LMECA2840 - Project in mechanical design
Technical Report II :

Brevi Matteo	7708-16-00
Creelle Robbe	3693-17-00
Diriken Axel	3382-17-00
Ibrahim Muhammad	1444-20-00
Marchal Youri	6170-17-00
Peres Hugo	4454-16-00
Philipin Aurélien	4622-17-00

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Contents

1 Introduction

1.1 Description of the industrial partner work

The client company Roadfour, is a Belgian company aiming to develop a new concept of water bomber aircraft (SEAGLE) in order to fight the increasingly recurrent forest fires in certain regions of the world. We have all heard of Canadair, an airplane that fills its tanks by passing over a body of (salt or clean) water. The Canadair pours 6,000 liters of water from its tanks onto the fire. The Canadair was designed in the 1960s and went through some updates during the 1990s.
Roadfour decided to commit to developing a new aircraft that would come to the aid of Canadair and have a larger capacity compared to the 6000 liters of water from Canadair.
The SEAGLE, designed by Roadfour, has a similar objective to the Canadair, except that its more recent development sets it apart from the Canadair on certain points. The SEAGLE is fitted with "foils" below its hull, which allows it to have limited contact with the water. "Foils" (already popular on windsurfers, catamarans, ...) are special profiles that look like inverted fins. They make it possible to eliminate direct contact between the floats (or the hull of an aircraft in our case) and the water, while ensuring that these floats remain at a more or less constant height from the surface of the water. This allows on the one hand to reduce friction with water, and on the other hand it also plays a role of shock absorber, because instead of hitting against the hull of a boat, the waves pass below it in a smooth way, which considerably reduces stresses due to contact with water. This is not negligible. The pilots of a Canadair come out regularly with bruises after an intervention, because of the brutality of the shocks when filling the tanks. This stress reduction allows the SEAGLE to fly at higher speed when filling its tanks and its materials will be subjected to significantly lower stresses, which would allow it to be more durable and reliable. Like the Canadair, the SEAGLE is also capable of landing on water. Although its tanks are much larger, it can reach higher speeds, while keeping a size more or less equivalent to the the one of the Canadair.

1.2 Description of the project

Roadfour and our team are working hand in hand for the assembly stage of the SEAGLE. We are responsible for developing a crane for the assembly line of the latter. Indeed, the construction of the aircraft will be entirely ensured by Roadfour and the traveling crane must be able to lift and handle any type of part: from the most bulky and heavy parts to more compact and light parts. We therefore need to develop a most versatile overhead crane. In addition, this bridge will also be used to assemble parts together and for that it is necessary to be able to orient them in an adequate way. The overhead crane transports various parts between three places: the "warehouse", where the parts are stored, the "assembly workshop", where certain parts are assembled together, modified and, finally, the "final assembly workshop", where all the parts (including some pre-assembled) of the SEAGLE are assembled to form the "finished" aircraft.

1.3 Description of the mechanical design project

The overhead crane must be able to lift loads of 15 tons (payload), handle them and orient them in several directions in order to make the assembly of any part possible between them. It should also be possible to transport these parts from one location in the hangar to another.
The bridge must be able to be controlled by a user; it will be used both for transporting and depositing large aircraft parts - so that these are attached to the aircraft - as well as for the assembly of smaller parts, such as the electronic installation in spare parts from the plane, for example. It is therefore important that our product is precise, versatile and fast.
In this particular report, we will go through all the steps that we have done so far in order to have the first outcome: the preliminary layout. This layout will most certainly not be our final solution, but after one semester we now have a very good idea on how our product will look like in the end.

2 Functional graph

In this section, we will explain how did we make our functional graph. To remember you, a functional graph is a graph that will detail, step by step, all the work required: move some piece from one location to another (in resume). First, we can see the main flux is starting with a state *Piece at rest in workshop*. Secondly, we apply a TF[1] *Attaching piece* starting the achievement of our task. We will obtain another state and we can switch between state and TF, to move the part like we want, until being in a *free state*, as you can see in the picture

[1]TF : Technical function

21. Our TFs come from the specifications : attaching the part (1), elevate the part (2), transport the part (3), presentation (4), maintain the part (5), liberate the part (6) and moving free (7). The technical function *pilot* in the specs is a secondary flux, because we need to pilot every function execept *Hold piece in a given position.* So, we consider this function as a secondary flux, like the energy. In fact, we use energy in each TF. Notice that some technical functions are in dashed box. The meaning is the TF need some human force to be realized. For boxes with solid line, we can do this task without human force. We can see that some TFx are divided into smaller TFx.1,TFx.2 etc. because the TFx regroup a big task to do. So we divided the job into smaller TF. The functional graph is shown on Figure 21, Appendix A.

3 Morphological charts

The morphological chart is an important step in the design of a product. It allows us to realise what different possibilities there are in order to achieve one particular functionality. Of course the different aspects should not be too precise as you should be allowed to somehow combine them together so that their combination gives a concept variant (see further). We decided to put all the morphological ideas into different matrices. Each technical function has its own morphological matrix. Some technical function needed to be split into different categories though, as the function was combining different concepts that could be considered separately. Take for example the horizontal movement on Figure 1 just below:

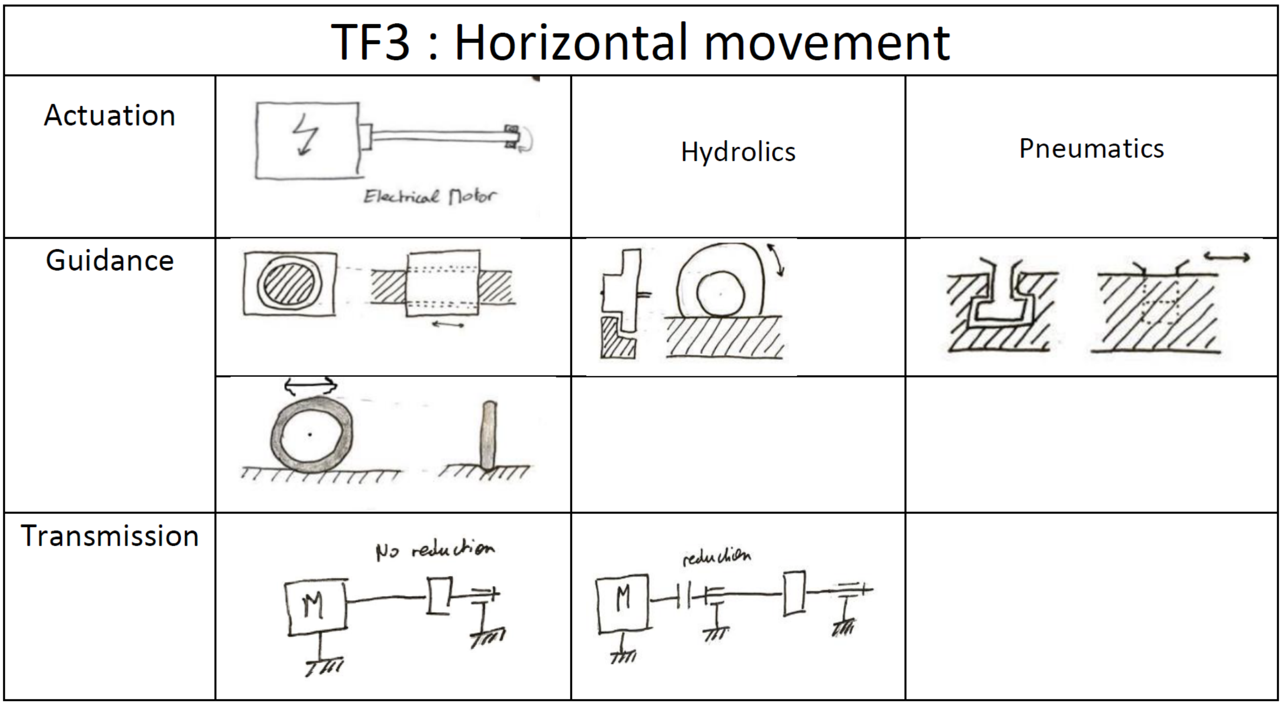


Figure 1: Morphological graph: TF3 : Horizontal movement

We split *Actuation* from *Guidance* and also *Transmission*. We did so because it was possible to use one actuation system with any guidance or transmission system. To build a concept variant you only have to choose one solution in each row of each technical function. For example : I can choose the electrical motor from the actuation, then the wheels on a rail from the guidance and finally choose to have a reduction between the motor and the wheels. These three combined gives me a possibility on how our horizontal movement system could work. By doing so for each technical function, one can put the solutions together and have one concept variant, which then needs to be evaluated as a whole (evalutaion matrix, see further). All the matrices can be found in the Appendix B. We will now explain what each category means and why we chose them for each solution.

3.1 TF1 : Attach

For this technical function, we only needed one category, which is the principle of attachment: *How is the lifting device going to be connected to the piece in order to move it ?* Different ideas were found: Simply through a hook or straps, or more complexly through suckers or magnetism for example.

3.2 TF2 : Elevate (vertical movement)

For this technical function, we needed a principle to actuate the vertical movement, as well ass one to guide it and/or to transmit the efforts. For the actuation of the motor, we thought about an electrical movement, pneumatic or hydrolics. As the actuation systems will be the same three for all the technical functions where an *actuation* needed to be found, we will not repeat this for each one of them. Similarly to what we have for other guidance categories, we can enumerate classical wheels with rubber, wheels on a rail or different kinds of sliding system. We could also choose to have no guidance and count on gravity to keep the movement perfectly vertical for example.

3.3 TF3 : Transport (horizontal movement)

This technical function has been taken a an example in the introduction of this section. The actuation systems are the same ones as for TF2, as are the guidance and transmission solutions.

3.4 TF4 : Presentation

The presentation has been split in a lot more different categories. The three categories for the translation are the same as the ones in TF3, but then we needed to scratch our heads on how we would implement the most delicate part of the problem: The rotation of the pieces. As explained in section 21, the rolling crane needs to be able to rotate the lifting objects in a minimum of two degrees of freedom (DOF). So we split the two rotations in two categories: the z-rotation, which is the rotation around the vertical axis and the y-rotation, which is any axis parallel to the ground (so perpendicular to the z-axis). For the y-rotation we made the difference between the actuation of the rotation and the principle of the rotation. Indeed the y-rotation is probably the most challenging part of the project, so we needed to find a way to solve it. The first idea we had was to use straps that surround the piece and by rotating the straps, it would drive the y-rotation. Another solution was to attach the piece at two different points and just by lifting up one side more than the other one, the rotation would happen. Finally, another solution was to have a solid attaching system that could rotate the piece by consolidating it to a shaft and rotate the latter to drive the rotation of the piece.
Then for the z-rotation, the two new concepts that are different than in the other technical functions that we already mentioned are the coaxial cylinders that slide into each other and the pair of bearings. For the transmission of the effort, we picked the three most common systems; the gear, the belt or the roller chain.

3.5 Pilot

As a piloting system, the first idea that comes to ones mind is the remote control that one is used to see in big industries. This obviously was part of our morphological matrix. Other than that, we also thought about having a user-friendly program on a laptop. This would enable to have a customized interface that is adapted to a complex piloting system. Then we also thought about piloting the device through a control panel that could be fixed to the trolley for example. These solutions could either work through a wireless connection or on the other hand through a cable.

4 Concept variants

In this section, we will put together different solutions that we found in the morphological chart so that we have a more global solution to a combinations of technical functions. We decided to find concept variants for 3 different concepts:

- Lift-up, attach and presentation
- Translations
- Pilot

Having found these concept variants, it is now easy to combine the different concept variants to have then different final solutions to our problem. These concepts will be evaluated in section 5, but first let us introduce our different concept variants:

4.1 Lift-up, attach and presentation

As explained just above, this concept variant regroups all the lifting up, attach and presentation concepts that you can find in the morphological charts in order to present a solution for these technical functions. Four different solutions have been found.

