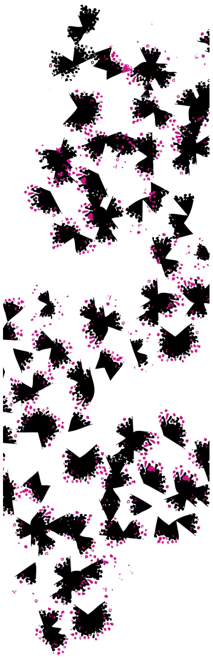

Test Rig for the Robird

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BSc Report

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Abstract

This bachelor thesis describes the design process of a test rig developed for the Robird, an ornithopter made by Clear Flight Solutions, that can be used for pest-bird control. The test rig that was build uses two Evans four-bar approximate straight line mechanisms, to allow for vertical translation and pitching. Torsion springs are used on the arms of the Evans mechanism to compensate for gravity acting on the Robird, while conical springs are used to prevent the Robird to get too far out of its equilibrium position. Tests to verify the proper functioning of the test rig found resonance, due to the increasing stiffness of the conical springs when compressed. To prevent the oscillations getting too large, the throttle is limited to 40%. Putting a higher pre-load on the torsion springs to prevent compressing the conical springs too much is recommended to prevent resonance from occurring. Various other improvements are suggested for a possible next version.

Contents

1 Introduction

1.1 The Robird

The Robird is a robotic bird designed to imitate the appearance, characteristics and flying method of real bird of prey. Currently two versions exist, one of a peregrine falcon and one of a bald eagle. Out of which the peregrine falcon is the one focused on most. Table 1 shows a comparison between some of the characteristics of the real peregrine falcon and the Robird.

	Peregrine falcon	**Robird**
Mass	600–1300 g	757 g
Body length	39–50 cm	56 cm
Wingspan	95–115 cm	112 cm

Table 1: Characteristics of real Peregrine falcons [1] and the Robird

1.1.1 Usage

The most important use of the Robird is to scare away real birds in situations where they cause large amounts of damage. This is especially important around airports, where birds colliding with air-planes causes safety risks and over a billion USD of damages worldwide yearly [2]. Conventional methods like noise, scarecrows, bright lights, hunting and introducing predators all have major downsides. Birds can get used to noise, scarecrows and similar audiovisual methods, making them quickly loose effectiveness. Bright lights can scare away some birds, but also attract others. Lasers have also been tested but their required intensity was too high. Shooting birds is costly and requires much effort and following strict regulations [3]. The introduction of predators to hunt the pest birds, has the advantage that it does not lose effectiveness over time as fear for these predators is naturally part of the nature of the pest birds. However real birds of prey have the disadvantage that their population now needs to be controlled, they may collide with air-planes themselves and are often only active during the night [3]. A robotic bird of prey can have the advantage of installing natural fear into pest birds, without the disadvantages of using real bird of prey.

1.1.2 Structure and functioning

Three main parts can be distinguished on the Robird, the body/hull, the wings and the tail. The Robird is constructed of a 3d-printed nylon hull, wings made of foam with a thin foil layer on them for strength and protection. The tail is made of a custom carbon-fibre material, that is strong and lightweight. The hull contains the motor, wing driving mechanisms, batteries and board computer. The wings are driven on two pins so that the front and back of the wing can move up and down separately. This is used to drive the wings in a wave-like flapping motion, which generates both the lift and thrust necessary to fly the Robird. The tail is v-shaped and can be controlled to act like a rudder and elevator.

The Robird can be flown in two different modes, gliding-mode and flapping-mode. In the former mode the wings are locked in a fixed position using a pawl, making the Robird behave as a glider. The other and far more interesting mode, is the mode in which the Robird flaps it wings to fly. The aerodynamics in this mode are not yet fully understood quantitatively.

1.2 Research opportunities

The Robird is not only useful for its commercial purpose of scaring away pest birds. It also offers various options for research. The Robird was originally developed from a hobby prototype by trial-and-error, combining experience with birds and model air-planes. Because the Robird was made by trial-and-error, instead of being made based on a well-understood theoretical design, much of the theory behind the design is still relatively unknown. This opens the opportunity to study the dynamics and aerodynamics of the Robird and ornithopters in general. Besides studying how the Robird currently flies, the Robird can also be studied to further improve its flight performance. Especially when more of the (aero)dynamics are uncovered. Understanding the dynamics of the Robird, means that the reaction of the Robird to controllable inputs, like the tail pitch, throttle and locking of the wings, and to disturbances can be predicted much more accurately. This can be used to improve the auto-pilot, as a path can be followed much more accurately when the inputs required to follow that path are known more accurately. Also the feedback used to correct errors can be improved by reducing the amount of over or under correction, keeping unwanted pitching, yawing and rolling under control. This increases the stability of the Robird and possibly allows safe flight under more extreme conditions. Other performance aspects, that are not control related, can also be improved by studying the Robird. Optimizing energy efficiency is important to increase flight times, possibly decrease battery sizes and reduce energy costs. For this air resistance has to be studied and minimized. Furthermore the effects of the shape of the wings and their flapping motion can be studied to maximize the thrust and lift generated.

Lastly the Robird might not only be used to study its mechanics, it could also be used to possibly learn something about real birds. Because the Robird mimics the flight of real birds understanding the flight of the Robird could lead to understanding of the flight of real birds. Researching the reaction of real birds to the presence of a robotic version of their natural predator, is important for understanding how ornithopters can be used to reduce the hindrance of pest birds. Do birds get used to the robotic version? How important are the looks of the robotic bird and how important its flight motion?

The research opportunities discussed above, can be split into two categories. Those relating to the mechanics of the Robird and those relating to the biology and ethology of real birds. The latter are not of interest for this bachelor assignment. For studying the mechanics of the Robird the motions of and forces on various parts of the Robird need to be able to be measured. For this a test set-up is required in which the dynamics of the Robird are similar enough to the dynamics of the Robird that occur during real flight. The test setup must thus allow sufficient degrees of freedom in order for the Robird to respond to forces, torques and stresses in the same way as it would in real flight. In real flight the body of the Robird heaves and pitches during flaps of the wing and it can also roll and yaw using the control surfaces. However the Robird must be restricted so that the test can be performed within the room available in the test environment. The test rig must therefore be able to fit on a tabletop. Besides this the constraints can also be used to more easily measure the motions of the Robirds. If the Robird is free to fly anywhere in the room it is much more difficult to perform measurements on it, as the measurement system must be able to work on all possible positions. When the Robird is confined by the test rig the amount of possibilities is greatly reduced and the measurement might even be able to be integrated in the test rig.

1.3 Comparison between existing ornithopter test set-ups

A couple of ways of testing the Robird have been used so far. These methods however had serious limitations on how well they can mimic real flight dynamics, how well measurements can be performed or how practical the method is to use. Besides test set-ups used by Clear Flight Solutions to test the Robird, various other companies and organizations have used different test set-up to perform measurements on ornithopters. It is useful to investigate these various test methods and determine their advantages and shortcomings, to see how they could be applicable to designing a good test rig for the Robird. Table 2 gives an overview of the test set-ups, which are further discussed below.

	Fixed on stand	**Real flight**	**Springs in frame**	**Rotating arm**
Practicality	++	−	+	-
Dynamics	−	++	+-	+
Measurements	++	−	+	+

Table 2: Comparison between various existing ornithopter test set-ups, on practicality (space taken up, ease of use), accuracy of simulating real flight dynamics and ease of performing measurements.

Fixed stand The most basic test set-up used is rigidly attaching the body of the Robird to a fixed stand. This stops all motion of the body and only allows motion of the wings and tail. This set-ups biggest strength is its simplicity. The amount of equipment needed is small and it requires no advanced equipment. Furthermore it is easy to set-up and make tweaks to the ornithopter and can be used in a small space. Because the ornithopter is fixed in position the measurement instrument only has to measure at that position. The major downside of this measurement set-up is that it greatly affects the dynamics and stresses in the Robird. In free flight the body of the Robird moves up and down and pitches during each wing flap, which cannot occur when the body is fixed. The extra forces applied by the frame to hold it in place also increase the stresses in the Robird. Fixing the body, however, not only affects the dynamics in the body, but also the (aero)dynamics of the wings and the stresses in them, as there is no airflow along the wings from forward speed.

Real flight A second very basic method to perform tests on the Robird is actually flying it. Although the dynamics are exactly as desired, performing accurate measurements is much harder. Sensors have to be either placed on the Robird or they must be able to track the Robird at any position it flies to. Tracking the path and pitch of the Robird is doable with this method, however, measuring things like wing bending and air turbulence is much harder. Even when accurate measurements can be obtained, it is hard to determine whether certain behaviour is a result of an intended input given to the Robird or was caused by disturbances in the environment. Besides this it takes much more effort to get all the equipment out, a pilot is needed and good weather is necessary to even be able to perform the test. This method should therefore mainly be used as last test to see if something works in practice after good results have been obtained with more controlled tests.

Springs in frame Another method, that was used for a short period of time by CFS, mainly for demonstrations, was hanging the Robird with spring from the corners of a rectangular frame (figure 1). This has many advantages over simply fixing the body to a stand. With this set-up the Robird can move in all D.O.F. to some extent, limited by the springs pulling it back. This gives room for the up and down and pitching movements of the body that occur during normal flight, mimicking the dynamics of free air flight more closely. This set-up still does not allow for forward movements, as the thrust from the wings will strike some balance with the springs pulling it back. Another problem with this set-up are the dynamics of the springs that are added to the system. These could give rise to oscillatory behaviour. The thrust during a wing flap is not constant, resulting in the Robird oscillating forward and backward in the frame. To prevent or reduce oscillations stiffer spring can be used, but using too stiff springs results in the not having enough freedom to move and behaving as if fixed in place completely, like in the fixed-to-stand set-up described above.

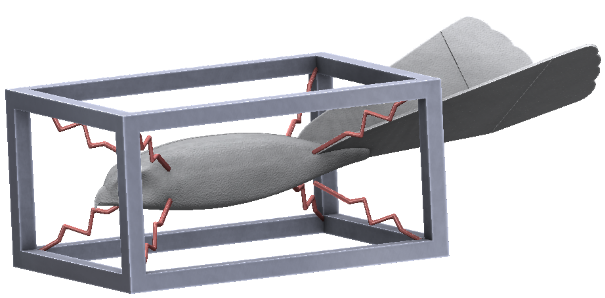

Figure 1: A set-up in which the Robird is hung from the corners of a rectangular frame using springs.

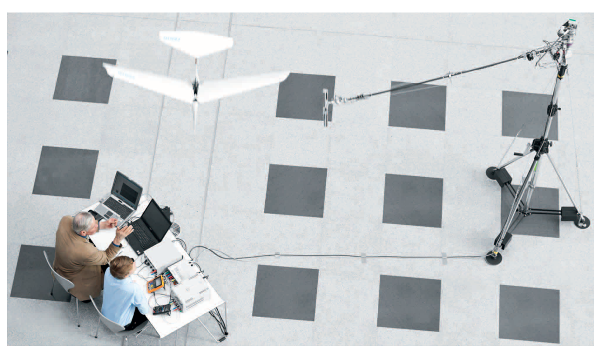

Figure 2: Test set-up for an ornithopter used by Festo. The ornithopter flies in a circle around the stand [4].

Rotating arm A very set-up, very different from the ones discussed above, has been used by Festo to test their ornithopter (figure 2). They used a tripod around which an arm rotates. At the end of the bar the ornithopter is connected, so that it follows a circular track. If the radius is large enough this accurately simulates forward motion. The flexibility of the arm allows for a small amount of up-and-down motion and pitching. This has as side effect that it also rolls a bit under the weight of the ornithopter [5].
The arm can be powered by a motor which allows the lift and drag forces to be measured. When the ornithopter flies on itself, the thrust force can be measured [4].

1.4 Goals of bachelor assignment

The main goal of the bachelor assignment is to develop a test rig for the Robird, in which various measurements on the performance of the Robird can be performed, under conditions similar to real flight. To make the design the requirements are first determined, including which degrees of freedom the Robird needs to have, in order to behave similar enough to real flight and which ones can be restrained. From these requirements various design options are considered. The best design will be build and used to test the dynamics of the Robird. These results when using the test rig are then compared to measurements of dynamics during real flight to verify if the test rig is working as intended. If the test rig works properly it can be used by CFS for further research on the Robird.

2 Design Considerations

2.1 Requirements

For the test rig for the Robird two groups of requirements can be distinguished. The ones that describe how accurately the real flight behaviour should be mimicked in the test rig and those that deal with the construction of the test rig itself. A summary of the requirements is given in table 3, which are further discussed below.

Property	Requirement
up-down D.O.F.	necessary
forward D.O.F.	necessary
sidewards D.O.F.	constrained
pitching D.O.F.	important
rolling D.O.F.	optional
yawing D.O.F.	optional
added inertia	max 400 g
spring dynamics	no resonance
size	table top
total weight	5 kg
integrated measurements	optional

Table 3: requirements on the test rig

For the former it is important to know which degrees of freedom should be allowed and which should be restricted. The most important degree of freedom that must be allowed is the up and down motion of the body that occurs during one wing flap. When the wings move upward the body moves downward and vice versa. Not allowing this motion would put large stresses on the connection between the wings and the body. The simulation of forward motion is also important. The forward motion causes airflow over the wings generating lift.
Pitching is not crucial to have, but can be significant. Pitching alters the angle of attack of the Robird. Measurements in free flight show that the pitching angle oscillates with an amplitude of around 2.5°, while a model of the effective angle of attack show that this oscillates with an amplitude of 22° [6].
Allowing rolling and yawing could allow for the testing of steering manoeuvres, yet is not necessary for simulating basic flight dynamics. Rolling and yawing are therefore not necessary to have, but can be optional if a design allows for simple implementation of them. A small amount of rolling should be allowed so that the wings can be balanced. This balancing needs to be done once before testing.
Sidewards motion is not needed to have as the Robird steers by rolling and yawing, always turning its nose in the forward direction.
Another important factor that influences how well the dynamics in the test rig mimic the dynamics of real flight is how much inertia is added to the Robird by the test rig. Parts of the test rig move as the Robird moves, thus adding inertia to the system. Because the same forces act on the Robird, a higher inertia leads to a lower acceleration and thus slower motion of the Robird than when flying with nothing attached. The maximum allowed added inertia is determined to be 400 g.
Lastly, any springs that are used to keep the Robird in its equilibrium, must not alter the dynamics of the system too much. For this reason the spring constant must be fairly small, so that the force applied by the springs is almost constant and just compensates for gravity. Also if the spring constant is small enough the natural frequency will be much smaller than the driving frequency, thus preventing resonance.

For the requirements of the construction of the test rig, the size of the test rig is the most crucial one. The test rig must be able to be used in a table top set-up.
In addition to the added inertia also the total weight of the test may not be too high. The maximum weight of the test rig is determined at 5 kg.

The cost of building the test rig must not be excessively high. A total budget is not given in advance, but along the way it is determined whether certain parts can be ordered or that they are too expensive.
Another criteria to judge possible designs on is how well measurements on the dynamics of the Robird can be performed with the test rig. The Robird has a build-in accelerometer, but the forces acting on the test rig in the restrained directions cannot be measured by them. A test rig in which measurements for these forces are integrated is preferable.

2.2 Rotating and fixed set-up comparison

In section 1.3 two main forms of test set-ups can be distinguished; Those in which the ornithopter follows a circular path and those in which the forward direction is fixed. A test rig in which the Robird follows a circular path allows forward motion. For a set-up with fixed forward direction a wind tunnel is needed to simulate forward speed. A problem with using a circular motion is that the speed is not uniform over the width of the Robird and also a non-uniform centripetal is introduced. With increasing distance from the centre-point the forward speed and centripetal force increases. To reduce this, the radius of the circle must be increased so that the relative difference in distance between the wing tips and the centre point is decreased. However, for doing so is little room without violating the tabletop size requirement. For these reasons the decision was made not to further consider rotating designs.

