force. The system will be tested for different weights, ranging from 1 Kg up to 8 kg. The **set-up** of the experiment consists of:

- High pressure PVC tube with a 32 mm diameter
- Piston
- Pulley and cable
- Weights
- Pneumatic circuit(Regulator, valve, air tank, compressor)

The air cylinder is on top of a table, the cable is attached to the weights which are on the ground. Then it is tested with different pressures until it the piston moves the weight. For every weight the pressure is calculated theoretically and compared to the pressure needed in the experiment.

Results

A graph with the results can be seen in Figure 3. From this it can be concluded that there is a large variation between theory and the experiment. The air cylinder needs 10 times more pressure experimentally for 10 N of force compared to the theoretical pressure. In contrast, for a force of 80 N, this difference decreased to only 3.5 times more. This is due to imperfections in the system. The theory takes into account a perfect, friction-less system but in real life there are other factors that influence the outcome of this experiment. These factors are:

- The friction of the piston with the air cylinder and the friction between the cable and the pulley.
- The air leakage of the cylinder. There are 3 main parts that are leaking. One is the piston which is does not perfectly fit in the cylinder therefore some air leaks around it. Another point is the leakage created by the hole where the cable passes through. Last but not least the connections between each part of the cylinder also have some leakage.

6.2.2 Final Velocity of the cart

The velocity that the cart reaches at the end of the piston stroke is the most important aspect of the pneumatic system. This is because the final velocity determines the maximum height the Robird will reach. The velocity of the piston (same as the velocity of the cart) does only depend theoretically on the air flow rate. This means that if the flow rate is known, the velocity of the piston is known or vice versa. This is explained in section 4.1.

The pneumatic piston is tested by changing the output pressure from the air tank causing a change in the velocity of the piston. The goal of this experiment is to determine the velocity of the piston at the end of the stroke.

In order to determine the final speed, the motion of the cart is filmed with a high speed camera and then processed with the program Tracker.

The **set-up** of the experiment consists of:

- High pressure PVC tube with a 32 mm diameter
- Piston
- cable
- High speed camera
- Laptop with Tracker installed
- Pneumatic circuit(Regulator, valve, air tank, compressor)

Results

After processing the data gathered by the high speed camera, the velocity at the end of the ramp is determined for different pressures. Figure 25 shows that the cart reaches a maximum velocity of $18 \frac{m}{s}$ using 5.5 bars.

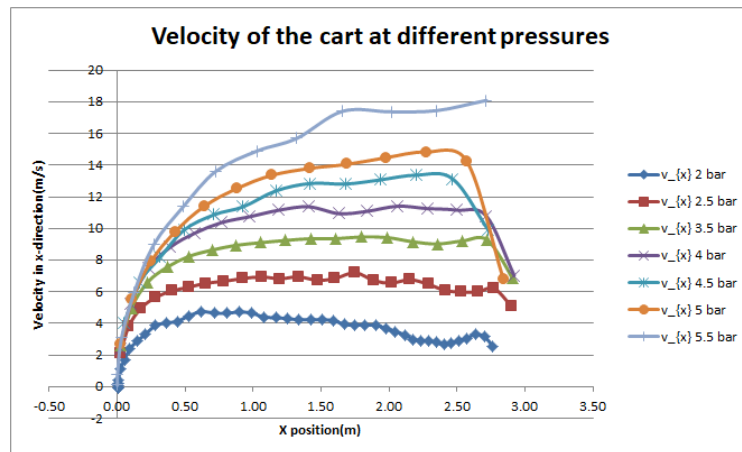


Figure 25: The graph shows cart velocity dependency with pressure. It also can be seen that the acceleration is mainly in first meter of the rails.

This final velocity is important to know because it shows what the maximum velocity is. From this experiment several things could be noted.

- The flow rate coming from the air tank highly depends on the output pressure.
- The large friction created by the wheels and the rails.
- The air leakage explained in the previous experiment.