4.1.1 Solution 1

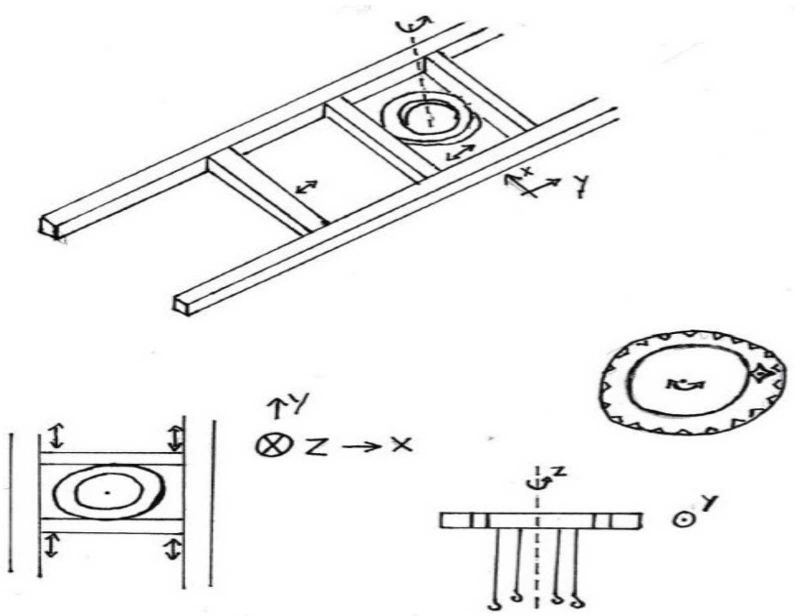


Figure 2: Concept variant 1 - Solution 1

The first solution, shown on Figure 2 is using a main trolley where 4 cables are attached. At the end of those 4 cables are some hooks to attach the piece. The z-rotation is done by a slewing ring where there is a inner toothed wheel actuated by a pinion. actuated by a pinion. The revolution in this idea is to add an additional trolley. This secondary trolley comes in bonus to the first one. It can be used to move more easily the big parts like wings of the plane. The only drawback is the weight of the whole device which increases.

4.1.2 Solution 2

The second solution for that concept variant would be to use a slewing screw actuated by an electrical motor. This allows an *"automatic"* braking system if the slewing screw is not actuated. For lifting up, a hoist drum actuated by an electrical motor will move up (or down) a cable. At the end of that cable is a hook on which 4 other cables would link 4 different anchor points on a lifting frame. Below this lifting frame, several hooks are provided in order to place the device which will enable the rotation of the piece along the axis with is parallel to the ground. That device is called a *"palonnier retourneur à sangles"*, in French. 2 kinematic schematics of the system are shown on Figure 28, in Appendix C.

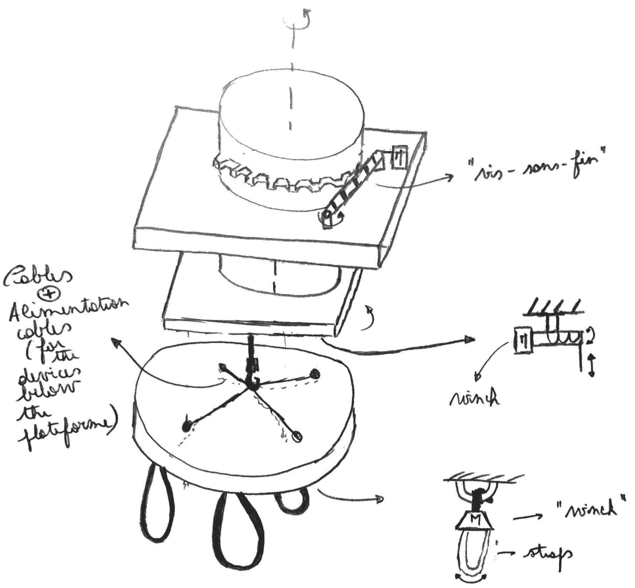


Figure 3: Concept variant 1 - Solution 2

4.1.3 Solution 3

The main idea of this concept variant is to use a scissor deployed structure for the lifting system. We have two platforms : one at the top of the lifting system and one at the bottom. The platform at the top is connected to a cylinder. The cylinder has an upper part that can turn because there is a toothed gear connected to a pinion. On the other part (bottom), there are 4 winches connected to the lowest platform. By adjusting the lengths of the cables through the winches, we can produce the Y-rotation. Notice that on the tilted platform, there are 4 points to fix the system used to attach the piece : hook or straps. For a better understanding, we can see the kinematic diagram of this concept variant at Figure 30.

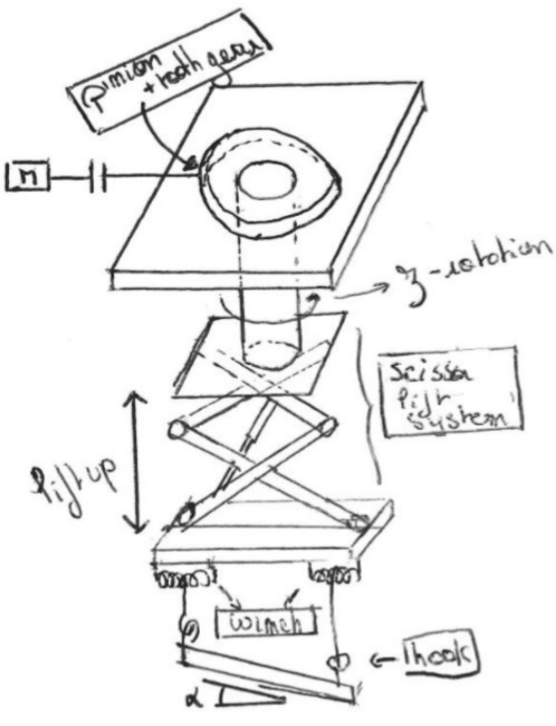


Figure 4: Concept variant 1 - Solution 3

4.1.4 Solution 4

For lifting up in Z-direction, an electrical motor is used, there are cables with drums which are further attached to the platform. The top part is rigid and is connected to a cylinder. The cylinder has an upper part that can turn because there is a worm gear and the rotation axis is parallel to ground. On the lower part (the platform) there are four different mounting points attached with for different sets of cables and motors. To obtain a rotation we just simply pull a cable more or less and in this way can have our desired rotation. The biggest issue with this concept variant is to use four different sets of motors which create much more complex solution. For the translation in Y-axis the whole trolley will be translated with rack and pinion and the for the guidance rails and wheels will be used.

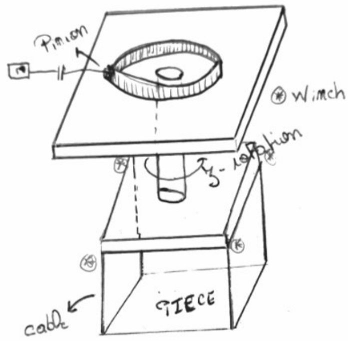


Figure 5: Concept variant 1 - Solution 4

4.2 Translations

This concept variant concerns the different translations of the crane. The X translation is the one occurring with respect to the length of the hangar. The Y translation is occurring along the transverse(s) beam(s). Again, we kept four different solutions. Kinematic schematics of the different principles used are shown in Appendix C.

4.2.1 Solution 1

The first solution for the second concept variant is to use rollers on rails for each X and Y translation, as shown is Figure 6. This solution uses two beams with the trolley located between the two. There are two rollers per rail and only one of those two is actuated by an electrical motor.

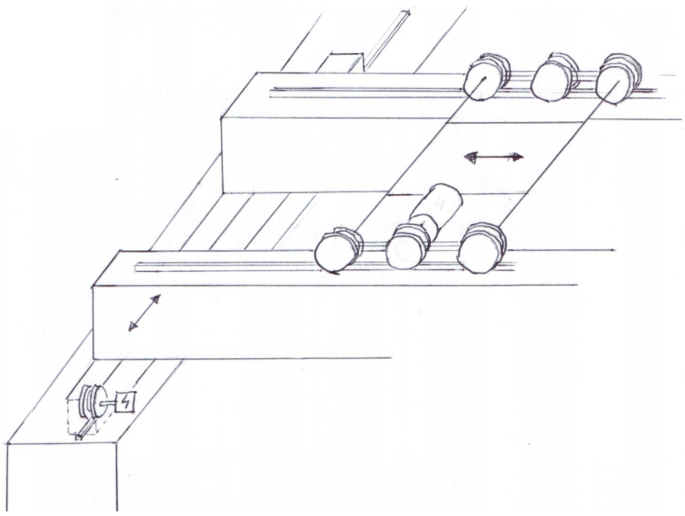


Figure 6: Concept variant 2 - Solution 1

4.2.2 Solution 2

This solution is similar to the previous one except that only one beam is used for the Y translation. The trolley is now situated bellow the beam.

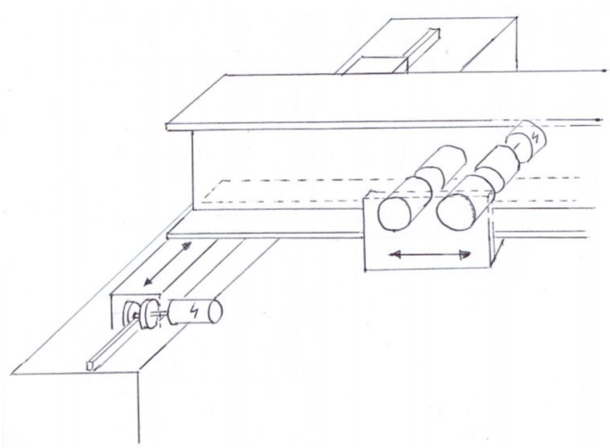


Figure 7: Concept variant 2 - Solution 2

4.2.3 Solution 3

For this solution, all the translation movements are possible thanks to cables which are connected to a pulley which is rotating. We can connect both pulleys on each side to the same motor so we don't have any problem of synchronization. We can repeat this process for the X and Y axis. We can note that for the X axis, we decided to use rollers for the same reasons as the previous solutions, but for the Y axis we choose to use sliders instead. Indeed, the distance to travel in the Y axis is not too long. In order to minimize the load on the trolley, we decided to use two beams instead of one, that way we can reduce the friction between the sliders and the beams and moreover we increase the safety.

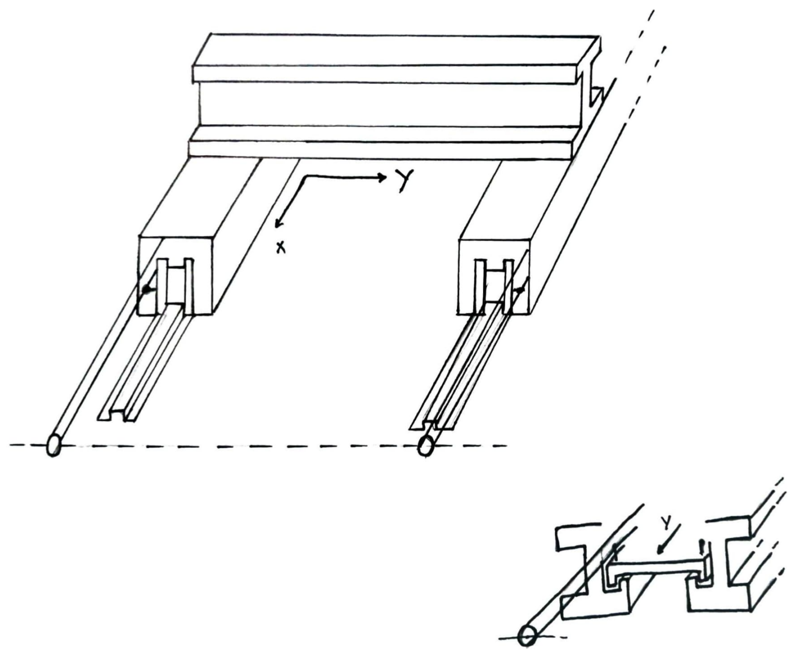


Figure 8: Concept variant 2 - Solution 3

4.2.4 Solution 4

The last solution for the translation concept variant uses once again some rollers on rails for both translations. The difference here concerns the actuation. While for the X-translation, one roller per rail is actuated with an electrical motor, it is not the case for the Y-translation. The actuation comes from a motorized rack and pinion situated on the transverse beam as you can observe on Figure 9.