2.3 Modelling heaving motion

A model was made to estimate the amplitude of the up-and-down oscillatory motion of the Robird body and the forces acting on the body to create that motion. This is done so that a design can be made that can handle this motion and accompanying forces. In the model the contribution of the vertical components of friction forces on the wings and the change in the place of centre of mass during a wing flap are considered. The lift force is assumed to cancel out with gravity and the drag force on the hull is assumed to be negligible compared to the drag force on the wings.

$$m_{\text{hull}} \cdot a_{\text{hull}} + 2 \cdot \int_0^L a_{\text{wing}} \cdot \rho_{\text{wing}} \cdot W \cdot dl = 2 \cdot F_{\text{fric,wing}} \tag{1}$$

Where W is the width profile of the wing, which depends on l. L the total length of the wing and ρ_{wing} the mass density of the wing per unit surface area.
Because the connection point of the wing has the same acceleration as the hull:

$$a_{\text{wing}} = a_{\text{hull}} + a_{\text{rotation}} = a_{\text{hull}} + \frac{d(\cos(\phi) \cdot \omega \cdot l)}{dt} \tag{2}$$

$$m_{\text{total}} \cdot a_{\text{hull}} + 2 \cdot \int_0^L \frac{d(\cos(\phi) \cdot \omega \cdot l)}{dt} \cdot \rho_{\text{wing}} \cdot W \cdot dl = 2 \cdot F_{\text{fric,wing}} \tag{3}$$

Where ϕ is the angle of the wing and ω its derivative, the angular velocity.
For the friction of the wings the drag equation is used.

$$F_{\text{fric,wing}} = \cos(\phi) \int_0^L \frac{1}{2} \cdot c_{\text{d}} \cdot \rho_{\text{air}} \cdot v^2 \cdot W \cdot dl = \cos(\phi) \int_0^L \frac{1}{2} \cdot c_{\text{d}} \cdot \rho_{\text{air}} \cdot (\omega \cdot l)^2 \cdot W \cdot dl \tag{4}$$

Where c_{d} is the drag coefficient of the wing and ρ_{air} the air density.
Substituting this equation in equation 3 and solving for a_{hull} yields:

$$a_{\text{hull}} = \frac{1}{m_{\text{total}}}(\cos(\phi) \int_0^L (c_{\text{d}} \cdot \rho_{\text{air}} \cdot (\omega \cdot l)^2 \cdot W \cdot dl) - 2 \cdot \int_0^L (\frac{d(\cos(\phi) \cdot \omega \cdot l)}{dt} \cdot \rho_{\text{wing}} \cdot W \cdot dl)) \tag{5}$$

Integrating this result twice will give the vertical position, while multiplying the mass of the hull gives the force on the hull and thus on the test rig. These are thus only a function of the angle of the wings.

This model was implemented in Simulink using the following values for parameters and the width profile shown in figure 3.

- $m_{\text{total}} = 700\text{g}$
- $m_{\text{hull}} = 500\text{g}$
- $L = 50\text{cm}$
- $c_{\text{d}} = 1.2$ (Based on flat plate perpendicular to flow [7])
- $\rho_{\text{air}} = 1.225\text{kg/m}^3$
- $\rho_{\text{wing}} = 1.11\text{kg/m}^2$

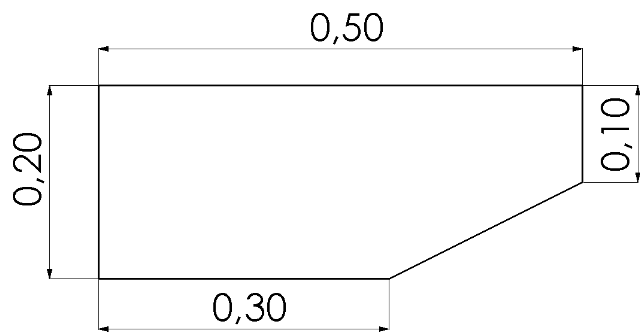

Figure 3: Simplified wing profile of the Robird, used for modelling the heaving motion of the Robird. (Dimensions in metres)

The Robird drives it wings with a frequency of 5 Hz with a maximum angle of 60° above horizontal and a minimum of 25° below the horizontal. The results of the simulation with this input are shown in figure 4. Because the vertical components are considered, the peak of the force is not when the wings are at their highest position, where their movement has a large horizontal component. The peak force is 30 N. The difference between the peak force during the up-stroke and the down-stroke come from the drag force on the wings.
The initial conditions for integration are chosen so that it oscillates around 0 cm height. The amplitude of the oscillation was found to be 0.7 cm. This is somewhat lower than expected from watching the Robird fly. This could be due to simulating with 5 Hz, while the frequency in flight is typically closer to 6 Hz. Additionally the drag coefficient might have been estimated too low and the lack of lift forces in the model might also reduce the amplitude. The actual amplitude is estimated at 1 cm to 2 cm.

2.4 Springs

In order to confine the movement of the Robird, it must be stopped when it moves too far from its neutral position. Springs are a good candidate to do this as they exert a force on the Robird to pull it back when it gets out of its equilibrium position. The springs need to fulfil two purposes; Counteracting gravity when testing outside a wind-tunnel where there is no lift force and stopping unusually large motions.
At the equilibrium point the Robird only experiences a force that counteracts gravity. To simulate flight dynamics accurately, the force should change as little as possible during small deviations from this point. This can be achieved by a spring with a small spring constant, under a large pre-load. This characteristic is shown in figure 5.
The springs used to stop large motions should not exert a force when the Robird is in its neutral position. At small deviations they should still exert a minimal force, but as the deviation gets even larger the force exerted by the springs should ramp up quickly. The ideal spring characteristic for this spring is shown in figure 6. The springs characteristic of both these springs combined is shown in figure 7.

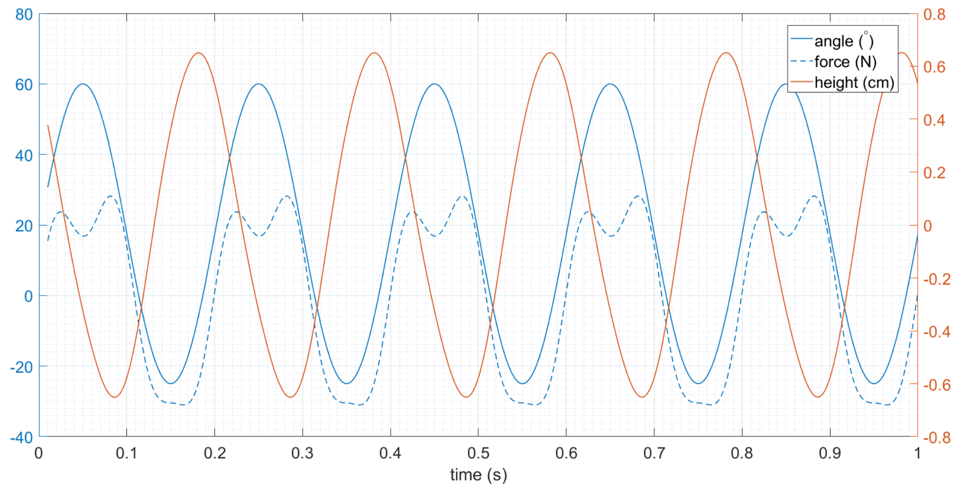

Figure 4: Simulation of the heaving motion of the Robird. The wings are driven with a frequency 5 Hz. The peak force on the hull is 30 N. The Robird heaves with an amplitude of 0.7 cm.

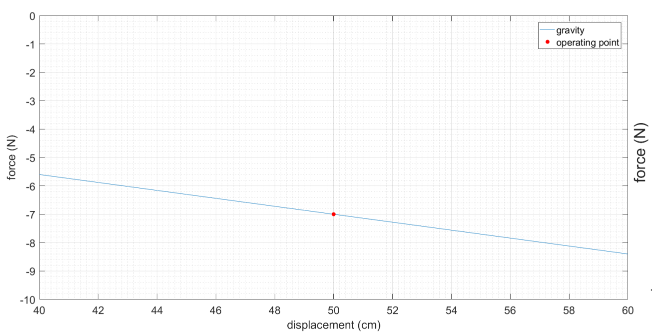

Figure 5: Ideal spring characteristic of spring to counteract gravity. The spring has a low stiffness and a large pre-load.

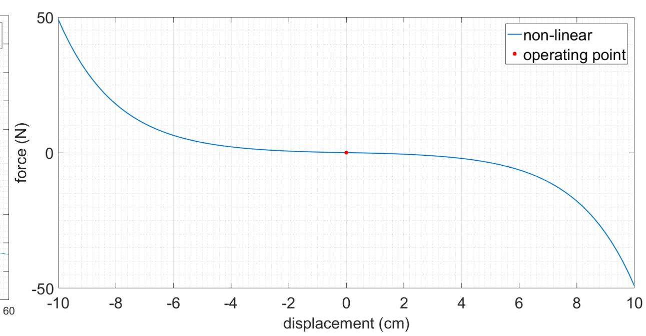

Figure 6: Ideal spring characteristic of spring to stop large motions. The force is very small for small motions, but rapidly increaes for larger deviations.

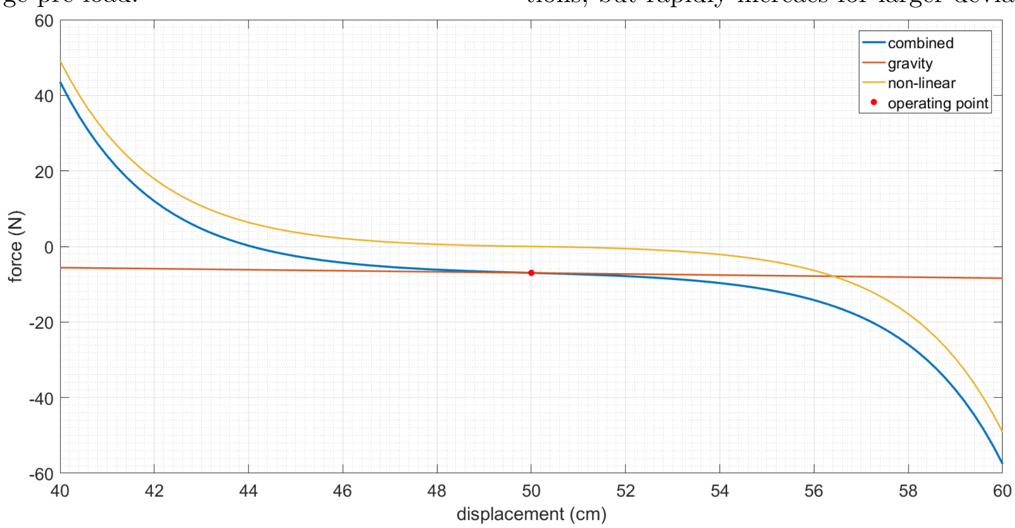

Figure 7: Ideal total spring characteristic. At the operating point, the springs counteract gravity, but the spring constant is low. At large displacements the stiffness increases rapidly.

3 Concept Designs

Based on the requirements and considerations set out in the previous section (2) a few concept design were made. The pros and cons of each design were weighed and the best design is further worked out in section 4: Final Design.

3.1 Moving platform

In this design a the Robird is placed on a horizontal platform which can move in the vertical direction. Springs, such as discussed in section 2.4, can simply be attached to the platform. Two options to allow for movement in the vertical direction are considered: a linear rail guide and a parallel four-bar linkage. Drawings of both are shown in figure 8. Using the four-bar results in a backward motion being coupled to motion in the vertical direction. To reduce this effect the bars need to be long enough so that the vertical motion is small relative to the length of the bars. Using the linear rail guide will therefore make the test rig much smaller than using rotating bars. However, the linear rail guide might not allow for very smooth movement when the platform is not only loaded with vertical forces, but also with pitching, rolling and yawing moments.
From the platform a connection can be made to the Robird. Because this connection is cascaded, the D.O.F. of the connection between the Robird and platform are added to the vertical D.O.F. of the connection between platform and the frame [8].The connection from the platform to the Robird, thus only needs to allow for pitching and optionally rolling and yawing. The axes of rotation should be close to the centre of mass of the Robird. Figure 8 shows a connection between the platform and the Robird with two bars that can hinge at both ends and intersect in the centre of mass of the Robird. This connection allows for pitching around the intersection of the two bars. This design can easily be extended to a 3D case, which also allows for rolling and yawing, by making a tripod of bars intersecting in the centre of mass and replacing the hinges with ball-and-socket joints.

Added inertia The weight of the platform and the bars connecting the Robird to the platform have to be added to the inertia of the Robird. Because the Robird is fairly long the platform needs to extend around 40 cm from the frame, to prevent the tail from colliding with the frame. Because of the length of the platform, it must also be strengthened to prevent it from bending too much. This also adds extra weight to the platform. In combination with the bars connecting the Robird and the platform, this puts the added inertia of this design close the maximum allowed inertia.

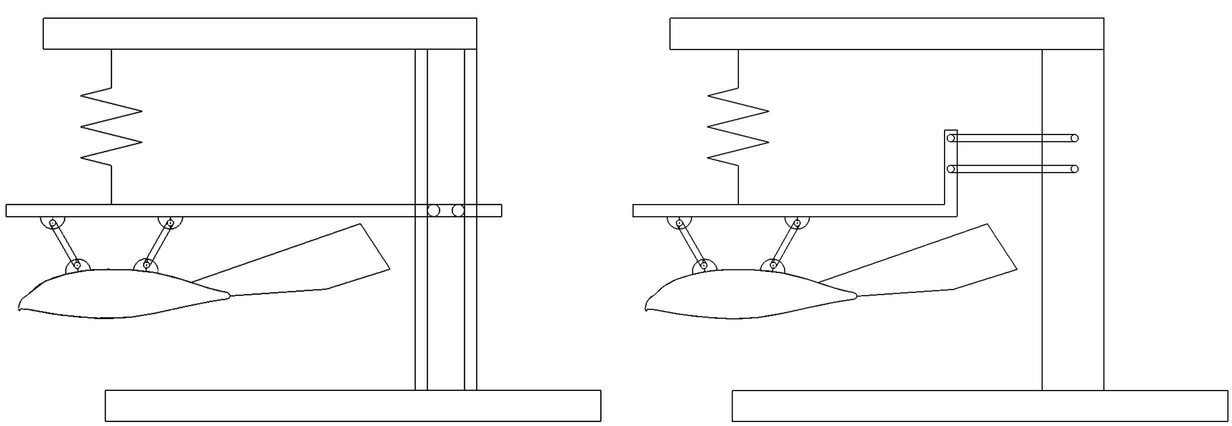

Figure 8: Concept design in which the Robird hangs from a platform. The platform can move vertically by a linear rail guide (left) or two rotating parallel bars (right).

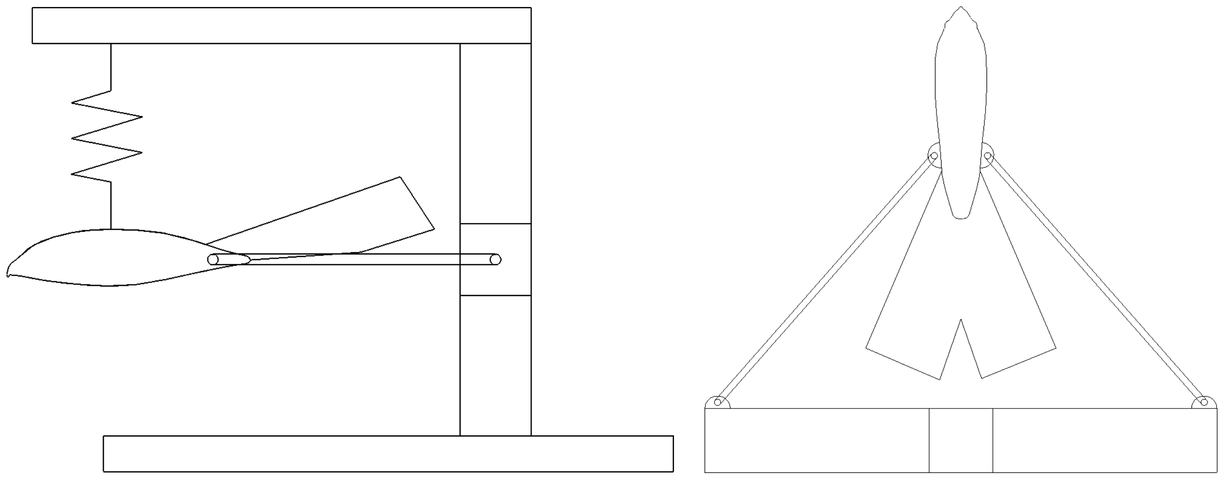

Figure 9: Concept design in which the Robird is constrained, by two (approximately) perpendicular bars in the horizontal plane. The bars can rotate at both ends. This prevents forward and sideways movement, while leaving the other D.O.F. free. Left: sideview, right: topview.