6.3 Robird final trajectory

The Robird launcher is finally tested with different angles and pressures. The goal of this experiment is to check whether the system behaves as intended and is compared to the mathematical model. The ultimate objective is to fulfill the client's requirement of reaching 3 meter's height. The **set-up** of the experiment consists of:

- The complete launching system
- Robird with controller
- High speed camera
- Laptop with Tracker installed

After building the set-up in an open space, the Robird is placed in the cart and launched at different angles and pressures. Furthermore the Robird is controlled via a remote controller to stabilize the Robird because if not, it would directly fall into the ground possibly breaking the bird. Because the Robird used is an older version and it does not have spoilers it is uniquely controlled with the tail (rudder/elevator).

Results

The results are plotted in a graph showing the different trajectories for different angles and pressures. Note that the position $x = 0$ is the end of the ramp. The graphs with the different trajectories can be seen in figures 26272829.

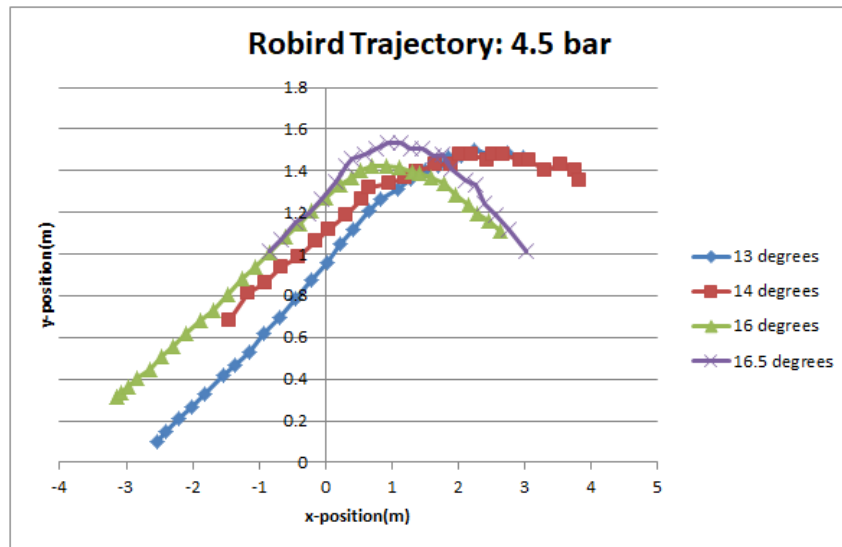


Figure 26: Trajectory of the Robird when using 4.5 bar of output pressure. The average exiting velocity at the end of the ramp is 11 m/s

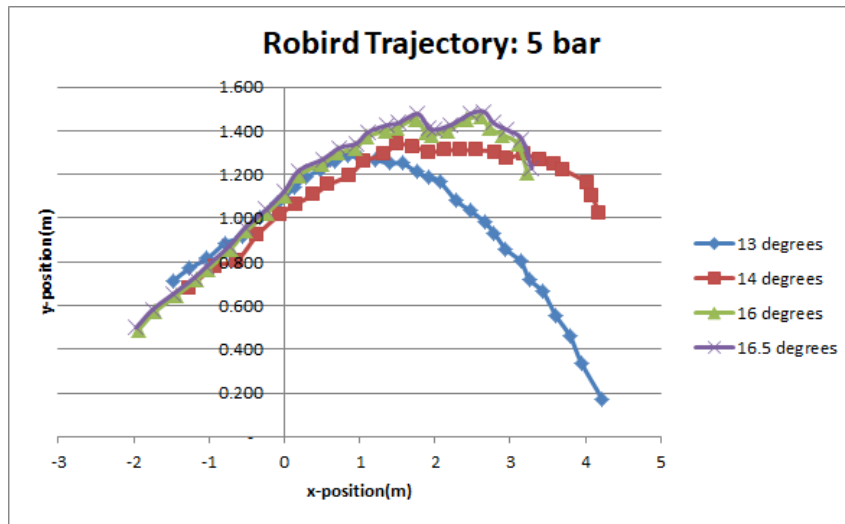


Figure 27: Trajectory of the Robird when using 5 bar of output pressure. The average exiting velocity at the end of the ramp is 11.75 m/s. The trajectory when using 13 degrees quickly falls to the ground this was because the tail of the Robird did not work as expected and it was not possible to stabilize the bird.