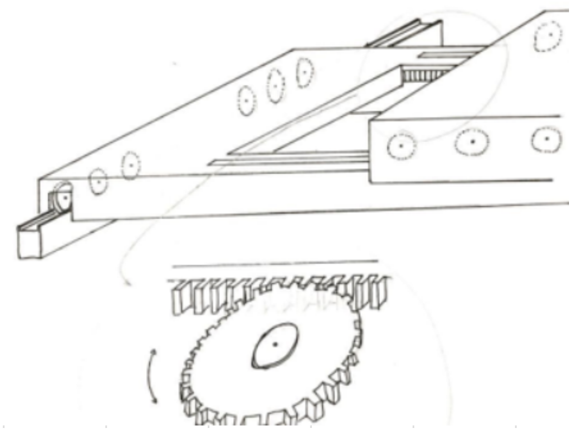


Figure 9: Concept variant 2 - Solution 4

4.3 Pilot

At last, the piloting system was kept apart from the rest as any piloting device can be implemented on any type of solution. So the combination of the connection type with a hardware solution gives us once again four different concepts.

4.3.1 Solution 1

The first concept variant is a remote control that can be connected either with or without wire. This remote control also contains a screen broadcasting security camera footage. The wire is directly connected to the trolley.

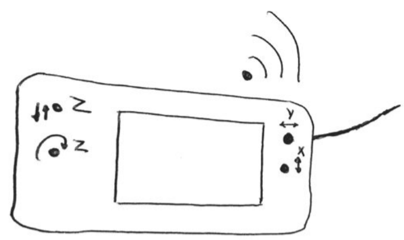


Figure 10: Concept variant 3 - Solution 1

4.3.2 Solution 2

The next solution is a basic remote control connected to the trolley through a wire.

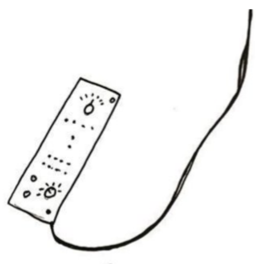


Figure 11: Concept variant 3 - Solution 2

4.3.3 Solution 3

Solution 3 uses a computer or a tablet connected with Wi-Fi. It controls the crane through a software.

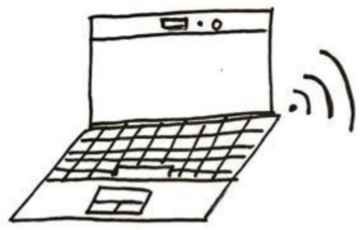


Figure 12: Concept variant 3 - Solution 3

4.3.4 Solution 4

The last solution is a cabin fixed to the trolley. It contains a control panel with a clear view of the moving piece.

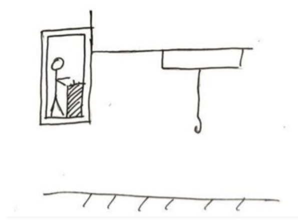


Figure 13: Concept variant 3 - Solution 4

5 Evaluation chart

The selection of the final solution comes by evaluating the concept variants and choose the best option. As shown in Section 4, Concept variants, there are 3 different concept variants groups. The first one merges the presentation and the lift-up. The second regroups the x-y translation and finally, the third one is the piloting. Criteria are defined in order to distinguish the solutions. Each solution is graded with respect to the criterion. The grading strategy is as follows :

- Choose a reference solution in each concept variants.
- Take a criterion.
- Evaluate the solution with respect to the reference. If the solution is better +1, -1 if it's worse and 0 if it's the same.
- Put a weight on each criterion and add up the grading.

As an example, if the x-y translation concept variants are taken, the reference solution can be seen on figure 6. If the criterion is weight, the grading is done comparing the weight of the other solutions with the reference according to a certain discretization. $+1$ if $w_{sol} \leqslant 0.9w_{ref}$.; -1 if $w_{sol} \geqslant 1.1w_{ref}$ and 0 in the other cases. Hereafter is a list of used criteria with their discretization :

- **Weight** : Total weight of the solution. The solution is better with a low weight for structural problems in the hangar.
  * $+1$ if $w_{sol} \leqslant 0.9w_{ref}$
  * -1 if $w_{sol} \geqslant 1.1w_{ref}$
- **Safety and reliability** : This criterion regroups the safety, which is the safety of the handler and reliability: are the parts suited for the whole lifespan? Concerning the safety : Does the solution give the handler enough situational awareness? The metric of this criteria is the number of degrees of freedom which are blocked.
  * $+1$ if all the degree of freedoms can be blocked
  * -1 otherwise.

- **Cost** : The cost is the cost of the installation, not the operating cost. Complexity is partly taken in this criterion as well as a more complex solution will be more expensive.

  * $+1$ if $\text{cost}_{sol} \leqslant 0.9\ \text{cost}_{ref}$
  * -1 if $\text{cost}_{sol} \geqslant 1.1\ \text{cost}_{ref}$

- **Versatility** : This criterion answers to the question : Can the solution adapt to all plane parts for the presentation and the lift up? Or, can the solution adapt to all types of trolley (for the x-y movement). For the grading :

  * $+1$ if it can rotate and translate all kind of pieces
  * -1 otherwise

- **Precision** : This criterion checks essentially what has been written in the specifications about the precision during the presentation. Moreover, it evaluates the performance of the braking system. The metric is the ability to hold the piece in a sphere of radius r.

  * $+1$ if the cost is 10% more to reach the precision required in the specification
  * -1 if the cost is 10% less to reach the precision required in the specification

- **Maintenance** : This criterion is only for the lift up and presentation concept variants. It treats the frequency of maintaining cost and the duration of the maintenance. For example : is it better to have 5 maintenances that last 20 minutes or 1 maintenance lasting 8 hours ? N is the number of maintenance needed over a given period and t its duration :

  * $+1$ if $N_{sol} \cdot t_{sol} \leqslant 0.9 N_{ref} \cdot t_{ref}$
  * -1 if $N_{sol} \cdot t_{sol} \geqslant 1.1 N_{ref} \cdot t_{ref}$

- **Power required** : This criterion is just for the concept variant X-Y translation. It is the power required to move the bridge and the trolley. In a sense, this criterion characterizes the friction and also the operating cost. The power required should be as low as possible as this is directly linked to the operating costs.

  * $+1$ if $P_{sol} \leqslant 0.9 P_{ref}$
  * -1 if $P_{sol} \geqslant 1.1 P_{ref}$

- **Size** : This criterion is only used for the piloting concept variants. Does the piloting device fit on the hands of the handler ? The optimal device should be easy to use by one person and not an overly complex huge solution.

  * $+1$ if it fits into the hands
  * -1 otherwise.

- **User friendly** : This criterion is only used for the piloting concept variants. For this one, there is only a simple question to be answered : Is there an interface between the handler and the rolling crane to help for the maneuvering ? The piloting device should be easy to master in less than a day.

Now that the criteria are defined and the grading made, there is still to put a weight on each criterion. This will be done independently for the three concept variants.

Table 14 shows the grading for the first concept variant (lift-up and presentation). The 4 solutions (4) are evaluated following the criteria defined. The reference solution is solution 4. After the grading, the marks are summed up. The evaluation charts for the x-y movement and pilot are done in Appendix D.

CV 1 : Attach + Lift up + 2 rotations		Solutions							
Criteria	Weight	Solution 1		Solution 2		Solution 3		Solution 4 (REF)	
Cost (installation, complexity,etc)	4	-1	-4	0	0	-1	-4	0	0
Safety/reliability	5	0	0	0	0	0	0	0	0
Weight	2	0	0	0	0	-1	-2	0	0
Maintenance	4	1	4	1	4	-1	-4	0	0
Versatility	4	0	0	1	4	1	4	0	0
Precision	5	0	0	-1	-5	1	5	0	0
TOTAL			0		3		-1		0

Figure 14: Evaluation chart - Concept variant 1

6 Preliminary layout

The final solution chosen will be the combination of the solution 2 for the first concept variant (see Figure 3) and the fourth solution of the second concept variant (see Figure 9). Regarding the pilot, it will be both the first and the second solutions (see Figures 10 and 11).

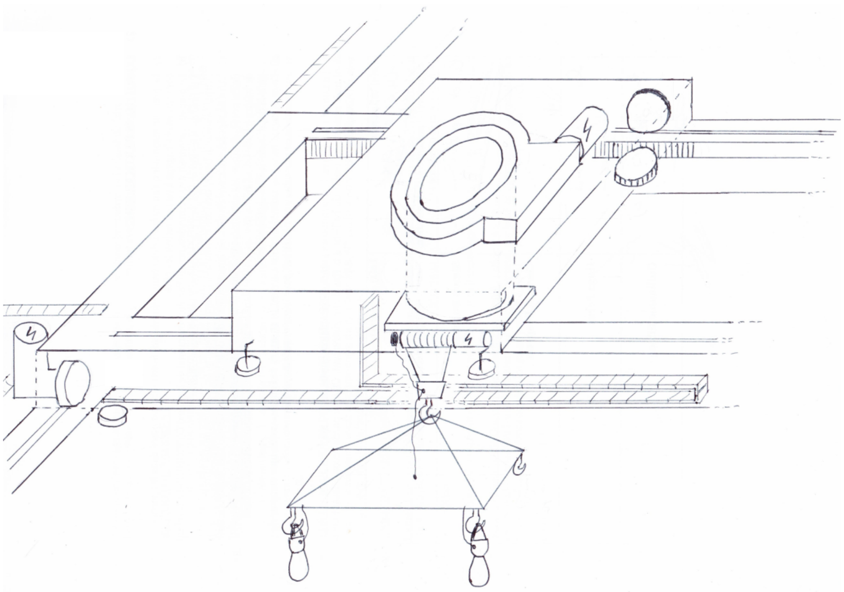


Figure 15: Preliminary layout : 3D view

As shown on Figures 15 and 16, for the x-direction, the translation is enabled by 2 (or 3) rollers on each steel beam. There will also be lateral rollers to ensure that the rollers do not leave the track. In addition to that, there will be a laser device to ensure that the trajectory is correct. On each beam, there will only be one roller which is actuated. It is important to notice that each actuated roller has its own electric motor. In order to avoid any blocking of the movement, the 2 rollers will be controlled by a *"master/slave"* controller. For the safety of the electric geared-motor [2], a frequency converter[3] will manage the amount of current, the tension and the frequency of the power supply. Moreover, it allows a synchronous working controlled by a position coder on each motor, which acts on the frequency converters. In order to slow down, the geared motors can be reversed and, if the braking power is more important, braking resistors will be used. In order to ensure that the whole crane does not move when it is supposed to be at rest, an electromagnetic brake will be used so that there is no need of power supply when the trolley is stationary.