Non-ideal dynamics In the version with the parallel four-bar linkage vertical motion is coupled to backwards motion. When the Robird moves up or down from its neutral position it thus is pulled back by the thrust force. This effect is fairly small for small changes in height and if the length of the bars is not too small.
The connection that allows for the rotational degrees of freedom is also affected by coupling of motions. Yawing is coupled to upward motion, which might lead to problem if yawing is easier than pushing the platform up. Additionally the thrust force of the Robird induces pitching.
Having a large flat plate above the Robird negatively affects the airflow around the Robird. It disturbs the airflow over the tail and wings, leading to a change in aerodynamics. Modelling the significance of this effect, is beyond the scope of the bachelor assignment.

Integrated measurement options In this design, tracking the height of the Robird can easily be achieved by tracking the height of the platform. Tracking the rotational degrees of freedom is hard in this set-up, as there is no specific part from the position of which uniquely determines the position of one of the rotational degrees of freedom.
The thrust force produced by the Robird can be measured, by measuring the force with which the platform pulls on the frame.

3.2 Direct constraint

In this design the Robird is constrained by two bars in the horizontal plane. One end of the bars is connected to the Robird by a ball-and-socket joint and the other end is connected to the frame, also by a ball-and-socket joint (figure 9). This results in three rotational D.O.F. around the intersection of the constraint lines of the two bars and one translational D.O.F. in the vertical direction. For motions that are not sufficiently small the vertical translation will actually be a rotation around the connection of the bars to the frame. The bars must therefore be long enough that the vertical motion during a wing flap is relatively small enough. For the backward displacement to be a maximum of 10% of the vertical displacement the bar, with a vertical displacement of around 8 cm, the perpendicular distance between the centre of mass of the Robird and the connection to the frame must be at least 40 cm long. Since the bars will be placed at an angle of approximately 45°, this means that the construction will be around 80 cm wide. Because the Robird can roll in this design, the springs keeping the Robird in place must be placed above the Robird to make it stable in equilibrium position. This means that the test rig would be around 50 cm high.

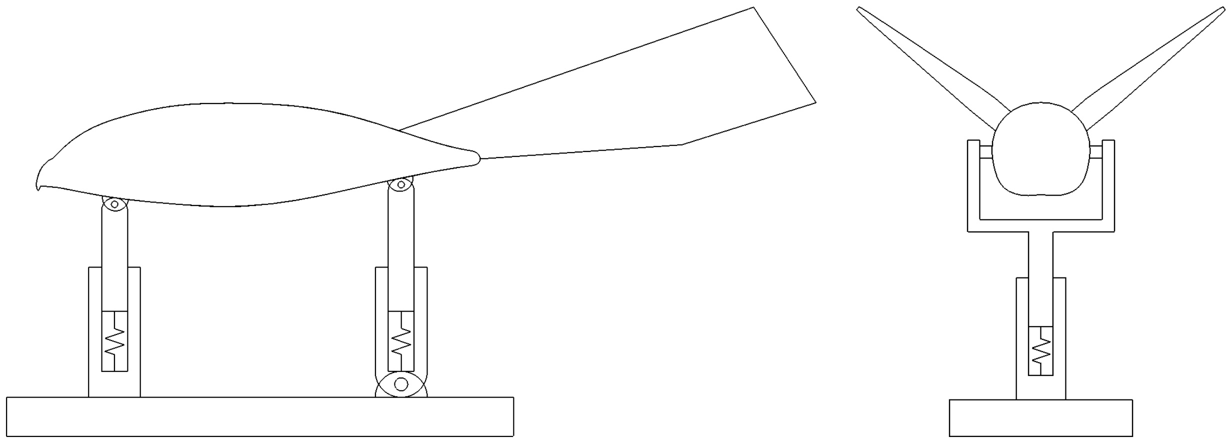

Figure 10: Concept design in which the Robird rests on two vertical guides. The back guide can rotate at both ends, while the front guide can only rotate at the side of the Robird. The design allows only for vertical translation and pitching. Right: a Y-bar design for the front guide that minimizes the moment of the thrust force.

Added inertia Although the size and weight of the total construction is large the inertia added to the Robird is relatively small. The end of the constraint bars connected to the Robird follows the motions of the Robird fully, while the others end stays in place. This means that on average it gains half the momentum as when the entire bar would have to follow the movements of the Robird. On top of that, the bars can be made of lightweight hollow tubes, while still being very strong.

Non-ideal dynamics When the Robird is in neutral position the Robird can rotate around all axes and move vertically independently. However once the Robird is slightly out of its neutral position, its intended motion are coupled to other motions. The vertical translation is coupled to a backwards translation. Rolling and pitching are also coupled to a backwards motion. Rotation around the vertical axis is coupled with translation in the horizontal plane. However, the thrust generated by the Robird counteracts the motions that are coupled to a backwards motion, thus reducing these coupled motion. The amount of reduction depends on the relative magnitude of the thrust force to the magnitude of the force causing the coupled motion and the angle of the Robird.

Integrated measurement options Thrust force can be measured by measuring the force that the cross bar, to which the constraint bars are connected, exerts on the frame. Other measurements are difficult to integrate in this design.

3.3 Double vertical guides

In this design the Robird is placed on two vertical guides. One of the two guides is fixed in the vertical direction to the frame, preventing forward movement. At the connection to the Robird it allows rotation around the sideways-axis, to allow for pitching. The other guide allows rotation around the sideways-axis on both ends (figure 10). This set-up allows for 2 D.O.F., vertical translation and pitching.
The guides need to be able to be elongated long enough for the vertical motion of the Robird. The test rig will be therefore around 20–30 high and will fit under the Robirds body.

Added inertia The extra mass that has to move with the Robird are the two bars that are attached to the Robird and fit into the vertical guides. Also the system that connects these bars to the Robird adds extra inertia. The bars could be made of hollow lightweight tubes, keeping their weight low.

Non-ideal dynamics When the Robird pitches downwards, the front spring tries to push it back up, while the one at the back pulls it down. This reduces the amount of pitching of the Robird. The spring constant of the must be small enough to allow sufficient pitching of the Robird. If the Robird is placed on the platform above the hinges, the thrust force creates a moment around the front hinge, resulting in a downward pitching motion. The extend to which this happens depends on how much the hinges are below the body of the Robird. This effect can be counteracted by placing the hinges on Y-shaped bars, so that they are higher along the body and the arm of the moment is reduced (figure 10).

Integrated measurement options The thrust force could be measured by placing a load cell under the front guide. No thrust force should be exerted on the back guide as it can hinge on both sides to allow forward motion. The vertical position can be measured from the amount of extension of the front guide and the pitching angle can be determined if the extension of both guides are known.

3.4 Comparison of concept designs

To find the best concept design, the designs were rated on the requirements set-out in section 2.1. The ratings are shown in table 4.
From these ratings it can be seen that the concept design with two vertical guides, clearly outperforms the others, unless a very high value is placed on having rolling and yawing. Since rolling and yawing are considered optional from the requirements, the vertical guides design was further worked out.

	Moving platform	**Direct constraint**	**Vertical guides**
Size	+-	-	+
Weight	-	+-	+
Added inertia	-	+	+
D.O.F.	2 or 4	4	2
Non-ideal dynamics	-	+-	+
Complexity	+-	+	+-
Integrated measurement options	+	-	+

Table 4: Ratings of the concept designs on the requirements set out in section 2.1

3.5 Evans straight line mechanism

Although drawn as two tubes sliding into each other in the concept design, various mechanisms exist that limit the motion of an object to an (approximate) straight line. For the test rig it is important that the point of the mechanisms describing the straight line is also the highest point of the mechanism, because the mechanism cannot go through the Robird. Furthermore, the mechanism should be compact, so that the test rig does not become too high.
Two parts sliding into each other is a simple solution, but might not allow for very smooth movement when it is not only loaded with vertical forces, but also with pitching, rolling and yawing moments.
An Evans mechanism does not have this problem, as it uses rotating bars, while still being compact and, depending on the chosen variant, has its highest point moving in a straight line. An Evans straight line mechanism is a four-bar linkage with four revolute joints in which a point fixed relative to the floating link moves in an approximately straight line. Many variants exist, with different lengths for the bars. The chosen variant is shown in figure 11. The angle of AD with the horizontal is approximately 4°.
Using an Evans mechanisms has the additional advantage over a sliding mechanism that it can be completely made out of flat plates. Flat plates can be produced fast and accurately by using a laser-cutter. The design of flat plates is also easier because all parts are 2D. Another advantage of the Evans mechanism is that it is easier to measure the position of the guides by placing a rotation sensor on the axis than it is to measure the extension of the sliding parts.

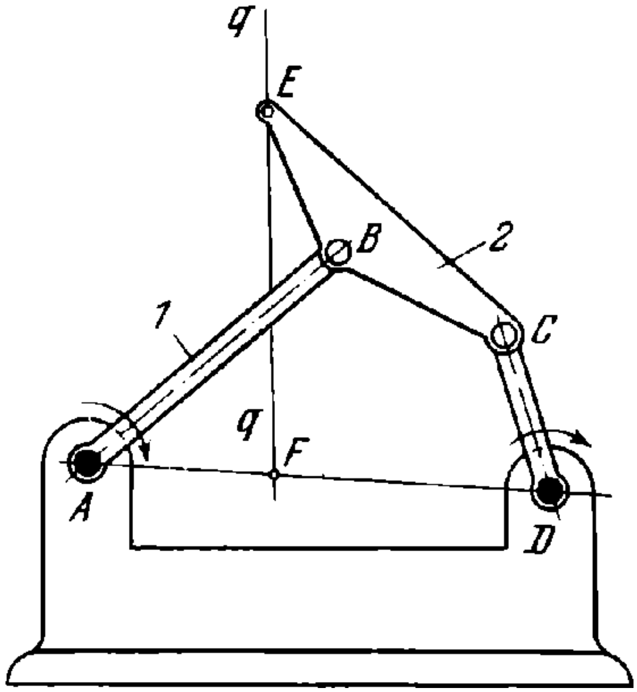

Figure 11: Evans straight-line mechanism used in the test rig. AD=1.41AB, AF=0.55AB, BC=0.55AB, BE=0.45AB, CD=0.48AB, CE=0.96AB. [9]

4 Final Design

The final design uses a Evans straight-line mechanism with AB=20 cm for both the front and the back guide. These are placed so that the back connection comes just in front of the tail and the front connection just in front of the wings. The full test rig weighs 2.8 kg, of which 1.3 kg comes from the wooden ground-plate and the bolts connecting the stands to the ground-plate. The final design is shown in figure 12 and 13.

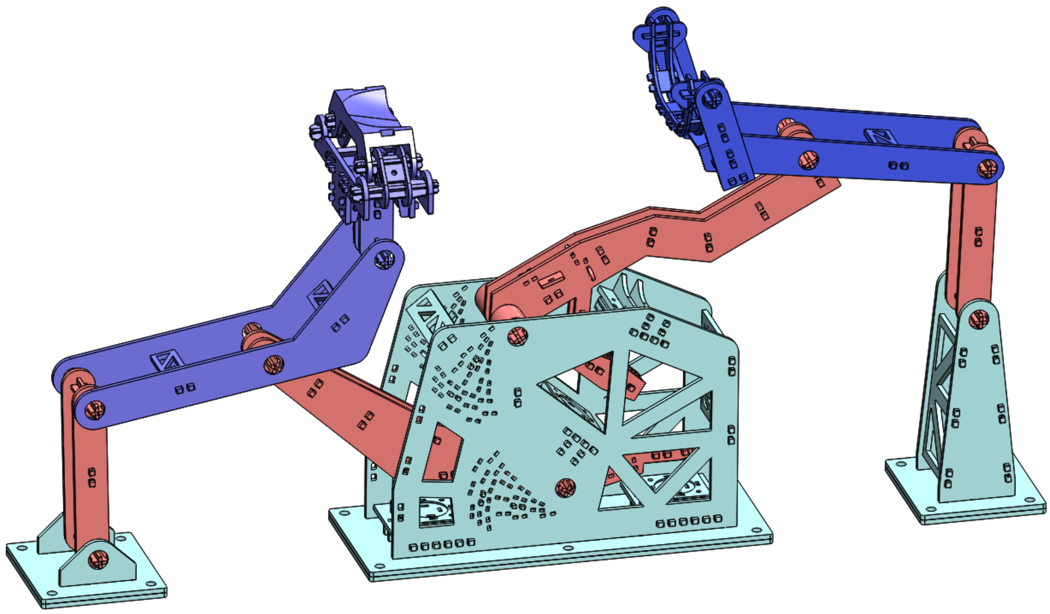

Figure 12: Coloured Solidworks model of the test rig. Light blue: base, red: arms, dark blue: front connection, purple: back connection

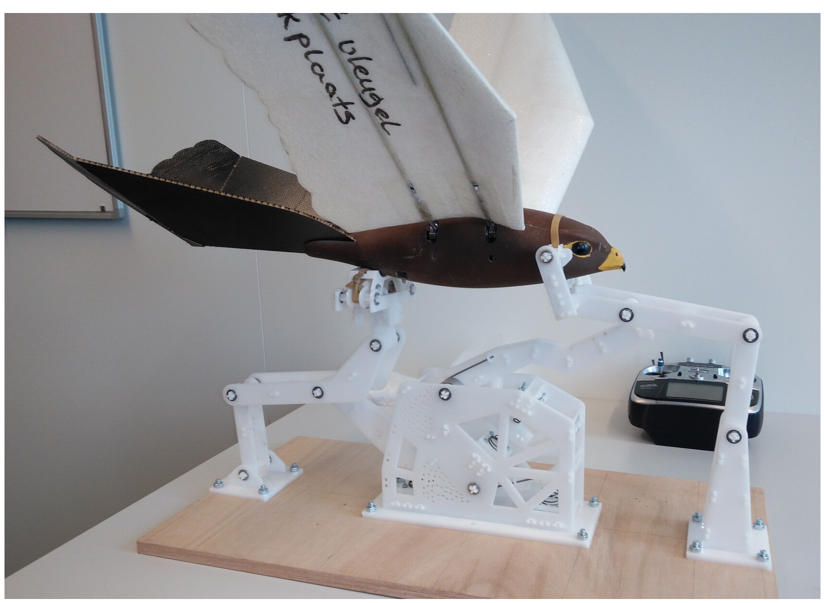

Figure 13: Test rig for the Robird completely build. The elastic strap on the back is placed over the Robird during actual tests.

4.1 Base

The base needs to provide the ground links for the four-bar linkages and fix them relative to each other. Additionally the base needs to hold the springs and provide as stable basis. The base consists of a ground-plate and three stands. The ground-plate is a wooden plate of $61 \times 30 \times 1$cm. The stands are connected to the ground plate by countersunk bolts.

4.1.1 Side stands

The side stands hold the axes of the short arm of the Evans straight line mechanisms. The stand at the front is 10 cm higher, than the stand at the back. The front stand therefore has two cross-plates for extra strength.
The side-plates that hold the axes have hooks on the bottom, that fit exactly in the slides in the two horizontal plates. The holes in the top plate are slightly shifted w.r.t. the bottom plate, so that sliding the top plate will lock the hooks.

4.1.2 Middle stand

The middle stand holds the axes of the long arms of the Evans straight-line mechanisms and the the springs that work on these arms. The middle stand is connected to the ground-plate with the same hooks as the side-stands. Four cross-bars are placed between the side-plates for extra strength.

Torsion-springs connection The side-plates of the middle stand contain a large number of slides in which the clips that hold the arms of the torsion-springs can be placed. These slides are placed in increments of 5° of turning of the spring.

Conical springs connection The conical springs are placed on square plates. These plates have various thicknesses and can be stacked to set the conical spring at the correct height. The plates are connected by 3M bolts and have slides in them through which the spring can be tied to the stack of plates.
The stack rests on a larger plate that is connected to the side-plates of the stand. This plate is further supported by two arches to reduce bending. The holders for the conical springs are shown in figure 14.