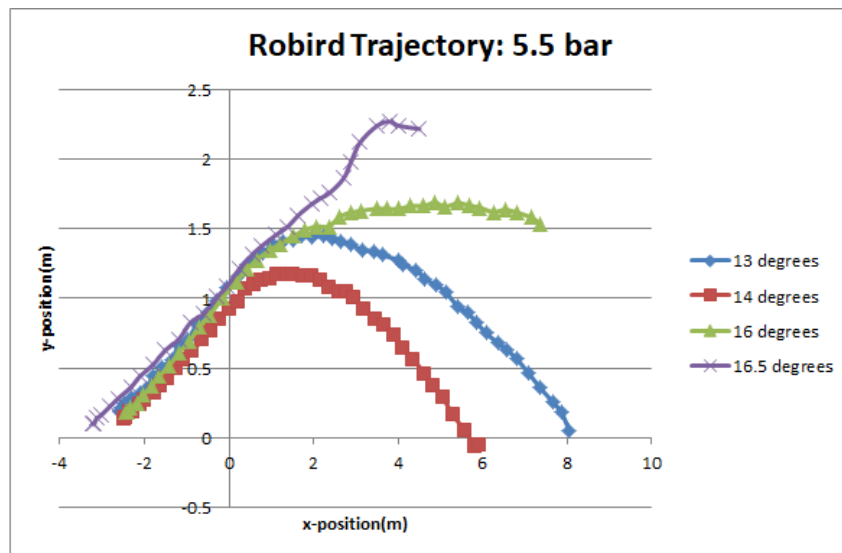


Figure 28: Trajectory of the Robird when using 5.5 bar of output pressure. The average exiting velocity at the end of the ramp is 13.2 m/s

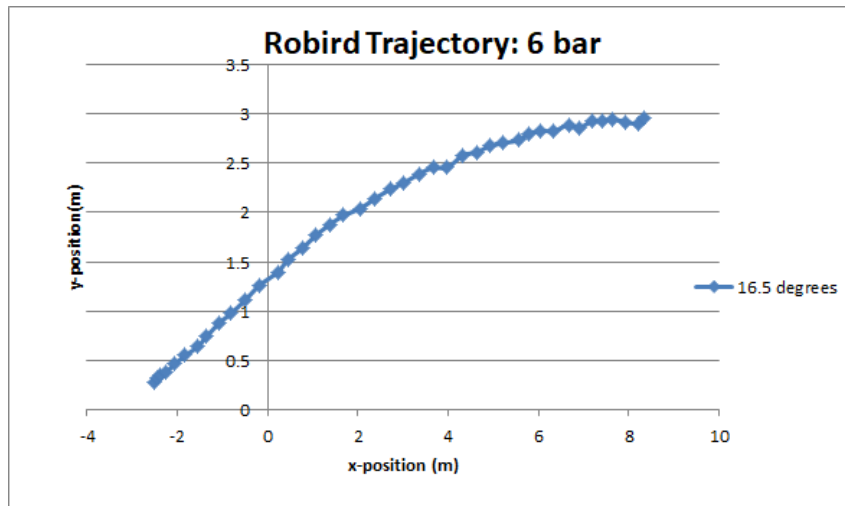


Figure 29: Trajectory of the Robird when using 5 bar of output pressure. The exiting velocity at the end of the ramp is 15.2 m/s

The trajectory is influenced by the initial conditions: the angle of the ramp and the exiting velocity. After testing, the trajectory found for different angles is compared to the trajectory calculated theoretically which can be seen in figures 15,16,17 and 18. For the experiment using 4.5 bar it started raining outside causing the need to store the camera and the Robird inside. This influenced the results since the camera was not in the same position and angle as before that is why the trajectories in the graph are not as consistent as in the experiments with 5 or 5.5 bars. The mathematical model overestimates the altitude that the Robird reaches. The higher the speed the higher the difference between model and reality. There are several reasons why this variation happens:

- The assumption that the coefficient of lift and drag remains the same is not accurate enough to describe the model. Also, the values used of coefficient of lift and drag are estimated from an older version of the Robird.
- The assumption that the tail of the Robird does not produce lift is another reason.
- The small hook attached to the Robird also adds some drag.
- By controlling and stabilizing the Robird, the control surfaces are moving therefore the lift and drag also changes. This was not taken into account in the model.
- The wind from the exterior, although it was low, it still had an influence on the Robird.