[2] *motoréducteur*, in French
[3] *convertisseur de fréquence*, in French

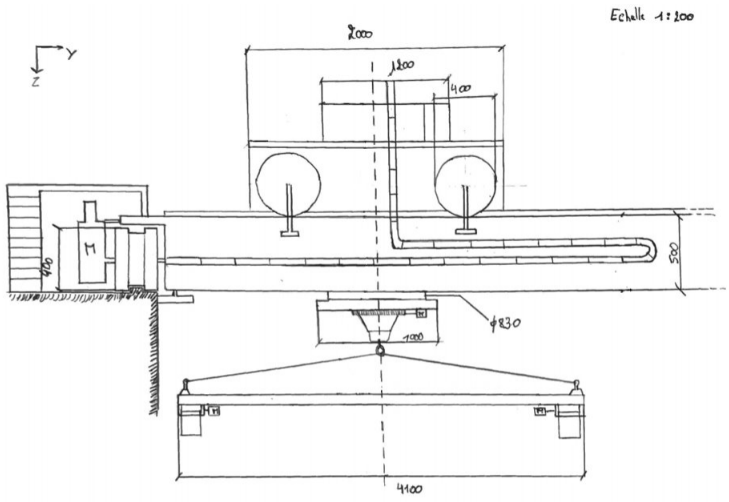


Figure 16: Preliminary layout : Front view

For the y-direction, the guidance is the same as for the x-direction while the actuation is managed by a rack and pinion actuated by a geared motor.

For the rotation along the z-axis, a slewing ring will be used. The latter will be actuated by an electrical motor which drives the rotation of a worm screw.

Regarding the rotation of the piece along a parallel axis to the ground, the system uses straps which are turned by a motor, as explained in section 4.1.2.

For lifting up, a hoist drum actuated by an electrical motor will move up (or down) a cable. At the end of that cable, there is a hook on which 4 other cables would link 4 different anchor points on a lifting frame, as already explained in section 4.1.2. Again, an electromagnetic braking system will be used for holding the drum in a given position without using any power supply. The full preliminary layout drawings is found in appendix E.

6.1 Main dimensions

In this section, some computations are made in order to know an order of the main dimensions. Other dimensions have been found on common applications. For all the motors or geared motors, a lot of devices are available on *Euronorm Drive System* website [6].

6.1.1 Guide rollers

The guide rollers could have a dimension of around $400 - 600$ $[mm]$ as the ones shown on Figure 17. That kind of rollers can withstand a load about $28-60$ $[t]$, as advertised on the *Euronorm Drive Systems* website [4].

6.1.2 Slewing ring

Concerning the slewing ring, the dimensions can vary a lot according to the use. Since the dimensions have not already been computed, we only looked for typical dimensions, found in the catalogues available on *Cetic* [2] and *Euronorm Drive Systems* [7] websites. We thus found typical dimensions of a slewing ring about $1000 - 2000$ $[mm]$ of diameter. On *Cetic* website, there are only slewing rings while on *Euronorm Drive Systems*, there are slewing ring with worm screw, as shown on Figure 18.

6.1.3 Rotation of the piece along with the ground

For the rotation of the piece parallel to the ground, some typical power and dimensions are available on the *Vetter* website [9]. We then *"choose"* the following dimensions :

- Maximal load : 20 $[t]$
- Turning moment : 6400 $[N \cdot m]$

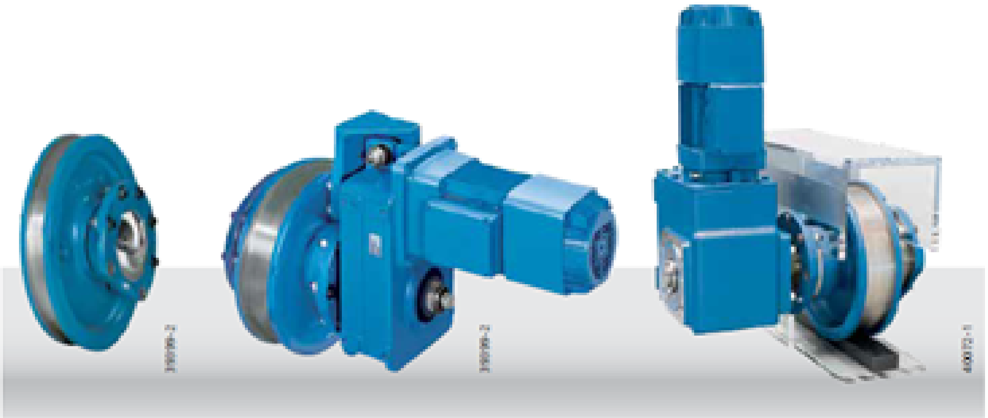


Figure 17: Guide rollers [4]

Figure 18: Slewing ring with worm screw [7]

- Weight of one device : 3.28 $[t]$
- Power required : 1.5 $[kW]$ DC

We would use minimum 2 devices like the one describer just above. We still need to discuss with the customer for a higher number.
Again, the braking device will be an electromechanic braking device on the motor of the geared motor (if not powered, the braking is actuated but if it is powered, the braking is not used).

Regarding the straps that would be used for the rotation and in order to carry the piece, different kind of straps are available on the *Lemmens* website [5]. We would need straps that can support a 15 $[t]$ load.

6.1.4 Rack and pinion

Translation in Y-axis is done through rack and pinion. Following are the calculations made in order to get a suitable rack and pinion system for our application. The following calculations are based on an example available in the catalogue of *Atalanta* [1].

Data :

- Mass : $20\,000\,[kg]$
- Maximal speed : $0.3\,[m/s]$
- Acceleration time : $1\,[s]$

- Gravity acceleration : $9.81\,[m/s^2]$

The tangential force and the permissible force can then be computed :

$$\text{Tangential force exerted : } F_u = \frac{(m \cdot g \cdot \mu + m \cdot a)}{1000}\,[kN] \tag{1}$$

$$\text{Permissible force : } F_{per} = \frac{F_{u,Tab}}{(K_a \cdot S_b \cdot f_n \cdot L_{khb})}\,[kN] \tag{2}$$

with $K_a = 1.25$, the load factor; $f_n = 0.85$ life time factor; $F_{u,Tab} = 47\ [kN]$, maximum feed force of pinion; $S_b = 2$ (range = 1-3), the safety factor and $L_{khb} = 1.5$, is the linear load distribution factor that considers the contact stress, while it describes unintegrated load distribution over the tooth width.

Condition for a right design : Permissible force > tangential force exerted.

The following steps have to be repeated if the condition at the end of a complete procedure is not respected.

1. Rack : We take a high precision rack for our case and start the calculation for module = 5 (see Figure 19), with a maximal force of 62 $[kN]$.
2. pinion : Now, we select a pinion. It should be of same module for good meshing between rack and pinion. There is a need of a minimum of 20 teeth for minimum backlash and the pitch diameter is 100 $[mm]$ so the module is 5.
   For that type of pinion the maximal force is 47 $[kN]$.
3. Check the condition by computing the value for the permissible force : $F_{permissible} = 9.94\,[kN] > F_{tangential} = 6.39\,[kN]$.

As it satisfies the criterion, these can be selected from the *Atlanta servo drive system catalogue* [1]. All the tables used are shown in Appendix F.

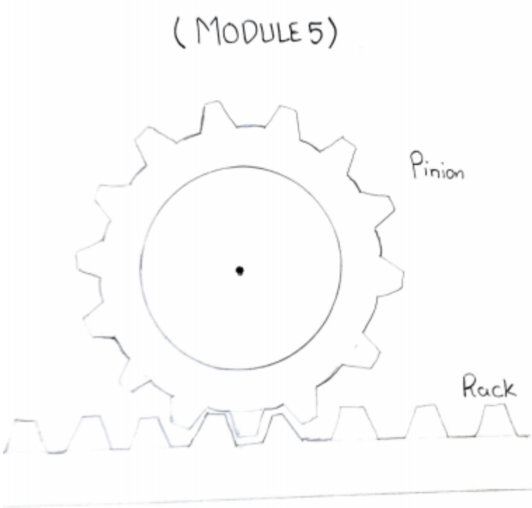


Figure 19: Rack and pinion

6.2 Weight estimation

6.2.1 Cables

In the preliminary layout, one cable makes the link between the platform and the drum. This cable has to hold a weight of 15 tonnes (according to the specifications). The height of the bridge is 13 m. The cable hangs vertically but can move right or left to attach the piece. Lets state that the cable can be inclined 45°, the minimum cable length becomes 13/sin(45) = 18 m.By adding 2 m for security, the total cable length is 20m.

The dimensionning follows the table found on the *The Engineering ToolBox* website [8].
The maximal tension in the cable will be about 157 kN (taking into account the weight of all the elements we need to lift up (15t) + the platform (1t) : $16t \cdot g = 157kN$).
Following the table (see Figure 20), a safe load of 164 kN is taken, and the minimum break strength will be 818 kN. In other words, a safety factor of 5.2 (818/157) is considered. The cable diameter is 38 mm and weight per meter is 5.62 kg/m. Thus, the total weight of the cable becomes 101.34 kg.

Rope Diameter		Minimum Breaking Strength		Safe Load		Weight	
(in)	(mm)	(lb_f)	(kN)	(lb_f)	(kN)	(lb_m/ft)	(kg/m)
1/4	6.4	5480	24,4	1100	4.89	0.11	0.16
5/16	8	8520	37,9	1700	7.56	0.16	0.24
3/8	9.5	12200	54,3	2440	10.9	0.24	0.36
7/16	11.5	16540	73,6	3310	14.7	0.32	0.48
1/2	13	21400	95,2	4280	19.0	0.42	0.63
9/16	14.5	27000	120	5400	24.0	0.53	0.79
5/8	16	33400	149	6680	29.7	0.66	0.98
3/4	19	47600	212	9520	42.3	0.95	1.41
7/8	22	64400	286	12900	57.4	1.29	1.92
1	26	83600	372	16700	74.3	1.68	2.50
1 1/8	29	105200	468	21000	93.4	2.13	3.17
1 1/4	32	129200	575	25800	115	2.63	3.91
1 3/8	35	155400	691	31100	138	3.18	4.73
1 1/2	38	184000	818	36800	164	3.78	5.63
1 5/8	42	214000	852	42800	190	4.44	6.61
1 3/4	45	248000	1100	49600	221	5.15	7.66
1 7/8	48	282000	1250	56400	251	5.91	8.80
2	52	320000	1420	64000	285	6.72	10.0

Figure 20: Cable choice table

6.3 Drum, trolley and bridge

The drum dimensionning follows the method on the Weihua Cranes website [3].
First of all, the drum diameter is fixed to 0.4 m. The groove pitch is about 80 mm. What is the length of this drum?

Knowing the cable length (20 m), the drum length is found by the number of times this cable can go round a cylinder of radius 0.4 m: $N = \frac{20}{\pi \cdot 0.4} = 15.91$. The length of the drum is found by multiplying the groove pitch times the number of encirclements. $L = 0.08 \cdot 16 = 128$ $[cm]$.

The length of the drum is 128 cm and the inner diameter 0.2 m. The total volume : $\pi/4 \cdot (0.4^2 - 0.2^2) \cdot L = 0.12$ $[m^3]$. The density of steel is around 8000 kg/m^3. Thus, the drum has a weight of 960 kg.
The dimensions of the trolley are estimated to 2 x 3 m. The masses following were roughly estimated as there remains many unknowns. The mass of the trolley is estimated to 5t (drum + slewing ring + motors). The bridge will then have to support 5t + 16t = 21t. The bridge has a span of 50.75 m. Its estimated mass is 40t. To sum up, adding the weight of the charge, cables, trolley and bridge, the estimated mass is around 60t.