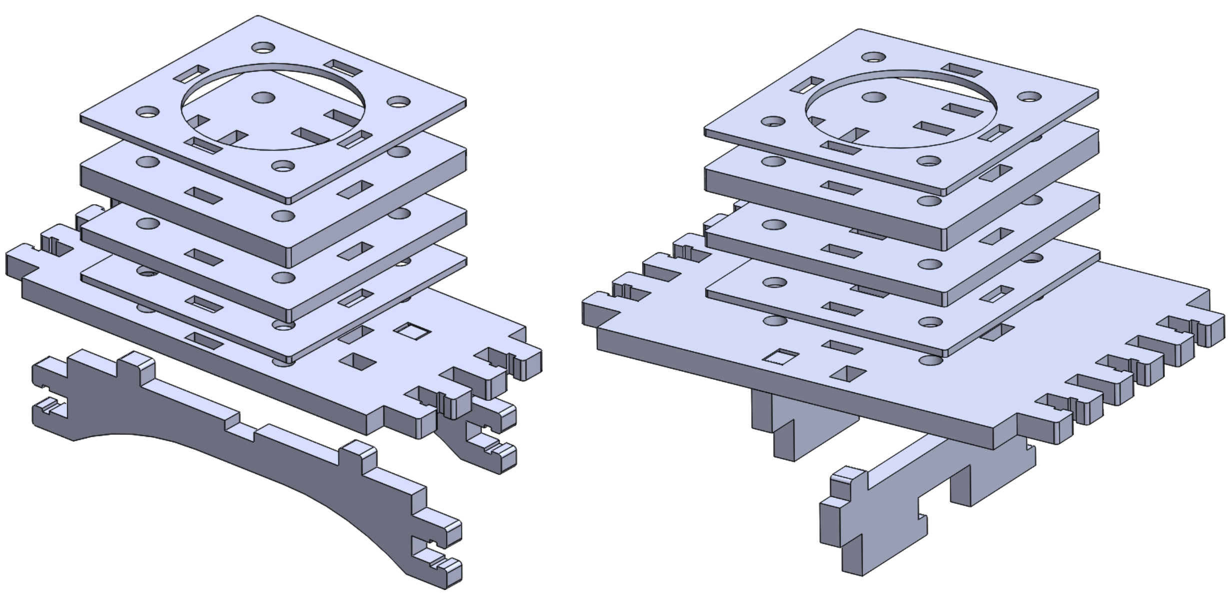

Figure 14: Exploded view of the holders in which the conical springs are placed. Left: holder for arm at front side, right: Holder for arm at back side.

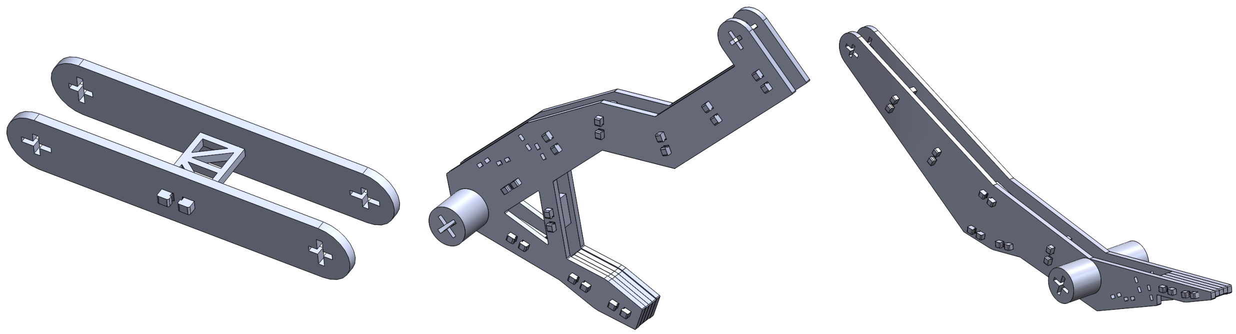

Figure 15: Grounded links of the Evans mechanisms. Left: short arm, middle: front long arm, right: back long arm

4.2 Arms

Each Evans straight line mechanisms has 2 arms. The short arms are identical for both mechanisms. The long arms have the same distance between their rotation points and fulfil the same functions, but have different shapes to be able to fit in the stand.

Short arms The short arms consist of two parallel bars that hold the pins of the axes at both ends. These arms connect the side stands to the floating links of the Evans mechanisms. The short arms are strengthened by a cross bar in the middle.

Front and back arm The front and back arm connect the middle stand to the floating links at the front side and back side of the Robird, respectively. The arms consist of two parallel plates, that are connected by multiple cross-bars to reduce bending.
The arms have two sets of slides for the clips that hold the arm of the torsional springs, with a 7.5° angle between the sets. The axis connecting the arm to the middle stand has a cylinder placed on it at both sides, that fits exactly inside the torsion spring.
At the point where the conical springs press on the arm, the space between the plates if filled with additional plates, which are curved so that the arm always presses straight down on the springs.

4.3 Front Connection

The front connection has two major components; The arc in which Robird is placed and the floating link of the Evans mechanism. They are connected by a rotating axis exactly on the point that moves in a straight line. The arc is so deep that the centre of mass of the Robird is approximately at the same height as the axis, so that the thrust force creates as little of a moment as possible around it. This prevents the thrust force from inducing a pitching motion.
The arc on which the Robird rests consists of two parallel plates, cut in the shape of the cross-section of the Robird at that position. One of the plates is also part of the axis. Another cross plate provides the other part of the axis. This plate and the two arc-plates are locked together by another plate that slides through the two arc-plates and is perpendicular to the axis of rotation. This locking plate has a slide cut in the centre through which an elastic strap can fit that goes around the Robird, securing it in place. The Elasticity of this strap allows for a few degrees of rolling.
The floating link is made of two parallel bars connecting the short and long arm of the Evans mechanism. These bars extends a bit further at the side of the long arm. At this extension another plate is placed through the parallel ones, that extends at both sides of the parallel plates. At both ends of this plate, another plate is attached, which holds the axis of the arc.

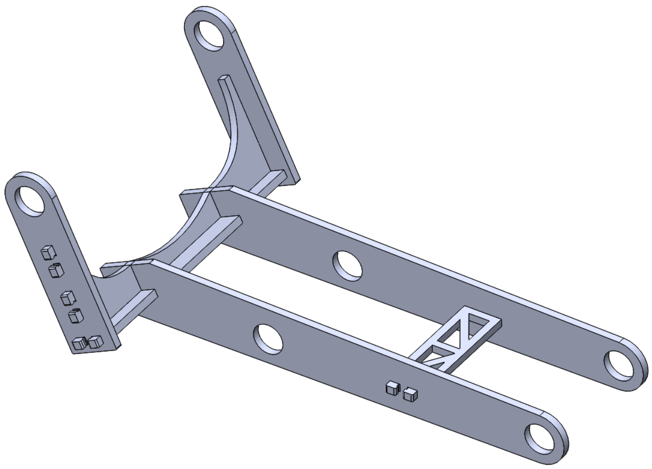

Figure 16: The floating link of the Evans mechanism at the front side of the Robird.

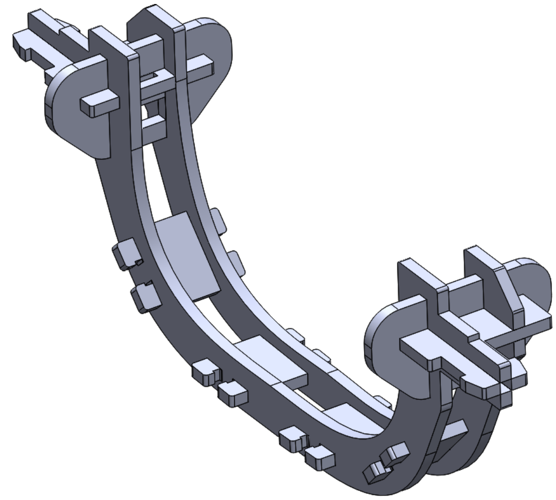

Figure 17: The arc in which the Robird is placed. An elastic strap fits exactly through the hole just below the axis.

4.4 Back Connection

Like the front connection, the back connection also is also made of a floating link and a component on which the Robird rests. The floating link is similar to the one on the front, except that is does not get wider, because it does not need to fit around the Robird. Unlike the front side, at the back side there is no room at the sides of the Robird, since this is taken by the wings and tail. Therefore the connection is placed under the Robird, just in front of the tail, with a strap over the Robird to keep it pressed on the support. This connection needs to allow for a few degrees of rolling and also around half a centimetre of forward movement. The forward movement is needed, because without it the Robird cannot pitch.
The rolling D.O.F. is achieved by the same method as discussed in section 3.1 for the connection between the platform and Robird. The top piece, on which the Robird rests, has a cut-out exactly in the shape of the hull of the Robird and is connected to a box below it by two short rotating bars. A compression spring is placed between the each roll-bar and the box, which presses the bar outwards. This makes the system stable around 0° of rolling.
The forward movement is achieved by the vertical link between the box and the floating link. This schematically shown in figure 18.

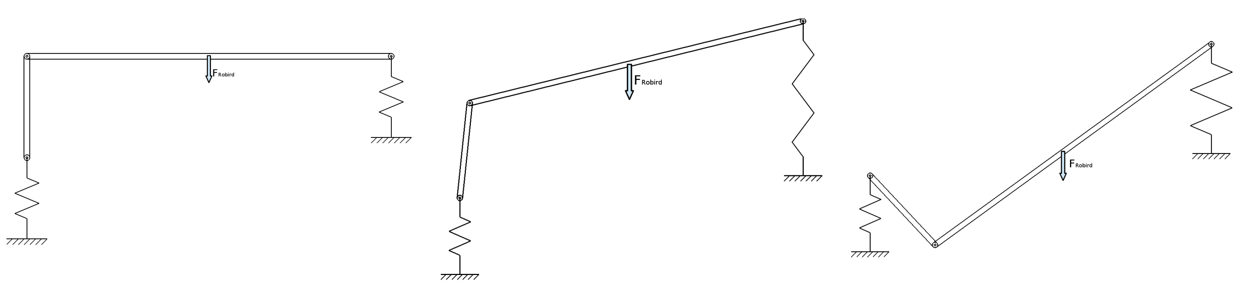

Figure 18: Schematic view of how pitching is achieved. The long bar represents the Robird, the short bar represents the link between the back Evans mechanism and the Robird. Left: neutral position, middle: some pitching, right: past stable point.

4.4.1 Stability of vertical link

From figure 18 it can be seen that the Robird might be able to push through to an undesired position. It is therefore investigated at which heights and pitches the Robird is pushed back to its neutral position and the vertical link thus provides a stable system. In order to do this first the equations of motions are found using Lagrange's equation (6).

$$\frac{d}{dt}(\frac{\partial T}{\partial \dot{q}_{\mathrm{i}}}) - \frac{\partial T}{\partial q_{\mathrm{i}}} + \frac{\partial V}{\partial q_{\mathrm{i}}} + \frac{\partial F}{\partial \dot{q}_{\mathrm{i}}} = Q_{\mathrm{i}} \tag{6}$$

$$T = \frac{1}{2}m\dot{y}^2 + \frac{1}{2}I\dot{\theta}^2 \tag{7}$$

$$V = mgy + \frac{1}{2}ku_1^2\frac{1}{2}ku_2^2 \tag{8}$$

$$F = 0 \tag{9}$$

$$Q = 0 \tag{10}$$

Where m is the mass of the Robird and I its moment of inertia, k is the effective spring constant of the Evans mechanisms and u_1 and u_2 are the compression of the front and back spring, respectively. u_1 and u_2 can be expressed in terms of the height and pitch (11,12).

$$u_1 = y + \frac{1}{2}L_1\sin(\theta) \tag{11}$$

$$u_2 = y - \frac{1}{2}L_1\sin(\theta) + L_2 - \sqrt{{L_2}^2 - (L_1 - L_1\cos(\theta))^2} \tag{12}$$

With L_1 the distance between the Evans mechanisms and L_2 the length of the vertical link. Plugging equations 7 to 12 into equation 6 gives the equations of motion (13, 14) in y and θ.

$$m\ddot{y} + mg + ku_1 + ku_2 = 0 \tag{13}$$

$$I\ddot{\theta} + (u_1 - u_2)k\frac{1}{2}L_1\cos(\theta) + u_2kL_1\sin(\theta)\frac{L_1 - L_1\cos(\theta)}{\sqrt{{L_2}^2 - (L_1 - L_1\cos(\theta))^2}} = 0 \tag{14}$$

From these equations a vector plot is made for the accelerations of y and θ which is shown in figure 19. As long as the pitch of the Robird does not get larger than 17°, which corresponds to a 10° angle of the link, the system is stable and will return the Robird to a 0° pitch. For this reason plates are placed on the box that prevent the angle to become than 10°.

4.5 Miscellaneous

4.5.1 Springs

Torsion springs For the springs that counteract the gravity when no lift force is generated, four torsion springs are used. Two are placed on each axis that connect the long arms of the Evans mechanism to the middle stand. When the Robird moves vertically the long arms rotate and work is performed on the torsion springs.

$$Fdh = Td\theta \tag{15}$$

Where F is the force with which the Robird pushes down, h is the vertical position of the Robird, T is the torque from the springs and θ is the angle of the long arms of the Evans mechanism. Substituting for the torque provided by the springs and rewriting for F gives equation 16.

$$F = -C\theta\frac{d\theta}{dh} \tag{16}$$

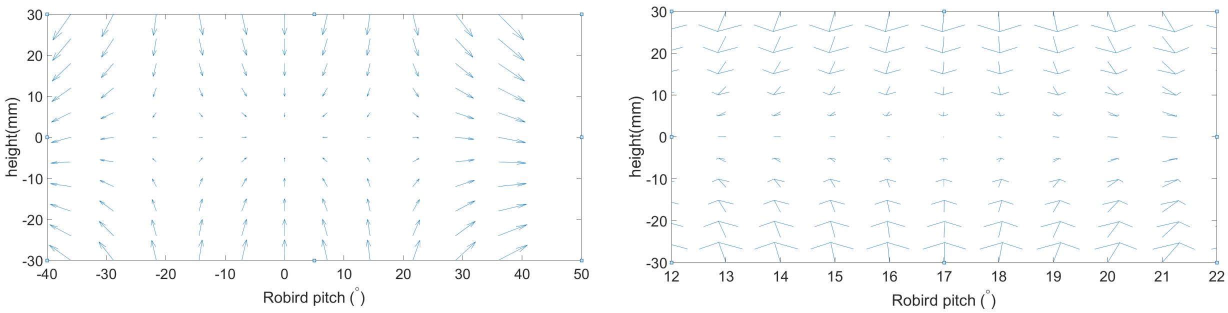

Figure 19: Plot of the stability when pitching. Left: plot over full range, right: zoomed around 17°. If the pitch is not larger than 17°, the springs working on the arms of the Evans mechanisms, will pull the Robird back to its neutral position.

With C the spring constant of the torsion springs. The relation between the vertical position and the angle of the arm is shown in figure . From this figure it can be seen that the relation is almost linear, with $\frac{d\theta}{dh} = 3.6\mathrm{rad/m}$. The spring for vertical movement can now easily be expressed as a function of the spring constant of the torsion spring. insert figure

$$k = C(\frac{d\theta}{dh})^2 \tag{17}$$

If at 5 cm from the neutral position the change in force of the torsion springs may not be more than 10% with a Robird of 750 g, the effective spring constant may not be larger than 15 N/m and the spring constant of the combined torsion springs thus not larger than $1.15\mathrm{N\,m/rad} = 20\mathrm{N\,mm/°}$. For this reason four identical torsion springs with a spring constant of 3.962 N mm/° were used. At a bending of 130° these springs provide enough torsion to counteract the gravity working on the Robird.

Conical springs Four conical compression springs are used to confine the Robird when it gets too far out of its neutral position. Because of the non-linear behaviour of these springs a small force is provided for small displacements of the Robird, but a much larger force when the Robird deviates much more than it would normally.
One conical spring is used for each direction of rotation of each arm. From equation 15 it can be seen that if the conical springs create a larger torque on the arms of the Evans mechanism, the force on the Robird increases. The springs should thus be placed far away from the axis of rotation of the arms of the Evans mechanisms. However, due to space limitations they could not be placed further than 7.5 cm. In order provide enough torque to counteract the peak force exerted by Robird, as modelled in section 2.3, the conical spring needs to produce 70 N. Four identical springs giving a force of 68 N at full compression were therefore used.