7 Discussion & Recommendations

Multiple experiments and results have been presented on the previous chapter. The purpose of this chapter is to discuss them in depth by interpreting the results and comparing them to the theory and literature research. In addition, suggestions for further research are given.

Design

One of the negative sides of a pneumatic system is that an air tank is required. Some air tanks can be heavy to carry, but this has been discussed with the pilots at CFS and they did not have any problem carrying an air tank to the field. Another option to tackle this problem, could be to build an air tank ourselves and integrate it to the complete system, improving even further the portability. In addition, a PVC self-made air tank weights less than the air tank currently used.

To measure the velocity of the cart more precisely, black-white detectors could be added and a

black-white strip along the rails. A single IR reflective sensor could be used for this purpose. In this way you could have real time feedback of the magnitude of the velocity from the system.

The electronic valves/regulators could be added to the system and replace the other ones. Electronic valves/regulator allows them to be programmed such that by pressing a button the valve would release the air. Also combined with the velocity sensor, the system could automatically choose a certain pressure to reach a certain speed depending on the bird and angle used. In this way the system could be fully automated which is an interesting aspect for the client.

The hook that is attached to the Robird does create extra drag because it is a part that sticks out of the body. Therefore it is recommended that the hook could be 3D printed within the body itself, without any part sticking out, thus reducing the drag.

The air cylinder had 3 main air leaks: one from the hole where the cable passes through and connects the cart and piston together. Another leak is due to the piston which does not fit completely in the air cylinder causing an air leak around it. Last but not least, there was some minor air leak due to the connections between each PVC tube. Therefore it is recommended to order a custom made air cylinder to specialized companies in pneumatics such as Festo. This can potentially increase the efficiency of the system dramatically, requiring less air pressure to launch and reach higher speeds.

One of the major problems with the design was the alignment with all the rails and PVC tubes. This misalignment caused large amounts of friction between the rails and the cart. In addition, it made harder for the piston to freely move along the PVC tubes because the tube was slightly curved. A solution for this problem is to order camera rails or robotic rails, although more expensive, it won't give alignment problems, therefore avoiding extra friction.

In section 6.2.2, Figure 25, it can be seen that a velocity of $15 \frac{m}{s}$ is reached for a pressure of 5.5 bars in the first 1.2 meters of the ramp. Thus, there is a possibility that the length of the ramp can be decreased to this value, since the cart reached the necessary speed for the Robird to reach the 3 meter height requirement. Thus, instead of having a 3.5 meter long ramp, it could be decreased up to 1.2 meters long.

Mathematical model

The mathematical model considers the force transmitted by the piston to the cart to be constant along the ramp but in reality, after testing, this is not the case. In order to improve the model, it should be considered that there is a large acceleration at the beginning of the air cylinder. This is caused by the increased friction in the system due to larger speeds and also the volume of air that is being compressed at the other end that acts as a damper.

In the mathematical model developed to describe the trajectory after launch there is an important wrong assumption. It has been demonstrated that the angle of attack is not constant when climbing, it changes because the Robird moves up and down due to low stability, the wind outside and the fact that the Tail of the Robird was controlled. Moreover, the Robird slowly decreases its angle of attack up to zero degrees w.r.t. the ground when reaching the maximum altitude. Thus, when the angle of attack changes, the coefficient of lift and drag also changes, concluding that a constant angle of attack is not a valid assumption.

Another recommendation is to re-do all the wind tunnel tests with the new Robird model, including the tail. This will yield more accurate results for the coefficient of lift and drag. These new values then can be used for modelling the ramp.

Experiments

Several of the experiments were done by filming with a high-speed camera. The problem with this approach is that it is not as precise as using other methods such as placing motion or velocity sensors. The camera angle when filming also has a relatively large influence in the results, if not placed correctly it can lead to a large error margin. Therefore it is highly recommended to use motion sensors to avoid this problem.