6.4 Power estimation

In this section the estimation of the lift-up motor will be made. The maximal load that has to be lift up is the wings (15t), the platform (1t) and the cables (0.1t). Thus, the maximal total load is:

$$16.1[t] \cdot g = 158[kN]$$

The lift up speed is 0.2 m/s (from the specifications). The lift up power becomes :

$$P_z = 158 \cdot 0.2/0.85 = 38\ [kW]\ ,$$

where 0.85 is the gross efficiency of the electrical motor.
For the estimation of the power needed in the X and Y translation, we proceeded the same way:
We considered a variation in kinetic energy to calculate the energy needed to accelerate the system:

$$\Delta E = \frac{1}{2} m (v_2^2 - v_1^2)$$

As the initial velocity is 0 and the maximum velocity is known due to the specifications, we can calculate the amount of energy needed. We also know the maximum acceleration for our system (also written in the specifications) and from this, we can calculate how much time it takes to reach the maximum velocity. As the definition of power is the amount of energy spent on a given period of time, we can compute:

$$P_x = \frac{\Delta E_x}{\Delta t_x}$$

For the Y-direction, we are using a rack and pinion system, which has more friction than a system actuated by its wheels, so the amount of power needed is calculated the same, but we added a friction coefficient factor:

$$P_y = \frac{\mu_f \Delta E_y}{\Delta t_y}$$

By computing all this, we get as a result:

$$P_x = 1\ 318 \quad [W]$$
$$P_y = 488 \quad [W]$$

7 Conclusion

All this work seems to be not much but we spent a lot of time on it. At several times we reworked on each part after having received a productive feedback from the teaching staff. After having followed all these steps we can see why it has been very useful to go through them. It allows us to take a step back on the initial ideas that we had or that we know already existed and that way we could add more things together in order to have the best solution for all areas that suits the best for our application. By doing all this work we really saw that it was sometimes a good idea to keep focused on things that already exist on the market but also that adding our personal creative touch would make the final product unique. We are also a bit more aware of how complicated it can be to design a product from scratch for a unique application. There are a lot of aspects that need to be taken into account and if you do not take time to organise yourself as well as analyse all the possibilities before starting, you can end up with a solution that you regret because you have gone too fast and some problems might appear later during the design of the product that you have not foreseen.