Compression springs Two compression springs are used between the roll-bars and the box in the back connection to the Robird. These springs keep the Robird stable around 0° of rolling. Two identical springs are used with a cross section of 5 mm and an initial length of 3.6 cm, which gives a maximum force of 5 N per spring.

4.5.2 Bearing-pins

All axes of rotation use a similar design of two long perpendicular flat bearing-pins that slide into each other. This forms a cross-shaped, instead of circular axis (figure 20). Two parallel plates are placed in the centre of the axis and form one of the connected parts. Two other parallel plates are placed at the end of the axis and form the other part that is connected by the axis. The plates on the end of the axis have a circular hole in them in which a flange bearing is placed. This bearing allows for smooth rotation relative to the bearing-pins. The plates in the centre have a cross cut into them, so that it cannot rotate relative to the bearing-pins. Because each plate has a different slit of the cross slightly longer than the other slit and the

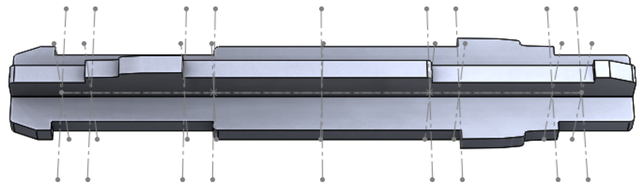

Figure 20: cross-shaped axis formed from two bearing-pins slid into each other. The dashed grey lines indicate the positions where the plates from the rotating parts fit. Dashed grey lines are also shown for the midplane and axis of rotation.

bearing pins get wider at two points along its length, the bearing-pin can slide further through the plate if it is placed in the long slit. When sliding the bearing-pins into each other, the two parallel plates are now locked in place.

5 Testing

5.1 Experiment set-up

To verify that the test rig is functioning properly, measurements were performed on the dynamics of the Robird in real flight and when placed in the test rig. In both situations the measurements were done by the on-board sensors of the Robird. The data is logged on the Robird during the flight by the Pixhawk autopilot controller. After the test, the data is extracted from the Robird using ArduPilot Mission Planner software.
For the real flight data, existing logs from previous flights were used. For the measurement with the test rig, the Robird was placed on the test rig after which the pre-loads on the springs were adjusted, so that when at rest the Robird is not pitched and is in the middle of the range in which the Evans mechanism produces a straight line movement. The ground plate of the test rig was fixed to a table using two clamps, to provide more stability.

5.2 Results

5.2.1 Real flight

The vertical acceleration and pitch measured during real flight are plotted in figure 21. It is observed that when the throttle is lowered, the amplitude and frequency of vertical acceleration decreases. At full throttle the amplitude is around 30 m/s^2 with a frequency of 6 Hz. At a throttle of 46%, this is lowered to an amplitude of 15 m/s^2 and a frequency of around 3.5 Hz. For the pitching the same change in frequency is observed, when lowering the throttle as this is the frequency with which the motor drives the wings. Due to large variations in the level around which the pitch oscillates during a wing flap it, observations about a change in amplitude of the pitching cannot readily be made. A high-pass filter was therefore used on the pitch data, the output of which is shown in figure 22. No significant change in amplitude of pitching was found when lowering the throttle; It remains at 3.5°.

5.2.2 In test rig

In the test rig no measurement with a throttle over 40% could be made, because the Robird would reach the limit for how far the conical spring on the back side can be compressed during the downward swing. The measurement results at low throttle are shown in figure 23. When the throttle is increased from 16% to 26%, the amplitude of both the acceleration and pitching increases. The amplitude of the acceleration goes from 7 m/s^2 to 15 m/s^2, while the amplitude of pitching goes from 1° to 5°. The frequency increases from 1.6 Hz to 2.3 Hz.
The vertical acceleration shows two additional peaks during each wingflap. These are due to the acceleration as a results of the force exerted by the springs, when the hull is at its lowest or highest position. As the Robird moves further down in the test rig than it moves up, the peak is bigger when the hull reaches its lowest point. The pitch has an additional bump shortly after reaching its highest pitch. This is at the moment where conical springs are compressed most and the hull is at its lowest point.

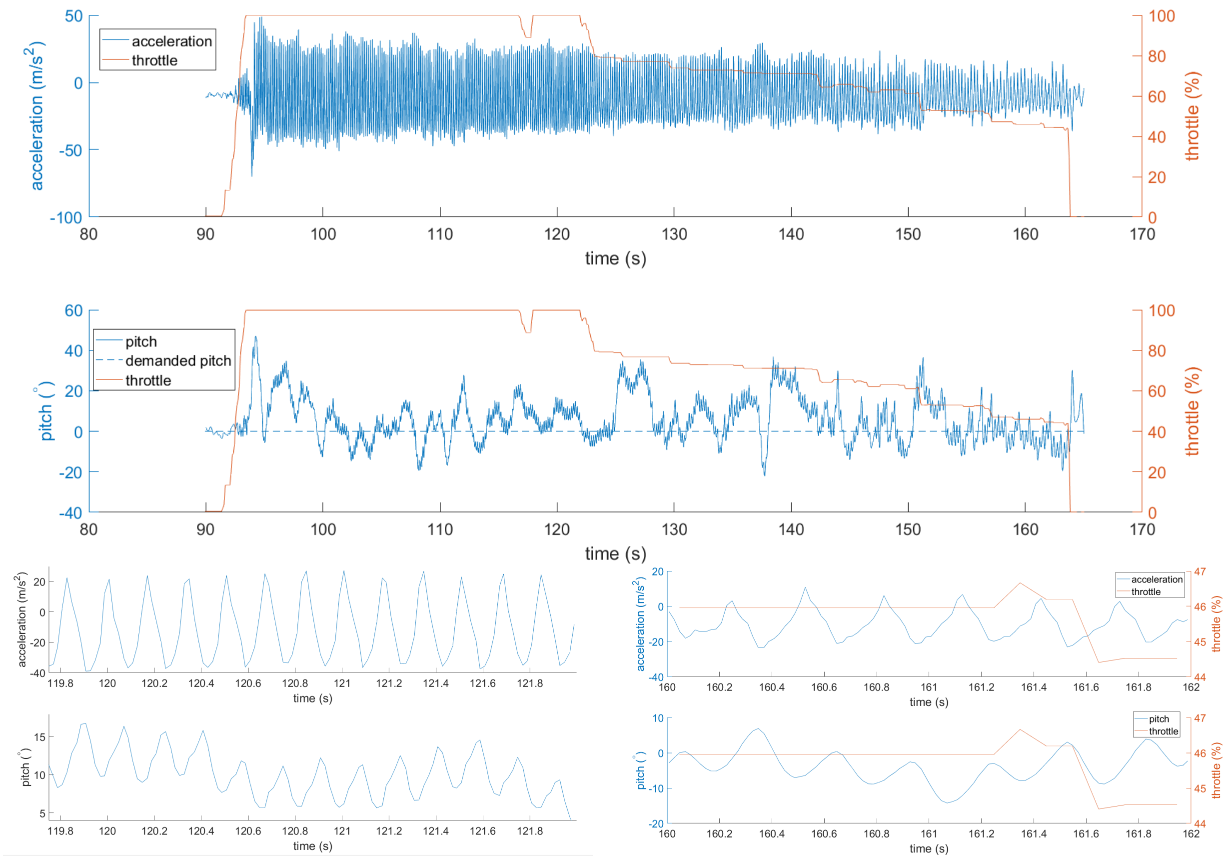

Figure 21: Measurement results of the acceleration and pitch of the Robird during real flight. Top: Overview of full flight, bottom left: zoomed in on part with full throttle, bottom right: zoomed in on part with low throttle.

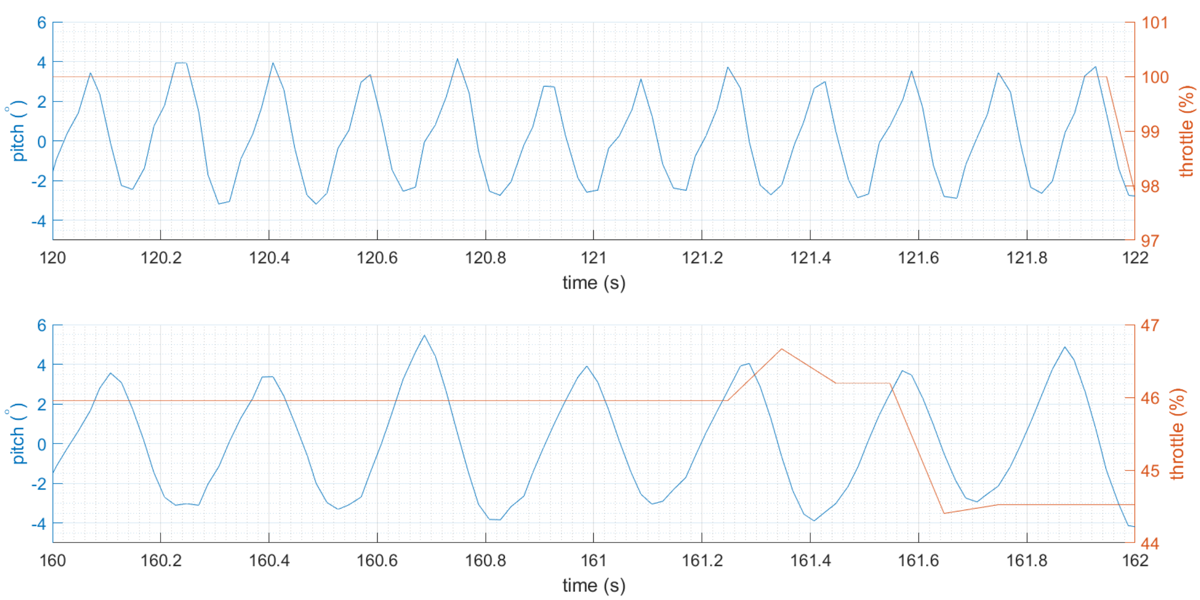

Figure 22: Pitch measurements during real flight, after being passed through a high-pass filter. Top: full throttle, bottom: low throttle.

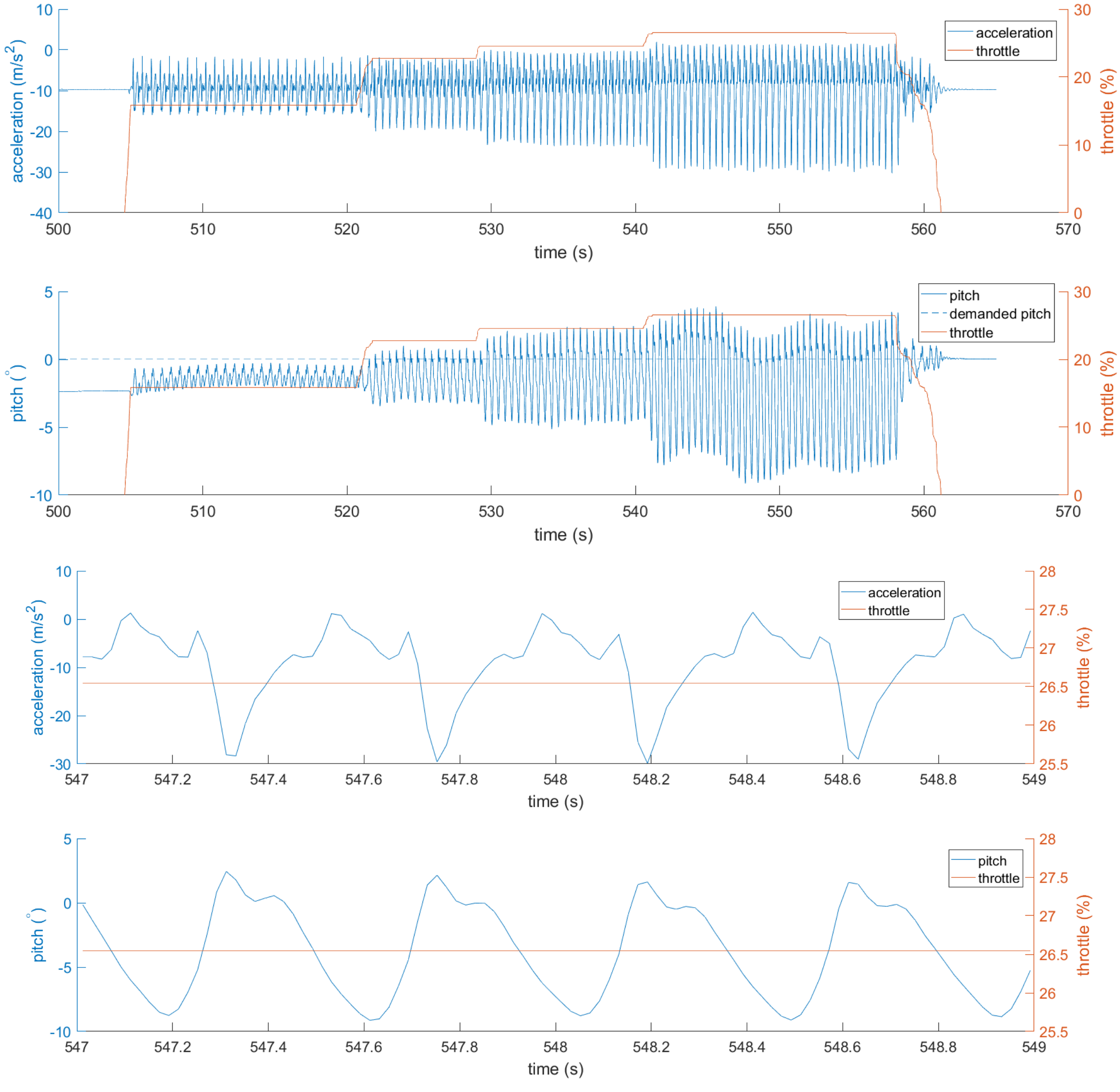

Figure 23: Measurement results of the acceleration and pitch of the Robird tested in the test rig. Top: overview of full test, bottom: zoomed in.

6 Discussion

6.1 Comparison of dynamics

When the throttle in real flight was lowered from 100% to 46%, the amplitude of the vertical acceleration was halved to 15 m/s^2. At a throttle of 26% in the test rig the amplitude is also 15 m/s^2. Extrapolating the decrease in amplitude in real flight, means that the amplitude in the test rig is higher than desired. Also the amplitude of the pitching increases rapidly with increasing throttle in the test rig, while in real flight changing the throttle had no effect on the pitching. Even in real flight the pitching should go to zero as the throttle goes to zero, so it should start to get lower at some point but the pitching amplitude in the test rig should not exceed that of real flight. At 26% throttle this does occur.
The test rig thus seems to amplify the motions of the Robird. This is caused by resonance in the springs. As the conical springs are further compressed their stiffness increases, thus increasing the natural frequency of the system. Because the Robird is driven at low throttle the frequency of the wing flaps is still low. These two effects combined with the pre-load put the test rig closer to resonance, thus producing a larger up-and-down motion of the Robird.
Testing in a wind-tunnel might reduce the amount of up-and-down motion, because when the wings move upwards and the body downwards, the wings are angled upwards. This causes the airflow passing the wings, to create an upward force on the Robird, which counteracts the downward motion of the body. The opposite happens during the downward swing of the wings. However, because tests with the test rig in the wind-tunnel have not been performed yet, the extent of this effect is still unknown. Also other effects that the presence of airflow and lift force might have on the performance of the test rig are still unknown.
Measurements in the test rig also showed two extra peaks per wingflap for the vertical acceleration, that do not occur in real flight. In real flight the two peaks in the acceleration occur in the highest and lowest position of the wings, where they have to reverse direction. In the test rig the two extra peaks occur when the springs are most compressed.

6.2 Possible further improvements

An issue that arose immediately when testing the Robird was that when the throttle was at around 20%, the wing tips bended more than expected and started hitting the table. This can be fixed placing the ground plate on a box. Alternatively the Evans mechanisms can be scaled up, so that the neutral position is at a larger height.

The springs were chosen so that only the torsion springs are needed to keep the Robird in the middle of the straight line range of the Evans mechanisms. With the slits in the side-plate of the middle stand the pre-load on these springs can be adjusted to account for variations in mass of the Robird and small differences between construction and design. However, during construction it was found that the torsion springs could not hold the weight of the Robird, even when using the slits to give the largest pre-load. Because of this the conical springs also had to be pre-loaded, to provide the missing force to keep it in the neutral position. To solve this, the current torsion springs should be replaced by ones with a slightly higher stiffness, another option is to cut more slits in the side-plate to allow for a higher pre-load on the torsion springs.