8 Conclusion

This thesis started with a description of the Robird and its aerodynamics, followed by the requirements set by the client in chapter 1. Then, a comprehensive literature study has been carried in chapter 2 exploring the different launching ramps used in RC aircrafts and the basics of aerodynamics. Then a concept design was presented in chapter 3. Chapter 4 shows the mathematical modelling of the ramp. Chapter 5 shows the final launching ramp after construction. The experiments and the results are presented in chapter 6 and discussed in chapter 7. The goal of this chapter is to summarize if the requirements of the client were met:

1. **Gliding mode:** The Robird does launch in gliding mode as specified by the client.
2. **Hooking mechanism:** The hooking mechanism is attached to the body, therefore avoiding any stress on the wings.
3. **Larger prototypes:** By increasing the pressure, larger and heavier birds can also be launched.
4. **Fixed parameters:** The launching ramp should have a fixed speed and angle which can be different for each prototype. This has not been achieved but it can be implemented.
5. **Portability:** The system is portable, it can be split in 3 pieces of 1 meter and one piece of half a meter. The system fits in a car and preparing the set-up approximately takes 1 minute and 30 seconds.
6. **Large wind speeds:** It was stated by the client that the system should work in wind speeds up to 11m/s. Unfortunately, this has not been tested.
7. **Operational temperature:** The launching ramp withstands temperatures ranging from -10 till 40 degrees Celsius.
8. **Weather resistant:** The structure is resistant to dust and rain.
9. **Weight:** One person is able to carry the mechanism without any problem since it is split in parts and each part has a low weight.
10. **Velocity sensor:** The system does not have a feedback mechanism that measures the launch velocity.
11. **Minimum height:** The minimum height required(3 meters) has been achieved by using 6 bars and an angle of 16.5 degrees.

Out of the eleven requirements eight were met, one has not been tested and two have not yet been achieved. In conclusion, a working launching ramp has been successfully design and constructed, nevertheless there are some aspects that can still be improved. The results from this thesis is a prototype that will prove useful as the first essential step towards the final goal of achieving a professional launching ramp.

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Appendices

A MATLAB codes

```

1
2 [T,X] = ode45(@robird,[0 3],[0 13.5 0 0]);
3
4 plot(T,X(:,1),T, X(:,3))          %%%position x and y vs time%%
5
6 %Rotation matrix to go to "normal" coordinates%
7 alpha=13;
8 x= X(:,1)*cosd(alpha) - X(:,3)*sind(alpha);
9 y= X(:,1)*sind(alpha) + X(:,3)*cosd(alpha);
10
11 plot(x,y)

1 function dx = robird(t,x)
2
3 g=9.81;          %%%gravitational constant%%
4 alpha=16.5;      %%%angle of attack%%
5 mtotal=0.63;     %%%mass of the Robird%%
6 mw=0.14;         %%%mass of the wings%%
7 rho=1.20;        %%%density of air at 20 degrees at sea level%%
8 V=15;           %%%velocity of the robird when launching%%
9 mu=1.8e-5;       %%%dynamic viscosity at standard conditions
10 Ct=0.335;       %%%tail length
11 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%Reynolds number calculation%%%%%%%%
12 %Rew= rho * V * Cw / mu; %Re for the wings
13 Ret= rho * V * Ct / mu; %Re for the tail
14 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%Calculation of drag depending on the Reynolds number%%%%%%%%
15 Cdw=0.33;        %%%coefficient of drag of the wing and body from literature%%
16 Cl=0.5;          %%%coefficient of lift of the wing and body from literature%%
17 Sw=0.18;         %%%area of the wings and body%%
18 St= 0.1;         %%%area of the tail%%
19 Cdt=2 *(1.328/sqrt(Ret)); %%%coefficient of drag of the tail%%
20
21 dx = zeros(4,1);
22 dx(1) = x(2);
23 dx(2) = (-1/(2*mtotal))*rho*((Sw*Cdw)+(St*Cdt))*(x(2)^2) - g*sind(alpha); %%%mass
    of the wing /= mass of the body
24 dx(3) = x(4);
25 dx(4) = (1/(2*mtotal))*rho*Sw*Cl*(x(2)^2) - g*cosd(alpha);

```

B Coefficient of drag calculations

In this section the derivation of the coefficient of drag of the tail of the Robird is shown. Note that: the velocity ranges from 11 to 15 $\frac{m}{s}$, the standard atmospheric density at ground level, at 20 degrees Celsius is $\rho = 1.2 \frac{kg}{m^3}$ and the dynamic viscosity $\mu_{\infty} = 1.8 * 10^{-5} Pas$.