A Appendix : Functional graph

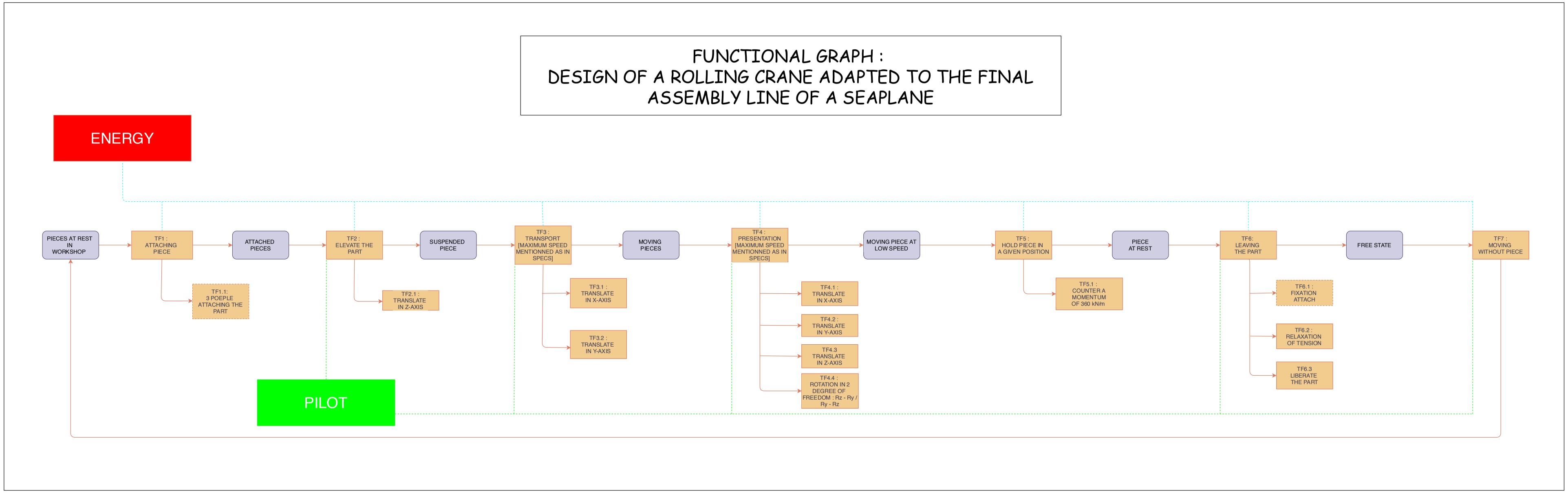


Figure 21: Functional graph

B Appendix : Morphological charts

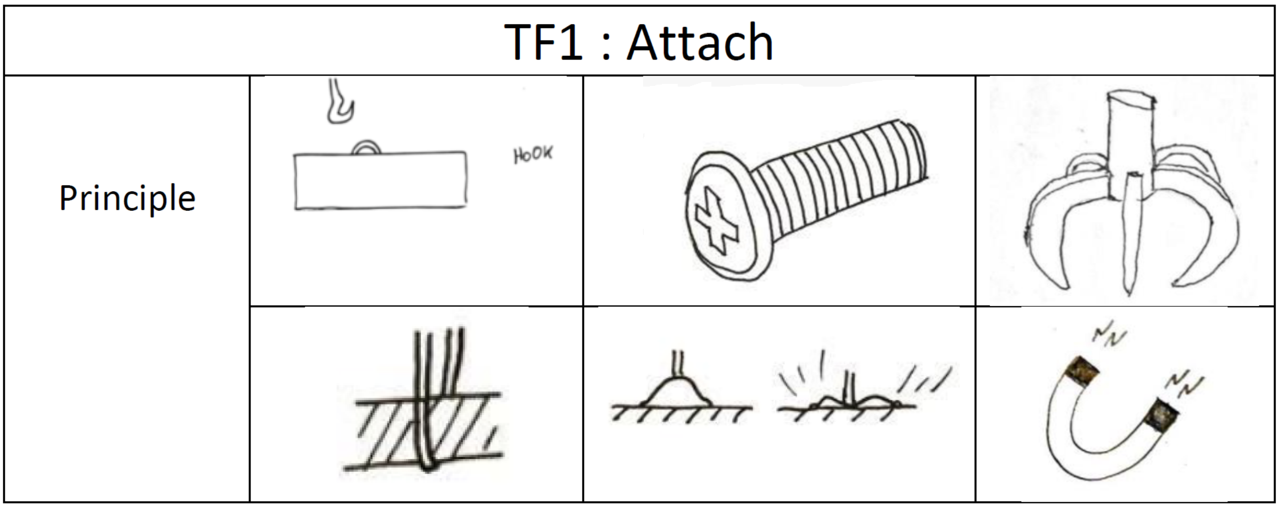


Figure 22: Morphological graph: TF1: Attach

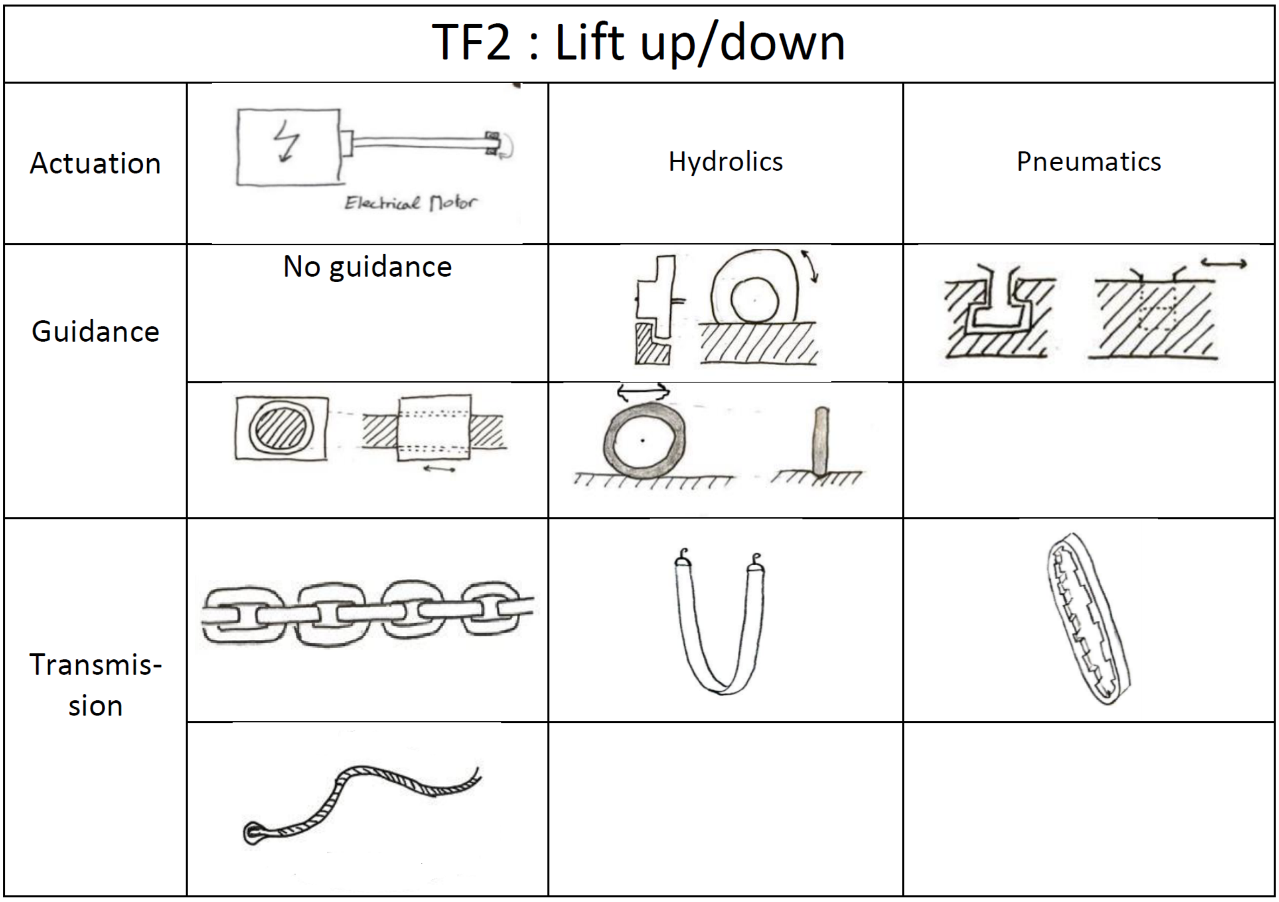


Figure 23: Morphological graph: TF2: Lift Up/Down

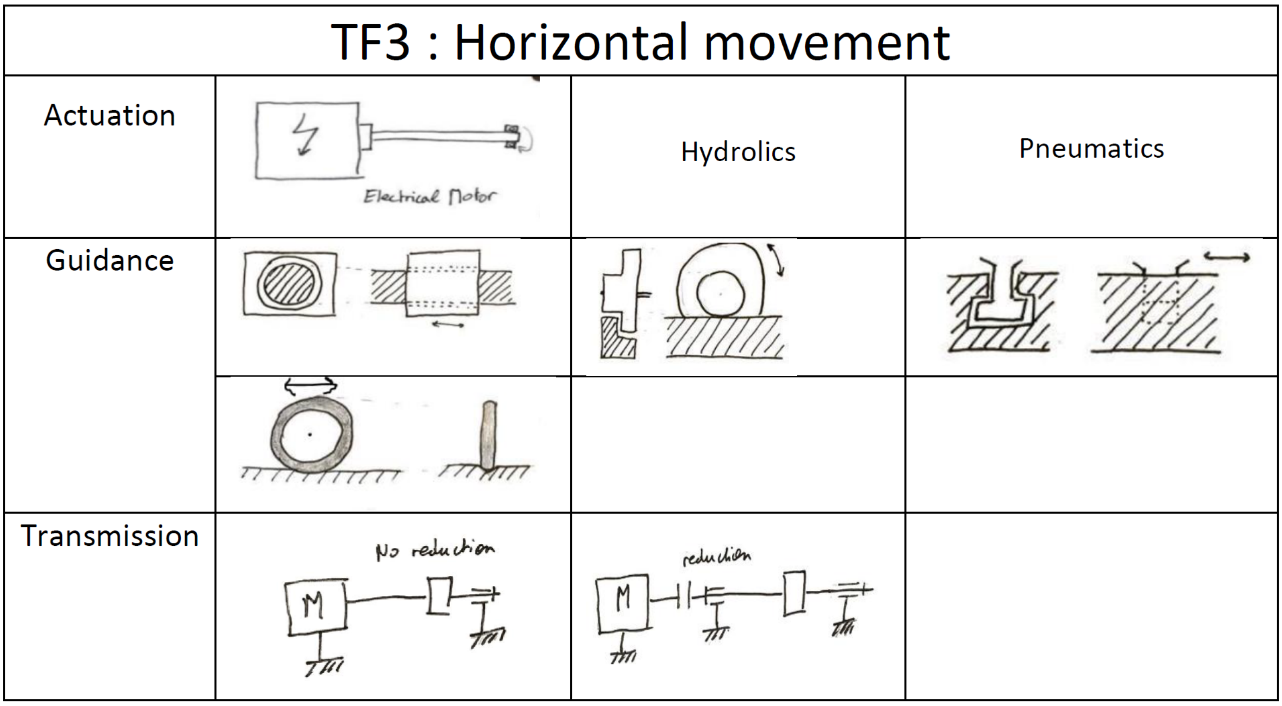


Figure 24: Morphological graph: TF3: Horizontal movement

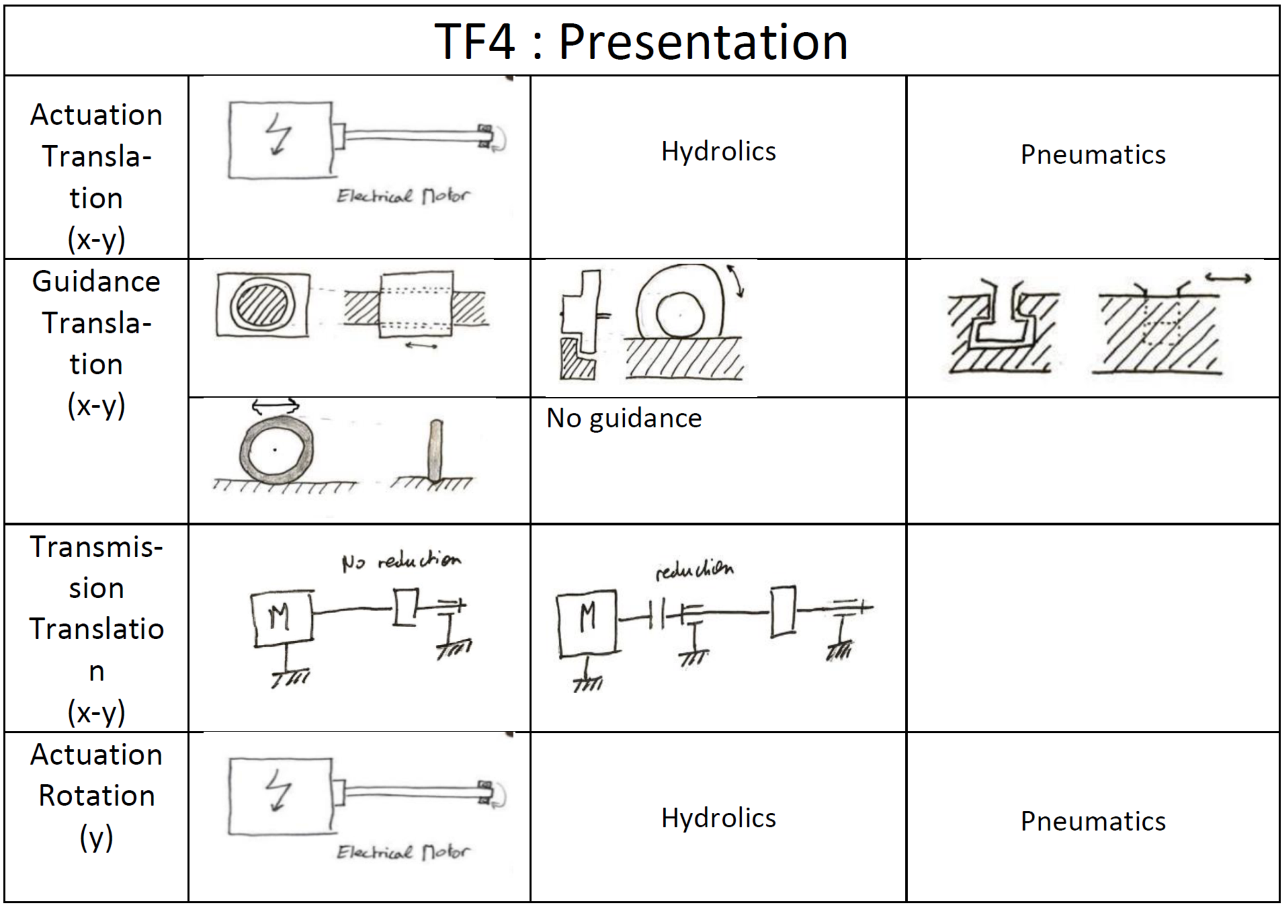


Figure 25: Morphological graph: TF4 : Presentation (1)

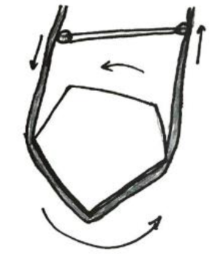
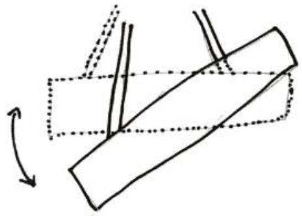
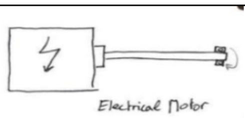
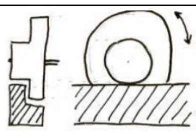
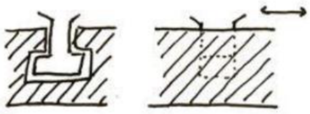
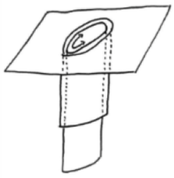
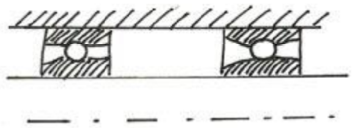
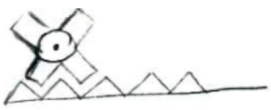
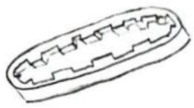
Principe rotation (y)			
Actuation Rotation (z)		Hydrolics	Pneumatics
Guidance Rotation (z)			
	No guidance		
Transmis-sion Rotation (z)			

Figure 26: Morphological graph: TF4 : Presentation (2)

TF6 : pilot			
Connection type	Wireless 	Wire 	
Hardware	Remote 	Laptop 	Panel control 

Figure 27: Morphological graph: TF6 : Piloting

C Appendix : Concept variants

Figure 28: Kinematic schematics of the solution 2 for concept variant 1 - Left : rotation along z-axis and lift-up - Right : rotation parallel to the ground

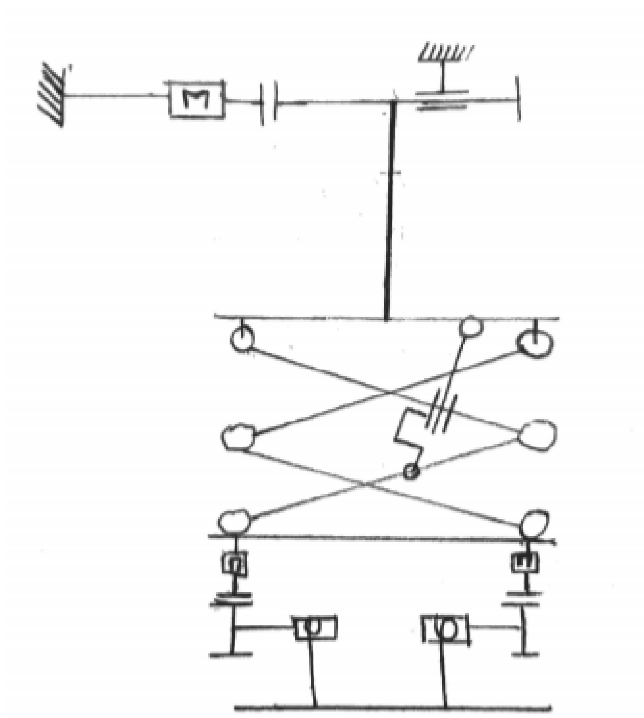


Figure 29: Kinematic schematics of the CV1.3

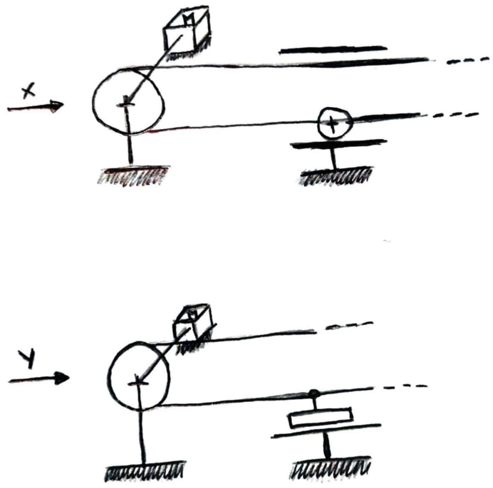


Figure 30: Kinematic schematics of the CV2.3

D Appendix : Evaluation charts

CV2 : X and Y TRANSLATION		Solutions							
Criteria	Weight	Solution 1 (REF)		Solution 2		Solution 3		Solution 4	
Cost	4	0	0	1	4	-1	-4	-1	-4
Weight	3	0	0	1	3	0	0	0	0
Power required	2	0	0	1	2	-1	-2	-1	-2
Precision	5	0	0	-1	-5	-1	-5	1	5
Safety	4	0	0	-1	-4	-1	-4	1	4
Versatility	5	0	0	-1	-5	0	0	0	0
			0		0		0		0
TOTAL		0		-5		-15		3	

Figure 31: Evaluation chart - Concept variant 2

CV3 : PILOT		**Solutions**							
Criteria	Weight	Solution 1 (REF)		Solution 2		Solution 3		Solution 4	
Cost (installation, complexity,etc)	4	0	0	1	4	-1	-4	-1	-4
Safety/reliability	4	0	0	0	0	0	0	-1	-4
Weight	2	0	0	0	0	-1	-2	-1	-2
Size	3	0	0	-1	-3	-1	-3	-1	-3
Maintenance	1	0	0	0	0	0	0	-1	-1
User friendly	3	1	3	0	0	1	3	1	3
			0		0		0		0
			0		0		0		0
TOTAL		3		1		-6		-11	