When the throttle approaches 40%, the arm of the back Evans mechanism starts hitting the holder of the conical spring, when moving downwards. Because of this testing was not possible for higher throttles. This indicates two issues; The amplitude of the up-and-down movement is larger than expected and the conical springs are not strong enough to stop this movement. The latter is tied in to the conical springs already being pre-loaded, because the torsion springs are not strong enough. However, the extra pre-load is small compared to the force the conical spring exerts at maximum compression, so stiffer conical springs are still needed.
The amplitude of the up-and-down motion could be due to resonance as discussed above. Running the Robird at high throttle increases the frequency of the wing flaps and thus reduces the amount of resonance which

might make the Robird function properly again. However even if this is the case, the problems at half throttle should still be solved. Firstly, as already mentioned above, the torsion springs should give a higher force, so that no pre-load is placed on the conical springs. Pre-loading the torsion springs more is preferred over using stiffer springs, as using stiffer springs would also increase the natural frequency. This would also allow to place the conical springs a small distance from the arm in neutral position, so that for small motions the conical springs are not compressed. Secondly a larger Evans mechanism can be used to give the Robird a larger range in which it can move in a straight line.

A small point for improvement is the rods used to guide the compression springs between the roll bars and the box on the back connection of the test rig to the Robird. At both ends the spring is placed on a bolt. The screw thread of the bolt, makes it harder for the spring to slide over the bolts during compression and decompression. An option is to file the thread where it is not needed, or a smooth rod should be found to use as a guide.

In the final build of the test rig no sensors were integrated. Placing rotation sensors on the axis connecting the middle platform and the arms of the Evans mechanisms, would allow for determining the position and pitch of the Robird as this is directly related by the geometry of the Evans mechanism. Additionally from the sensors the compression of the springs can be derived and thus the force exerted by them on the Robird.

7 Conclusion

This bachelor thesis began with an introduction to the Robird and an investigation of existing test set-up for ornithopters in chapter 1. In chapter 2 a framework was set-out for the criteria the test rig needs to meet. Multiple concept design were considered in chapter 3, from which the direction of the design was further shaped. The final design was presented in chapter 4. In chapter 5 the measurement methods were introduced and the results were presented. These results were interpreted in chapter 6 to asses the performance of the test rig and to give recommendations to further improve the test rig.

The requirements from 2.1 are shown again in table 5 and whether they have been achieved or not. The test rig allows for all the degrees of freedom that are important and additionally allows for a small amount of rolling. It also meets all requirement for weight and size.

Property	**Requirement**	**In test rig**
up-down D.O.F.	necessary	yes
forward D.O.F.	necessary	only in wind-tunnel
sidewards D.O.F.	constrained	constrained
pitching D.O.F.	important	yes
rolling D.O.F.	optional	only for wing balancing
yawing D.O.F.	optional	no
added inertia	max 400 g	350 g
spring dynamics	no resonance	at 40% throttle
size	table top	fits under Robird
total weight	max 5 kg	2.8 kg
integrated measurements	optional	not included

Table 5: List of the requirements and whether they have achieved in the final build of the test rig.

The test rig usability is limited by unexpectedly large up-and-down motions which prevent the test rig being used with a throttle of over 40%. These motions are caused by resonance effects due to the increasing stiffness of the conical springs and low frequency of wing flaps at low throttle.
The test rig has some other non-ideal dynamics introduced by the springs. The conical springs create two extra peaks in the vertical acceleration at the moments when the body of the Robird is in the highest or lowest position, in addition to the normal peaks when the wings change direction.

Despite these issues, there is reason to be optimistic that the limitations of the current build of the test rig can be overcome without drastic changes. Implementing the changes proposed in section 6.2, should greatly reduce the amount the conical springs are compressed and the undesired dynamics introduced by them.

8 References

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[2] John R. Allan and Alex P. Orosz. The costs of birdstrikes to commercial aviation. In *2001 Bird Strike Committee-USA/Canada, Third Joint Annual Meeting, Calgary, AB*, page paper 2, 2001.

[3] Abd El-Aleem Saad Soliman Desoky. A review of bird control methods at airports. *Global Journal of Science Frontier Research*, 14(2), 2014.

[4] Festo. Smartbird. pages 40–41, 2011.

[5] Festo. Festo smartbird - bird flight deciphered.

[6] Clear Flight Solutions. Robird: a robotic bird of prey. 2015.

[7] Mohammad Sadraey. Chapter 3: Drag force and drag coefficient. In *Aircraft Performance: Analysis*. VDM Verlag Dr. Mller, 2011.

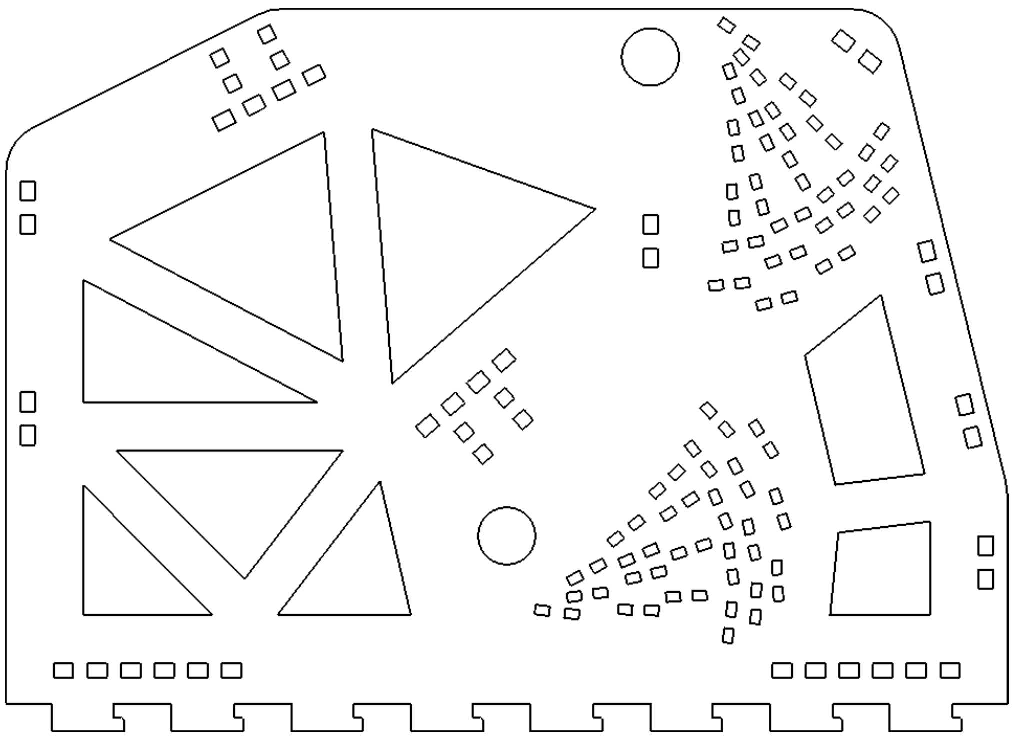
[8] Douglas L. Blanding. *Exact Constraint: Machine Design Using Kinematic Principles*. ASME Press, 1999.

[9] Digital Mechanism and Gear Library. Evans four-bar approximate straight-line mechanism.

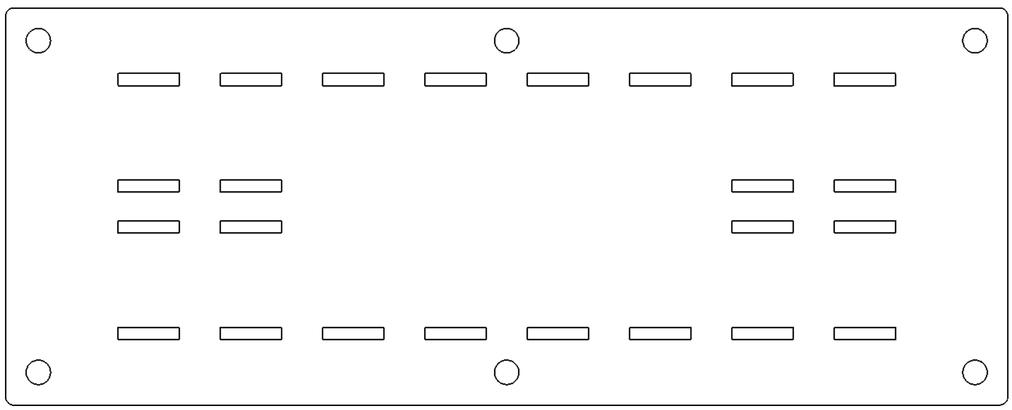
A Part list

A.1 Base

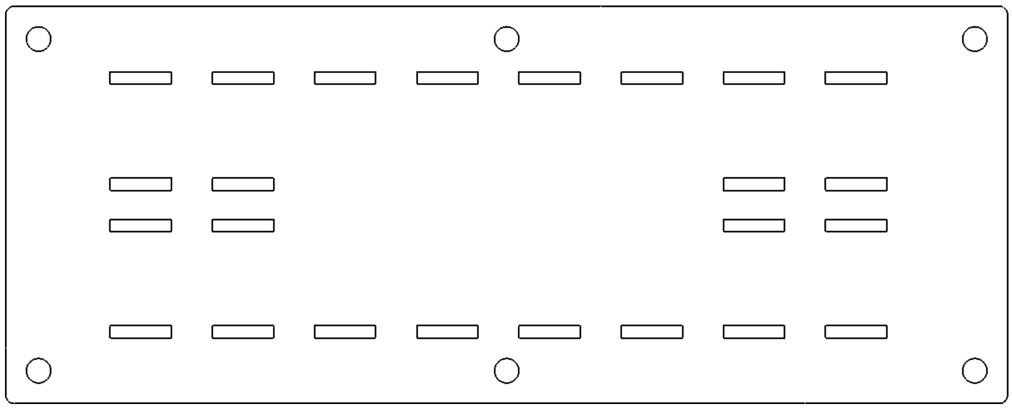
Middle stand: side plate
Thickness: 3 mm - Amount: 2



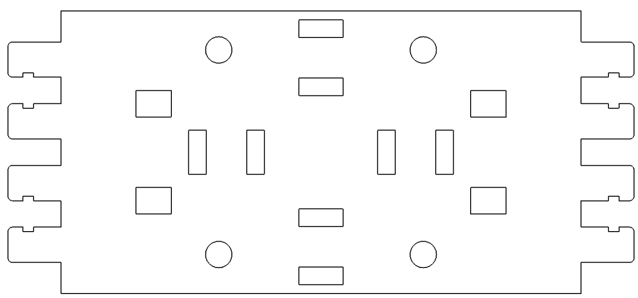
Middle stand: bottom ground plate
Thickness: 3 mm - Amount: 1



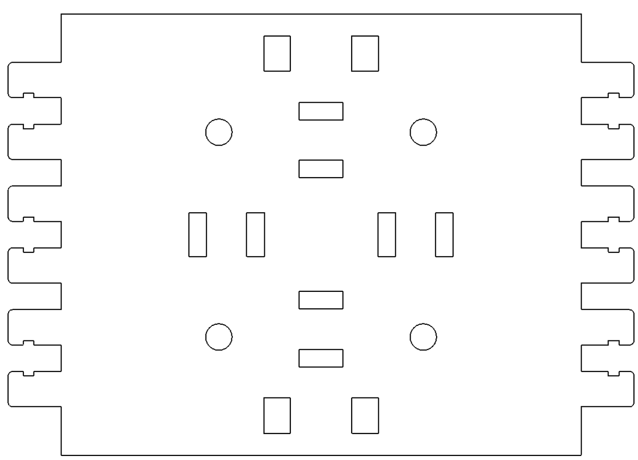
Middle stand: top ground plate
Thickness: 3 mm - Amount: 1



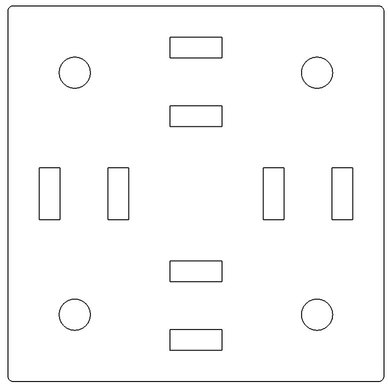
Middle stand: top conical spring holder
Thickness: 3 mm - Amount: 2



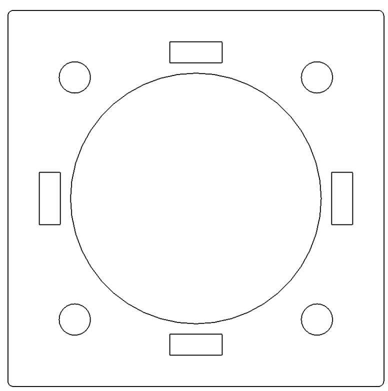
Middle stand: bottom conical spring holder
Thickness: 3 mm - Amount: 2



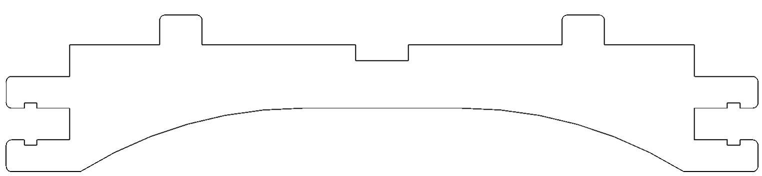
Middle stand: conical spring holder: filler plate
Thickness: 3 mm - Amount: 4
Thickness: 2 mm - Amount: 4
Thickness: 1 mm - Amount: 4



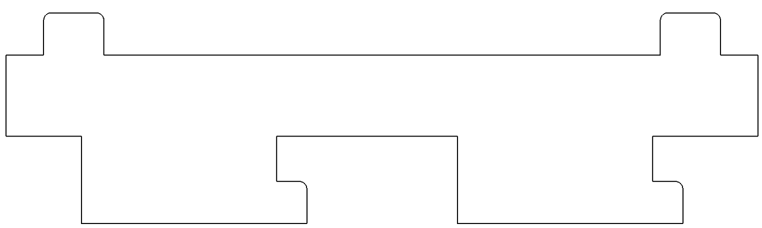
Middle stand: conical spring holder: ring
Thickness: 1 mm - Amount: 4



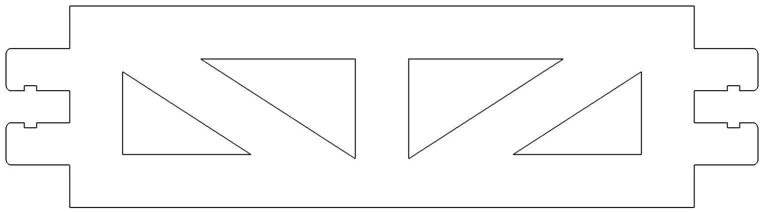
Middle stand: top conical spring holder: support
Thickness: 3 mm - Amount: 4



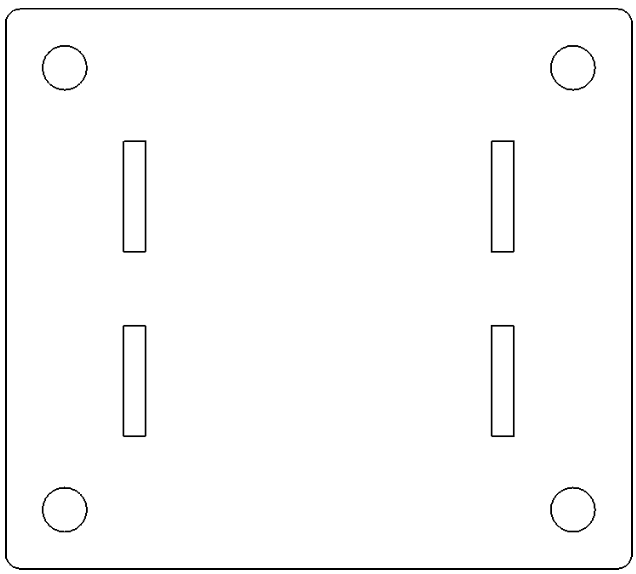
Middle stand: bottom conical spring holder: support
Thickness: 3 mm - Amount: 4