Tail

The largest Reynolds number is used in order to know whether the flat plate has a turbulent flow or laminar. Therefore by using equation 1 and the largest velocity $15 \frac{m}{s}$, the Reynolds number is found to be $Re = 335000$. Thus, the flow is laminar since it is lower than $Re < 5 * 10^5$. The length of the tail is 0.335 m and the friction drag coefficient of a flat plate is given by: [5]

$$C_f = \frac{1.328}{\sqrt{Re}} = 0.00229 \quad (21)$$

Which gives the total drag:

$$C_D = 2C_f = 0.004 \quad (22)$$

This seems to be in the correct order of magnitude since the expected drag coefficient of a flat plate for a laminar flow is between 0.001 and 0.005.

C Concept design figures and tables

In this section the tables comparing different options are shown.

Table 4: Comparison between different cylinders

	Weight	Aluminium cylinder	Copper cylinder	Stainless steel cylinder	PVC-U pressure rated
Cost	1	2	3	4	5
Weight	3	4	2	3	5
Easy to work with	2	3	3	3	5
Total		20	15	19	30

Table 5: Comparison between different piston materials

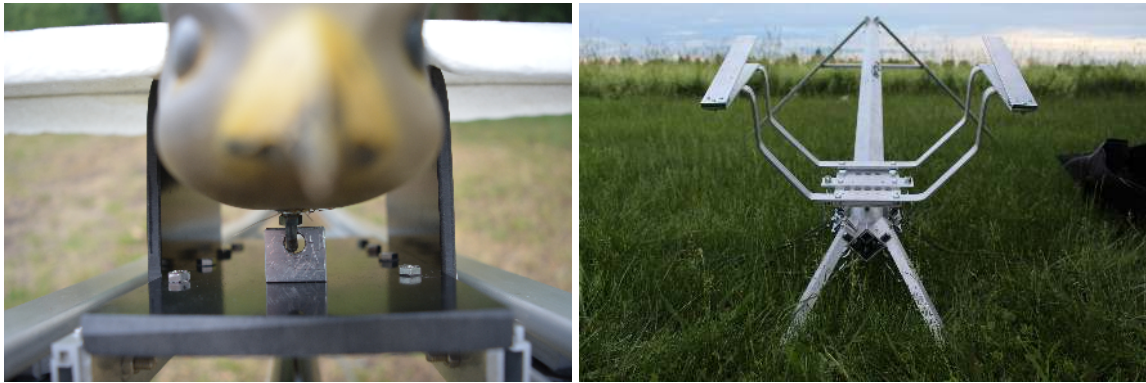
	Weight	Aluminium	Delrin	Perspex
Cost	1	2	5	5
Weight	3	3	4	4
Temperature resistant	3	5	4	3
Strength	2	5	5	2
Total		36	39	30

Table 6: Comparison between different types of dampers

	Weight	Pneumatic damper	Hydraulic damper	Simple springs	High impact foam
Weight	3	2	2	4	5
Availability	3	1	1	5	5
Cost	1	1	1	5	5
Durability	3	5	5	3	3
Total		25	25	41	44

Table 7: Comparison between different rails

	Weight	Camera trolley rails	Robotics Rails	Door Rails
Weight	2	5	3	4
Availability	3	4	4	5
Cost	1	1	1	5
Durability	2	4	4	3
Total		31	27	34



(a) Hook mechanism that puts the stress on the body of the Robird and not the wings. (b) The "RC Plane (X8) Catapult Launcher" has a V-shaped aluminium frame on top of the cart where the wings can be placed. This mechanism puts all the stress on the wings. [13]

Figure 30: Two different hooking mechanisms

Table 8: All the weights of each individual part of the system

	Weight(kg)
Small 0.5 meter section	2
Middle section with the legs	3.4
Middle section without the legs	3.15
End section including damper and pulley	4.316
Air tank	9
Cart	1.334
Robird	0.63
Total	23.83

D Construction

In this section a detailed description of the process of constructing the Robird is given. In addition the weights of each parts are given in table 8. For a more detailed description of each part and technical drawings, these can be seen in my colleague's thesis (Koen Heemskerk)

D.1 Pneumatic system

The first part constructed was the air cylinder, then the rest of the pneumatic system was built. Firstly, a list of the materials used is given, why they were chosen and then how it was assembled.