Figure 32: Evaluation chart - Concept variant 3

E Appendix : Preliminary layout - drawings

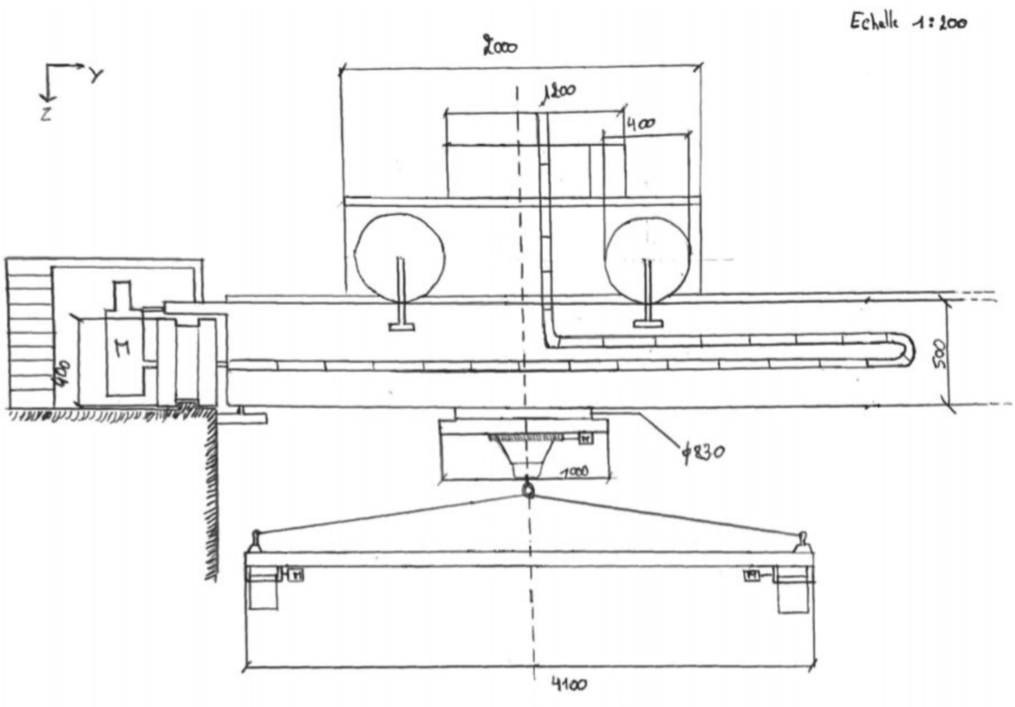


Figure 33: Preliminary layout : Front view

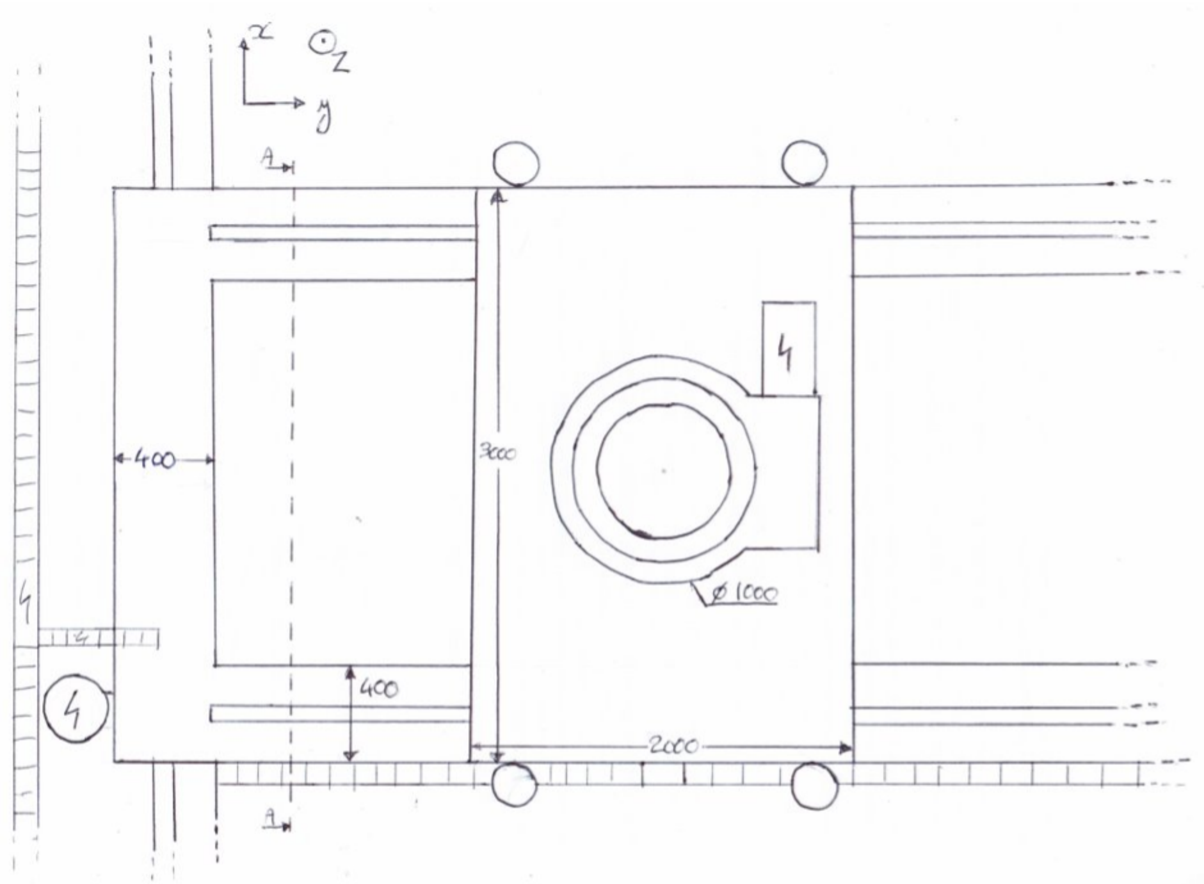


Figure 34: Preliminary layout : Top view

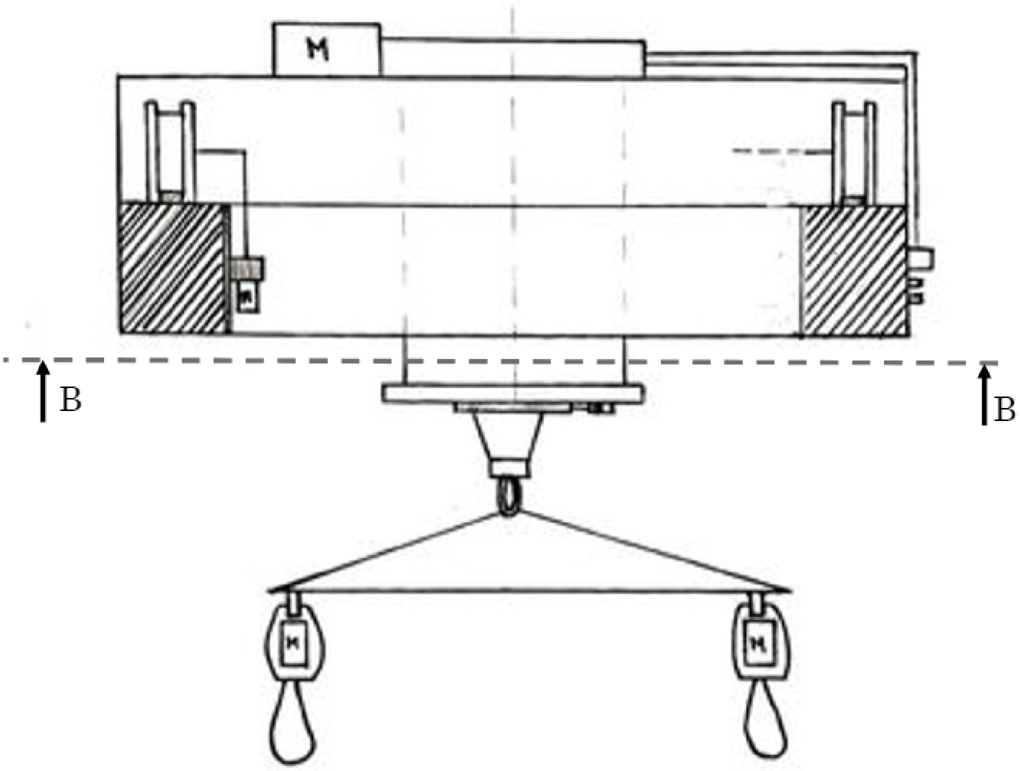


Figure 35: Preliminary layout : Section view A-A

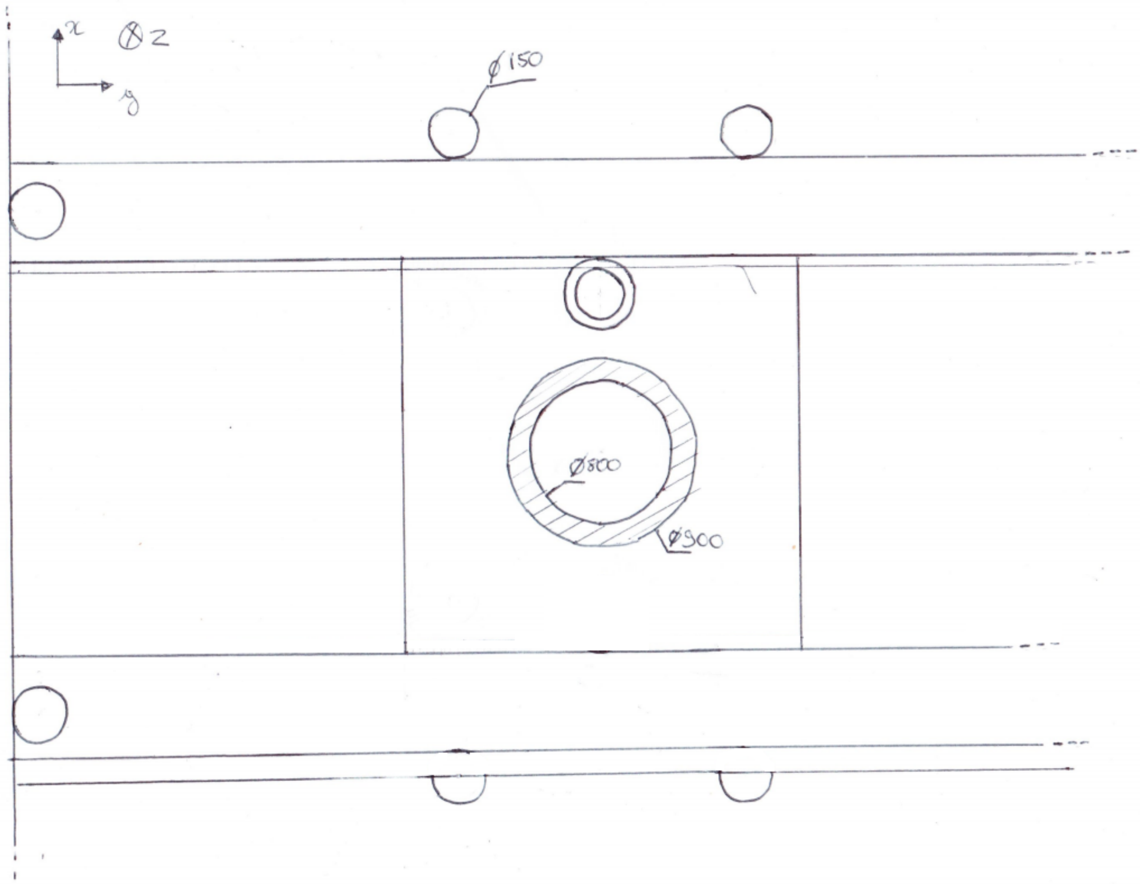


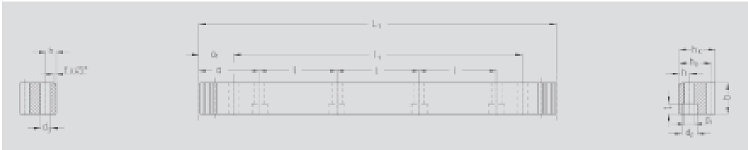
Figure 36: Preliminary layout : Section view B-B

F Preliminary layout - rack and pinion dimensions

For the selection of all dimensions, see Figure 37, the rack selected is the one corresponding to the reference : code : 28 60 155 (module 5, page ZB-7) with maximal length of 1500 [mm]. For the selection of the pinion dimensions, see Figure 38. The pinion selected is the one corresponding to the reference : code : 21 50 020 (module 5, page ZB-34). For the selection of the module of the rack and the maximal feed force, see Figure 39. For the selection of the pinion module and the maximal feed force, see Figure 40.