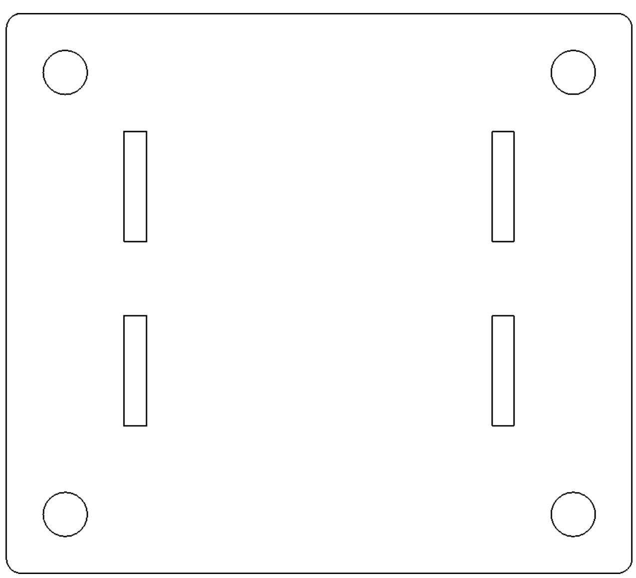
Middle stand: cross-bar
Thickness: 3 mm - Amount: 4



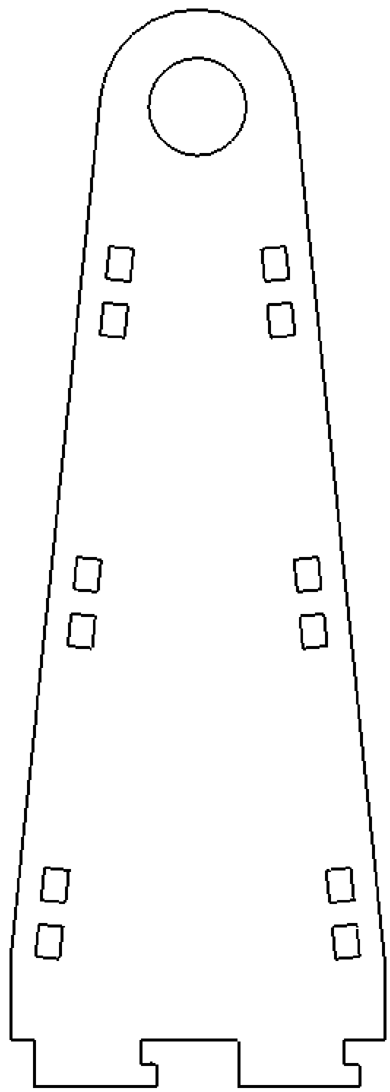
Side stand: bottom ground plate
Thickness: 3 mm - Amount: 2



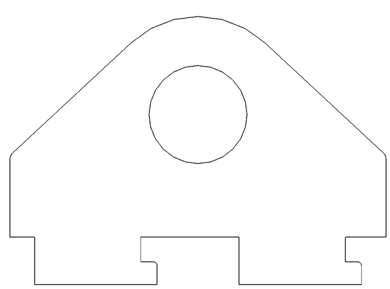
Side stand: top ground plate
Thickness: 3 mm - Amount: 2



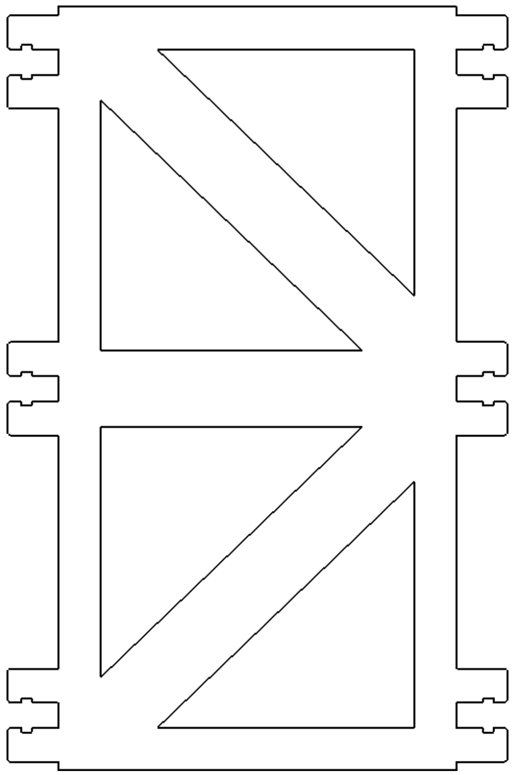
Side stand: high side plate
Thickness: 3 mm - Amount: 2



Side stand: low side plate
Thickness: 3 mm - Amount: 2

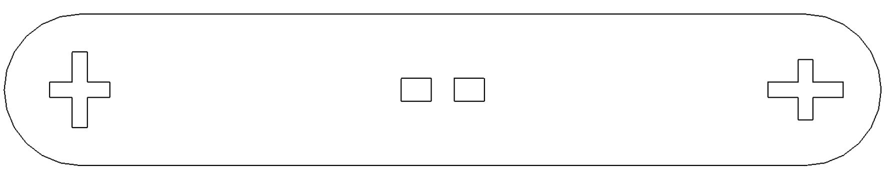


Side stand: cross-plate
Thickness: 3 mm - Amount: 2

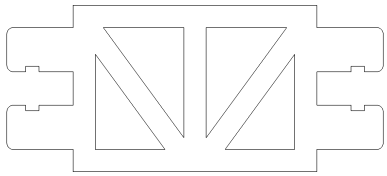


A.2 Arms

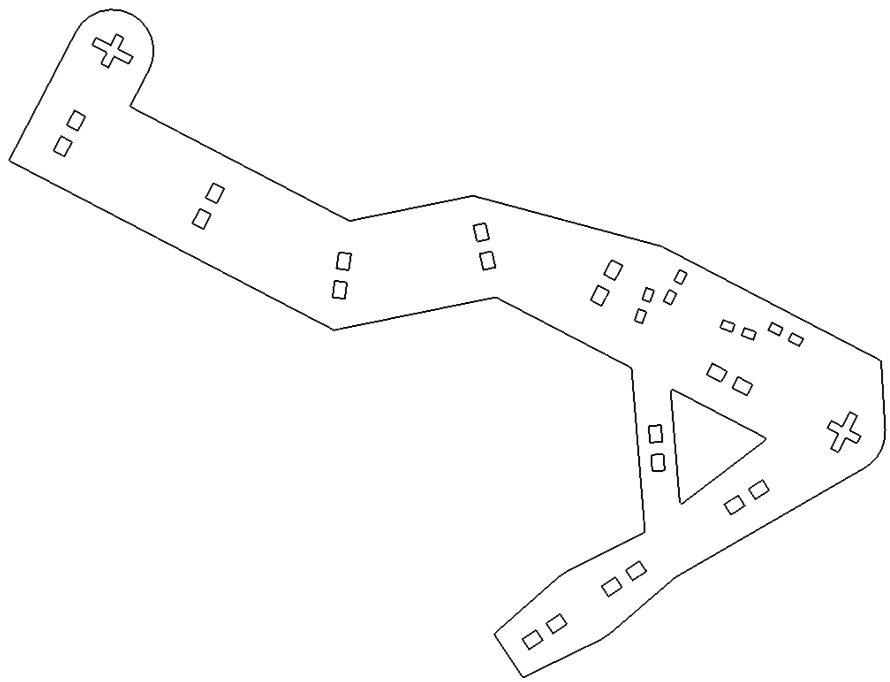
Short arm: side-plate
Thickness: 3 mm - Amount: 4



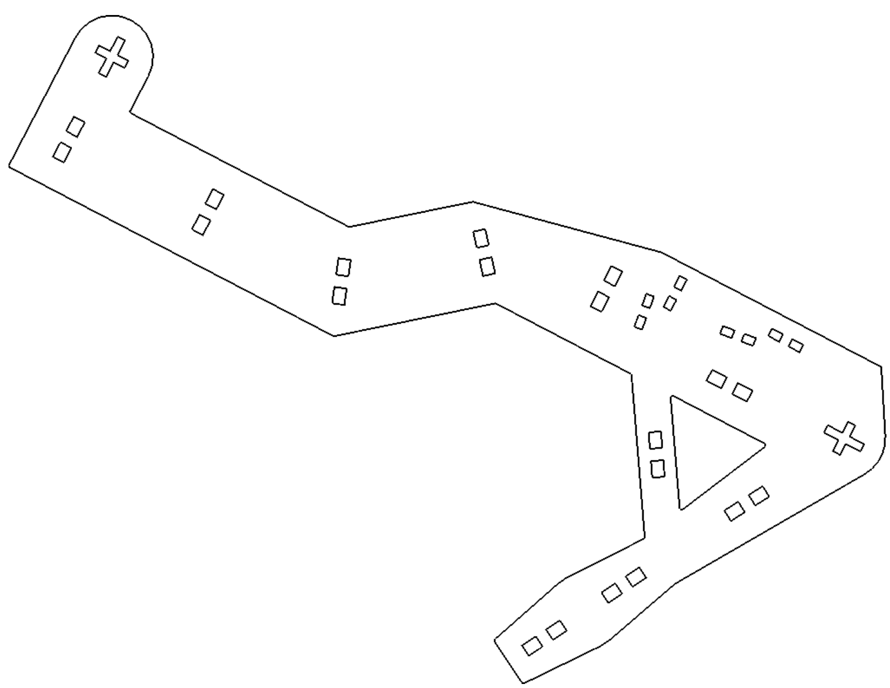
Short arm: cross-plate
Thickness: 3 mm - Amount: 1



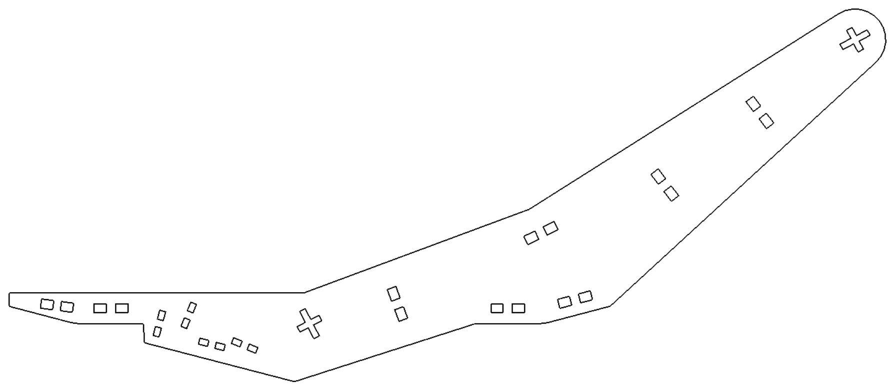
Front arm: side-plate
Thickness: 3 mm - Amount: 1



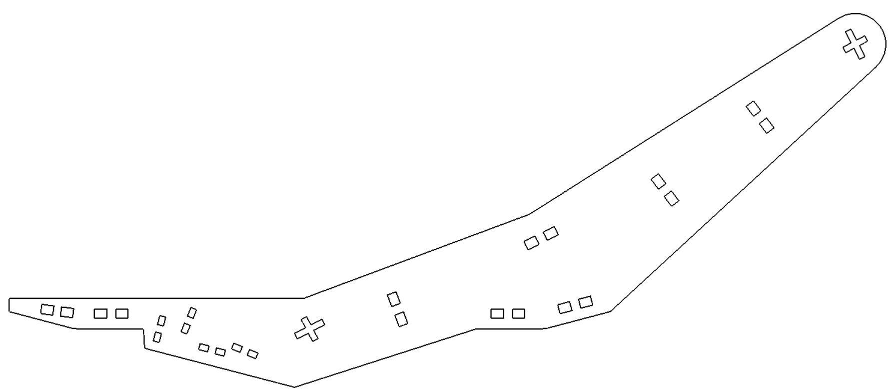
Front arm: side-plate mirrored
Thickness: 3 mm - Amount: 1



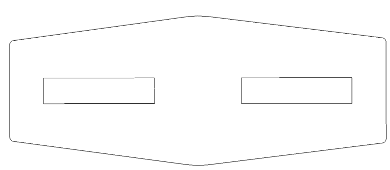
Back arm: side-plate
Thickness: 3 mm - Amount: 1



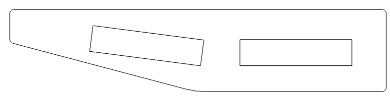
Back arm: side-plate mirrored
Thickness: 3 mm - Amount: 1



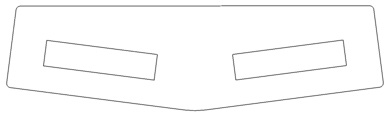
Front arm: conical spring connection: filler plates
Thickness: 3 mm - Amount: 3



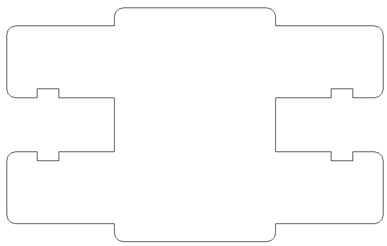
Back arm: conical spring connection: filler plates 1
Thickness: 3 mm - Amount: 3



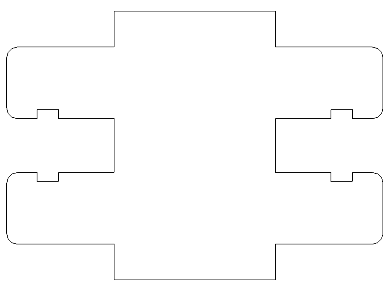
Back arm: conical spring connection: filler plates 2
Thickness: 3 mm - Amount: 3



Long arms: conical spring connection: connector
Thickness: 3 mm - Amount: 6

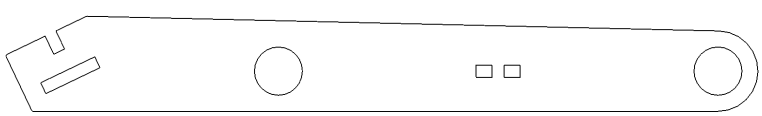


Long arms: cross-plate
Thickness: 3 mm - Amount: 13

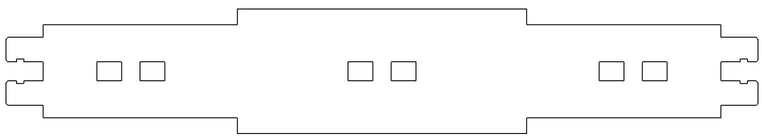


A.3 Front connection

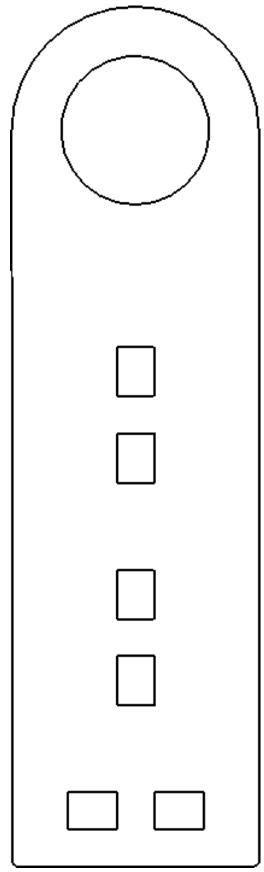
Floating link: bar
Thickness: 3 mm - Amount: 2



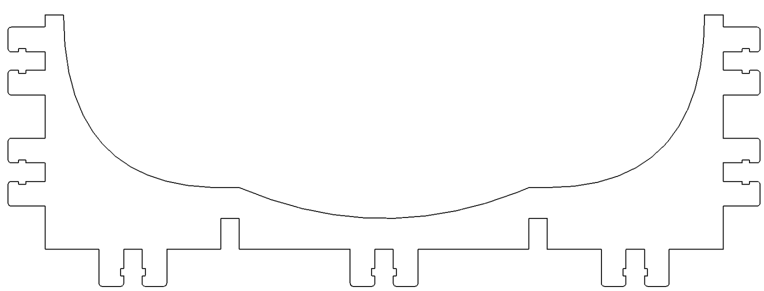
Floating link: wide plate
Thickness: 3 mm - Amount: 1