- Four **high pressure PVC tubes** of 1 meter long, 32 mm diameter and 1.5 mm thickness
- **High pressure PVC end caps**, ERA PVC LIJMKAP 32mm PN16.
- Three **high pressure couplers**, VDL PVC SOK 32 x 32mm PN 16
- **Fittings** RIKI G1/4
- **Piston**: Delrin rod with a diameter of 30 mm and a length of 7 cm.
- **Steel cable** that can withstand up 50 kg of tension.
- One **regulator**, PVER 3000 - 1/4
- One **valve**, IKI 10 mm

- **Tubing:** PU Tube 10mm x 6,5mm
- One **quick coupler:** "Snelkoppeling vrouwelijk 1/4 "

The PVC tube, end caps and couplers are pressure rated this means that they can withstand up to a certain pressure. The PVC tube can withstand up to 10 bar and the end caps and couplers up to 16 bars. [15] [16] [17] This is an important aspect to take into account since normal PVC can explode and shatter into pieces.

The fittings and valve can also withstand up to 10 bar and have a tube connection of 10 mm diameter which is the tube size chosen. [18] [19] Since theoretically the flow rate is almost 700 l/min, the regulator chosen is the "PVER 3000 - 1/4" because it can have flow rates up to 2500 L/min. [20] This regulator will be useful for larger birds since it can also withstand high pressures. The tube needs to be connected to the air cylinder, a hole of 1/4 inch was drilled and for the connection. Then a hole for the cable in the end cap is created. The end cap then is glued with PVC cement to the PVC tube. Next step is the creation of the piston. A Delrin rod is grinded until it perfectly fits and slides through the cylinder.

D.2 Rail system and damper

The rail system was installed on top of the air cylinder after the construction of the complete pneumatic system. First, platforms at the end of each tube were added with pins that serve as alignment. On top of these platforms clamps were added to secure the connections between each tube. This can be seen in figures 31, 33, 32, 34. To make a sturdier ramp 3mm thick aluminium L-profiles were implemented on each side of the ramp. The rails were secured with the use of bolts and nuts to the L-profile.

At the end of the ramp, the pulley and the damper, the high impact foam "Neopor", were installed. Furthermore the legs at the end and at the mid section of the ramp were added. The legs were connected to the system by using a hinge therefore it makes the system collapsible. Moreover, the legs length can be changed by adding pins to the pre-calculated holes. Therefore you will have a certain angle at the end of the ramp. This can be seen in figures 35, 36, 37.



Figure 31: PVC tube with the platform holder glued to it



Figure 32: Two different tubes connected and aligned



Figure 33: Two different tubes connected and aligned



Figure 34: The clamps and pins are added to improve alignment



Figure 35: One meter piece with the rails installed and connected to each platform.



Figure 36: The damper and the pulley installed at the end of the ramp.

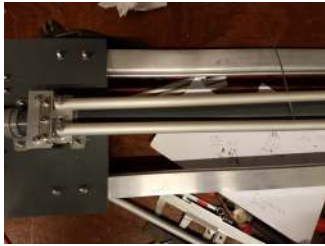


Figure 37: Collapsible and extensible legs attached to the bottom part of the platform.



Figure 38: Complete cart with the hook and wheels.

D.3 Cart and hook mechanism

The cart was simply made with black PVC and the door wheel rails. The cart wheels can be adjusted manually making it more tight or less, depending on the circumstance. The wings of the Robird are on top of two PVC blocks adding more stability to the launch. The hook is simply a small piece of L-profile aluminium that can be connected to the Robird's hook. See figure 38.