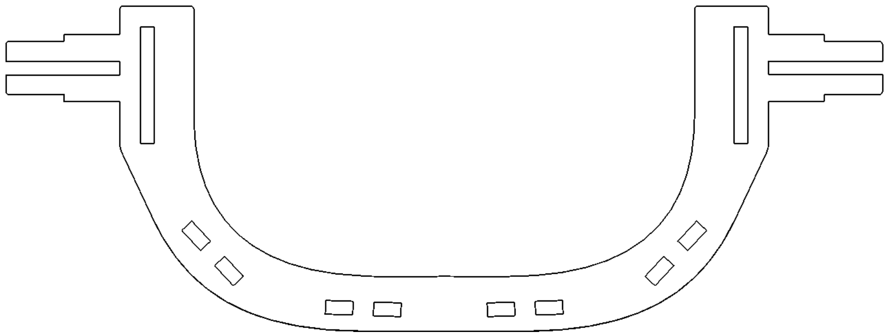
Floating link: side-plate
Thickness: 3 mm - Amount: 2



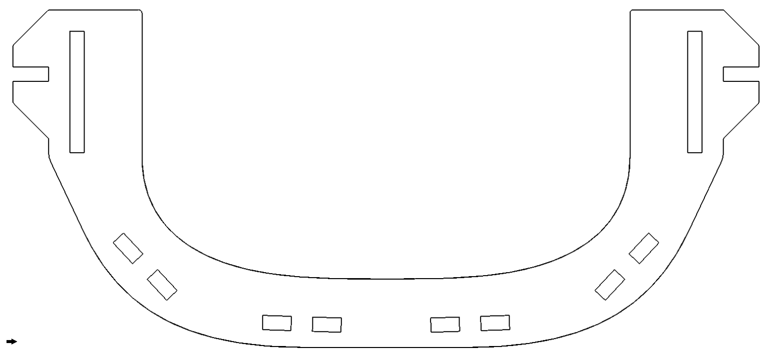
Floating link: support arc
Thickness: 3 mm - Amount: 1



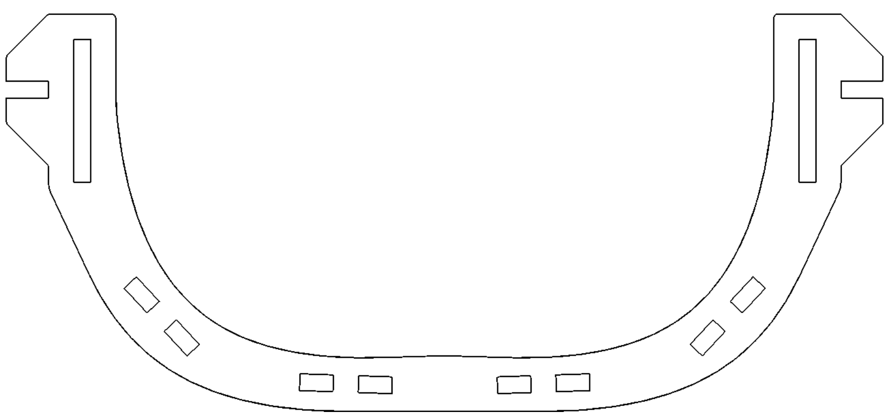
Robird holder: middle arc
Thickness: 2 mm - Amount: 1



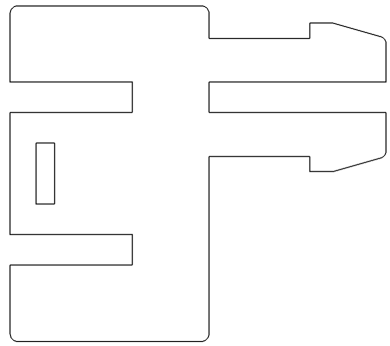
Robird holder: front arc
Thickness: 2 mm - Amount: 1



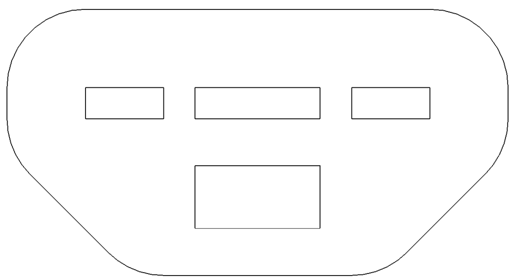
Robird holder: back arc
Thickness: 2 mm - Amount: 1



Robird holder: axis plate
Thickness: 2 mm - Amount: 2

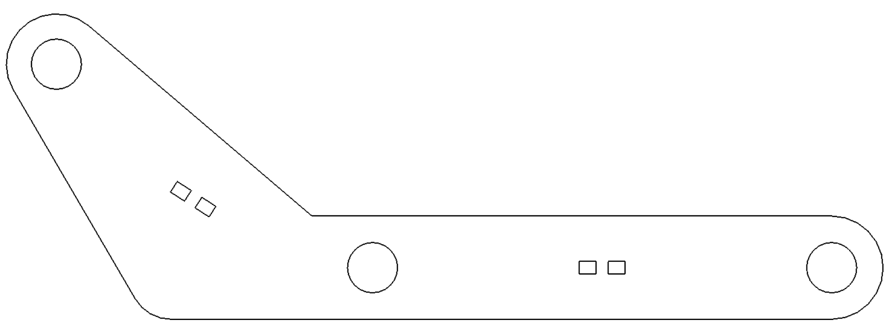


Robird holder: locking plate
Thickness: 2 mm - Amount: 2

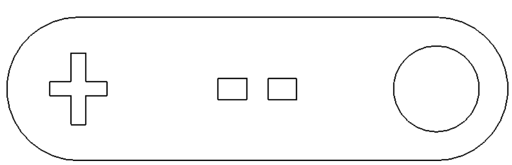


A.4 Back connection

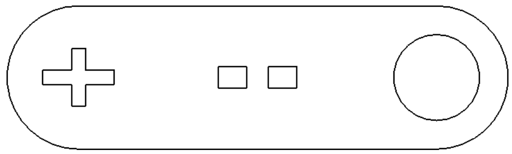
Floating link: bar
Thickness: 3 mm - Amount: 2



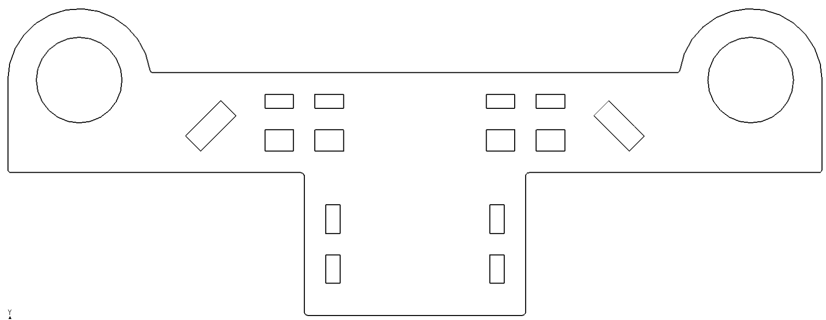
Pitching link: side-plate
Thickness: 3 mm - Amount: 1



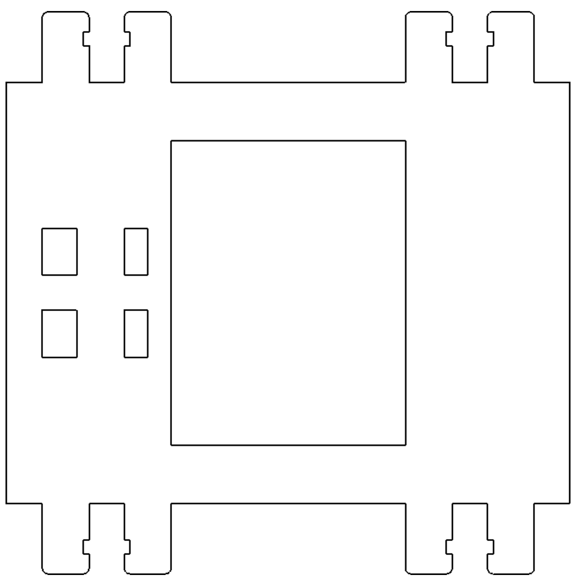
Pitching link: side-plate mirrored
Thickness: 3 mm - Amount: 1



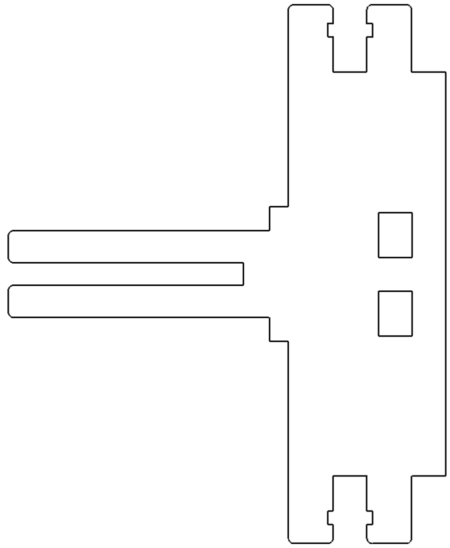
Robird holder: side-plate
Thickness: 3 mm - Amount: 2



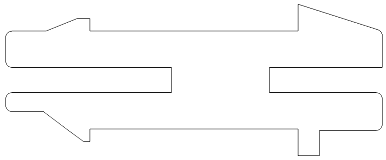
Robird holder: lower plate
Thickness: 3 mm - Amount: 1



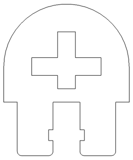
Robird holder: upper plate
Thickness: 2 mm - Amount: 1



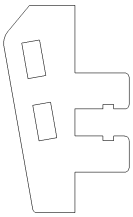
Robird holder: axis bearing
Thickness: 2 mm - Amount: 1



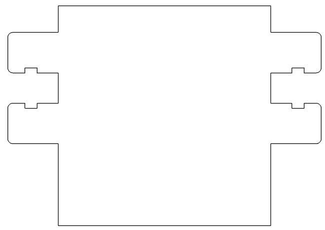
Robird holder: axis bearing lock
Thickness: 2 mm - Amount: 1



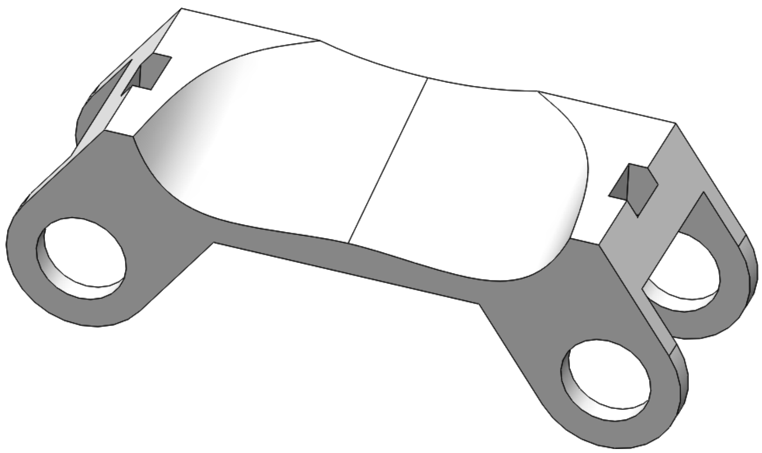
Robird holder: pitch limiter
Thickness: 2 mm - Amount: 4



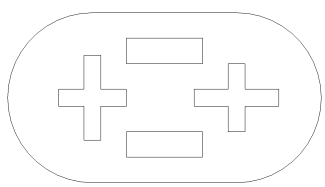
Robird holder: pitch limiter plate
Thickness: 2 mm - Amount: 2



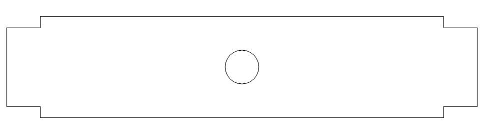
Robird holder: Robird support
Amount: 1



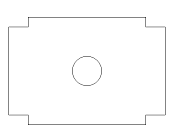
Robird holder: roll bar
Thickness: 2 mm - Amount: 4



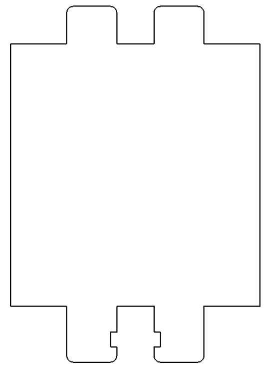
Robird holder: spring holder large
Thickness: 3 mm - Amount: 2



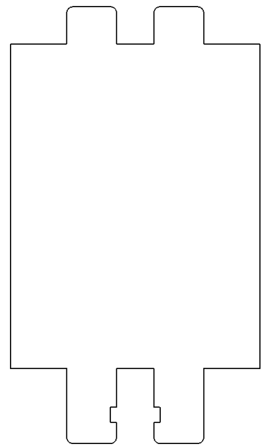
Robird holder: spring holder small
Thickness: 3 mm - Amount: 2



Robird holder: roll lock upper plate
Thickness: 3 mm - Amount: 1

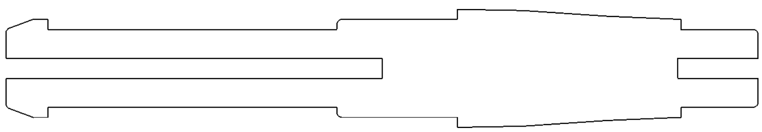


Robird holder: roll lock lower plate
Thickness: 3 mm - Amount: 1

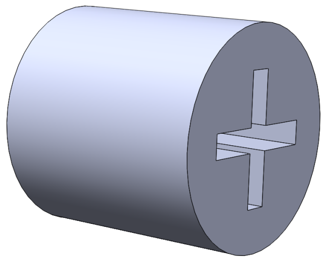


A.5 Miscellaneous

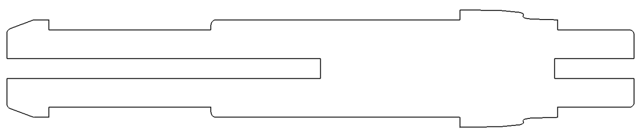
Bearing pin: middle stand
Thickness: 2 mm - Amount: 4



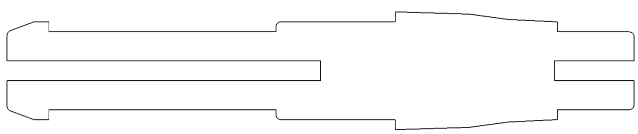
Torsion spring axis
Amount: 4



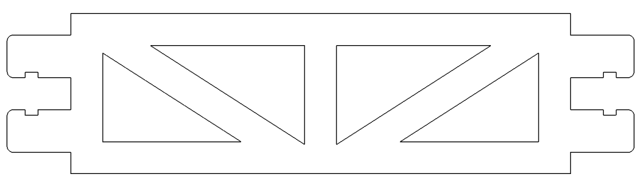
Bearing pin: Evans short arm
Thickness: 2 mm - Amount: 8



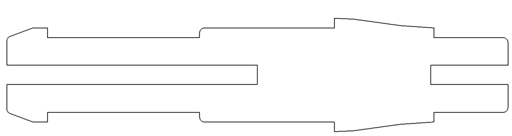
Bearing pin: floating link
Thickness: 2 mm - Amount: 6



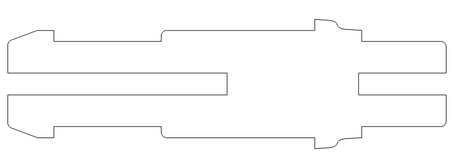
Floating links: cross-plate
Thickness: 3 mm - Amount: 3



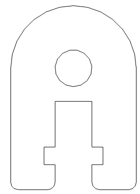
Bearing pin: back connection 1
Thickness: 2 mm - Amount: 4



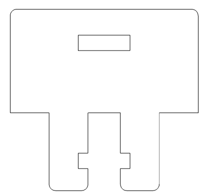
Bearing pin: back connection 2
Thickness: 2 mm - Amount: 4



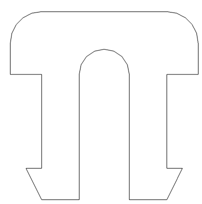
Torsion spring hook
Thickness: 2 mm - Amount: 8



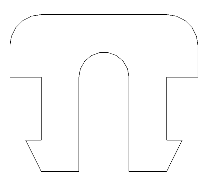
Torsion spring guide
Thickness: 2 mm - Amount: 8



Lock for 3mm plates
Thickness: 1 mm - Amount: 120



Lock for 2mm plates
Thickness: 1 mm - Amount: 50



ddlf-1280 flange bearing
Amount: 30

Tevema TS102240 torsion spring
Right-handed coiling - Amount: 2 left-handed coiling - Amount: 2

Tevema KV941 conical compression spring
Amount: 4

Tevema D11080 compression spring
Amount: 2