HPR Zahnstangen Modul 2–12
HPR racks module 2–12

ATLANTA-Qualität 6 ATLANTA-Quality 6



Bestell-Nr. Order code	Modul Module	L_1	Zähnezahl N° of teeth	b	h_k	h_0	f	a	l	Anz. Bohr. N° of holes	h	d_1	d_2	t	a_1	l_1	d_3	
28 20 105	2	1005,30	160	24	24	22,0	2	62,8	125,66	8	8	7	11	7	31,4	942,70	5,7	4,20
28 21 105	2	1005,30	160	24	24	22,0	2	ohne Befestigungsbohrungen / without mounting holes										4,2
28 20 205	2	2010,62	320	24	24	22,0	2	62,8	125,66	16	8	7	11	7	31,	1948,00	5,7	8,40
28 21 205	2	2010,62	320	24	24	22,0	2	ohne Befestigungsbohrungen / without mounting holes										8,4
28 30 105	3	1017,90	108	29	29	26,0	2	63,6	127,23	8	9	10	15	9	34,4	949,10	7,7	6,00
28 31 105	3	1017,90	108	29	29	26,0	2	ohne Befestigungsbohrungen / without mounting holes										6,0
28 30 205	3	2035,75	216	29	29	26,0	2	63,6	127,23	16	9	10	15	9	34,4	1967,00	7,7	12,00
28 31 205	3	2035,75	216	29	29	26,0	2	ohne Befestigungsbohrungen / without mounting holes										12,0
28 41 105	4	1005,30	80	39	39	35,0	2	ohne Befestigungsbohrungen / without mounting holes										10,5
28 42 105	4	1005,30	80	39	39	35,0	2	62,8	125,66	8	12	14	20	13	37,5	930,3	11,7	10,50
28 42 155	4	1507,90	120	39	39	35,0	2	62,8	125,66	12	12	14	20	13	37,5	1432,9	11,7	16,00
28 40 205	4	2010,62	160	39	39	35,0	2	62,8	125,66	16	12	10	15	9	37,5	1935,60	7,7	21,00
28 41 205	4	2010,62	160	39	39	35,0	2	ohne Befestigungsbohrungen / without mounting holes										21,0
28 42 205	4	2010,62	160	39	39	35,0	2	62,8	125,66	16	12	14	20	13	37,5	1935,6	11,7	21,00
28 50 105	5	1005,30	64	49	39	34	2,5	62,8	125,66	8	12	14	20	13	30,1	945,00	11,7	13,40
28 51 105	5	1005,30	64	49	39	34	2,5	ohne Befestigungsbohrungen / without mounting holes										13,4
28 50 155	5	1507,96	96	49	39	34	2,5	62,8	125,66	12	12	14	20	13	30,1	1447,70	11,7	20,10
28 51 155	5	1507,96	96	49	39	34	2,5	ohne Befestigungsbohrungen / without mounting holes										20,1
28 50 205	5	2010,62	128	49	39	34	2,5	62,8	125,66	16	12	14	20	13	30,1	1950,40	11,7	26,80
28 51 205	5	2010,62	128	49	39	34	2,5	ohne Befestigungsbohrungen / without mounting holes										26,8
28 60 105	6	1017,88	54	59	49	43	2,5	63,6	127,23	8	16	18	26	17	31,4	955,00	15,7	18,50
28 61 105	6	1017,88	54	59	49	43	2,5	ohne Befestigungsbohrungen / without mounting holes										18,5
28 60 155	6	1526,81	81	59	49	43	2,5	63,6	127,23	12	16	18	26	17	31,4	1464,00	15,7	27,80
28 61 155	6	1526,81	81	59	49	43	2,5	ohne Befestigungsbohrungen / without mounting holes										27,8
28 60 205	6	2035,75	108	59	49	43	2,5	63,6	127,23	16	16	18	26	17	31,4	1973,00	15,7	37,00
28 61 205	6	2035,75	108	59	49	43	2,5	ohne Befestigungsbohrungen / without mounting holes										37,0
28 80 105	8	1005,30	40	79	79	71	2,5	62,8	125,66	8	25	22	33	21	26,6	952,00	19,7	44,76
28 81 105	8	1005,30	40	79	79	71	2,5	ohne Befestigungsbohrungen / without mounting holes										44,76
28 80 205	8	2010,61	80	79	79	71	2,5	62,8	125,66	16	25	22	33	21	26,6	1957,30	19,7	89,50
28 81 205	8	2010,61	80	79	79	71	2,5	ohne Befestigungsbohrungen / without mounting holes										89,5
28 10 105	10	1005,30	32	99	99	89	2,5	62,83	125,66	8	32	33	48	32	125,66	753,96	19,7	68,72
28 11 105	10	1005,30	32	99	99	89	2,5	ohne Befestigungsbohrungen / without mounting holes										68,72
28 12 105	12	1017,90	27	120	120	108	2,5	63,60	127,23	8	40	39	58	38	127,23	763,40	19,7	111,00
28 13 105	12	1017,90	27	120	120	108	2,5	ohne Befestigungsbohrungen / without mounting holes										120,0

500 mm und andere Längen auf Anfrage. / 500 mm and other length on request.

Figure 37: Rack dimensions

ATLANTA — Zahnräder mit geschliffener Verzahnung – Modul 5–10 / Gearwheels with ground teeth – module 5–10

gerade verzahnt, mit Bohrung Ø^{H6} und Passfedernut nach DIN 6885
Straight tooth system, with bore Ø^{H6} and keyway acc. to DIN 6885

16MnCr5, 1.7131
einsatzgehärtet / case-hardened
Verz.-Qual. / Gearing grade **6 e 25**

Bestell-Nr. / Order code	Zähnezahl / N° of teeth z	d	d_k	d_1^{H6}	d_N	b_1	b_2	u	t	kg	Spannsatz lt. Seite GH-1 / shrink-disc on page GH-1
Modul / Module 5											
24 56 421	21	105	115	45	68	50	85,0	14	48,8	3,7	80 80 068
24 57 421	21	105	115	55	80	50	90,0	16	59,3	3,7	80 87 080
24 56 425	25	125	135	45	68	50	85,0	14	48,8	5,2	80 80 068
24 57 425	25	125	135	55	80	50	90,0	16	59,3	5,1	80 87 080
24 58 425	25	125	135	75	110	50	110,0	20	80,4	4,7	80 80 110
Modul / Module 6											
24 67 421	21	126	138	55	80	60	100,0	16	59,3	5,6	80 87 080
24 68 421	21	126	138	75	110	60	120,0	20	79,9	4,7	80 80 110
24 67 425	25	150	162	55	80	60	100,0	16	59,3	8,0	80 87 080
24 68 425	25	150	162	75	110	60	120,0	20	79,9	7,1	80 80 110
Modul / Module 8											
24 88 420*	20	160	176	75	110	80	140	20	79,9	12,0	80 80 110
24 89 420*	20	160	176	85	125	80	145	22	90,4	12,1	80 80 125
Modul / Module 10											
24 09 620*	20	200	220	85	125	100	165	22	90,4	23	80 80 125

* Verzahnungsqualität 5 f 23 / Gearing quality 5 f 23

Figure 38: Pinion dimensions

ATLANTA — Übersicht geradverzahnte Zahnstangen / Overview of straight toothed racks

Klasse / Class	ATLANTA Qualität / ATLANTA Quality	Modul / Module	Gesamtteilungsfehler[1] / Total pitch error[1] (±µm/m)	Zahndicken-Toleranz / Tooth thickness tolerance (µm)	max. Länge / max. length (mm)	Max. Vorschubkraft pro Ritzeleingriff[2] / Max. feed force per pinion contact[2] kN	Einsatzgebiete (Beispiele) / Applications (examples)
UHPR Ultra High Precision Rack	3	5	12	-13	1005	62,0	**Hochpräzise Werkzeugmaschinen mit elektronischer Vorspannung** High precision machine tools with electrical preload
		6	12	-13	1018	89,0	
		8	12	-13	1005	156,0	
		10	12	-13	1005	234,0	
		12	12	-13	1018	333,5	
	5	3	26	-15	1018	25,5	**Spielfreie Antriebe mit elektronischer Verspannung, Werkzeugmaschinen, Hubachsen, Mehrfachzahneingriff** Backlash free drives with electronical preload, machine tools, lifting axes, multiple pinion contact
		4	26	-15	1005	49,0	
		5	26	-15	1005	75,0	
		6	26	-15	1018	107,0	
HPR High Precision Rack	6	2	36	-37	1005	15,5	**Holz-, Kunststoff-, Composit-, Aluminiumbearbeitungsmaschinen** Wood, plastic, composite, aluminium working machines
		3	36	-37	1018	25,5	
		4	36	-37	1005	49,0	
	6	2	36	-37	2011	12,5	**Werkzeugmaschinen, Führungszahnstangen, Wasserschneideanlagen, Rohrbiegeanlagen, Plasmaschneidanlagen** Machine tools, integratable racks, water cutting machines, tube bending systems, plasma cutting machines
		3	36	-37	2036	23,5	
		4	36	-37	2011	42,0	
		5	36	-22	2011	62,0	
		6	36	-22	2036	89,0	
		8	36	-22	2011	155,5	
		10	36	-22	1005	234,0	
		12	36	-22	1018	333,0	
	7	2	52	-51	1005	12,5	**Holzbearbeitungsmaschinen, Linearachsen mit erhöhter Anforderung an die Laufruhe** Wood working machines, linear axes with high requirement for a smooth running
		3	52	-51	1018	23,0	
		4	52	-51	1005	42,0	
		5	52	-37	1005	62,0	
		6	52	-37	1018	89,0	
		8	52	-37	1005	155,5	
PR Precision Rack	8	2	60	-59	2011	12,0	**Portale, Handhabung, Linearachsen** Portals, handling linear axes
		3	60	-59	2036	22,0	
		4	60	-59	2011	39,0	
		5	60	-59	2011	57,5	
	8	2	100	-110	2011	7,0	**Linearachsen** Linear axes
		3	100	-110	2036	12,0	
		4	100	-110	2011	23,0	

Figure 39: Rack module and maximal feed force

1/2015

Berechnung und Auswahl für Ritzel-Zahnstangen-Triebe - Modul 10 – gerade verzahnt
Rack and pinion drive – calculation and selection – module 10 – straight tooth system

Zahnstange / Rack		UHPR	HPR	BR			
ATLANTA-Qualität / ATLANTA-Quality		3	6	9		10	
Zahnstange Rack	Werkstoff / material	Vergütungsstahl nach ATLANTA-Norm / heat-treatable steel according ATLANTA-Standard					
	Wärmebehandlung Heat treatment	Hochleistungs-Härteprozess high performance hardening process		weich soft		Hochleistungs-Härteprozess high performance hardening process	
Ritzel Pinion	Werkstoff / material	16MnCr5	16MnCr5	16MnCr5	C45	16MnCr5	C45
	Wärmebehandlung Heat treatment	einsatzgehärtet case hardened	einsatzgehärtet case hardened	einsatzgehärtet case hardened	weich soft	einsatzgehärtet case hardened	ind. gehärtet ind. hardened
Ritzelzähnezahl 1) No. of pinion teeth 1)	Teilkreis d pitch circle dia.	Max. Vorschubkraft (Werte gelten nur für Material nach ATLANTA-Norm) max. feed force (values are only valid for material according ATLANTA-Standard)					
12	120 mm	78,0 kN	77,5 kN	21,0 kN	8,5 kN	71,5 kN	41,5 kN
13	130 mm	94,0 kN	94,0 kN	22,5 kN	10,0 kN	84,0 kN	49,0 kN
14	140 mm	117,0 kN	117,0 kN	25,0 kN	11,5 kN	96,0 kN	56,0 kN
15	150 mm	128,5 kN	128,5 kN	26,5 kN	13,0 kN	107,0 kN	63,0 kN
16	160 mm	141,5 kN	141,5 kN	29,0 kN	15,0 kN	114,0 kN	70,0 kN
17	170 mm	159,5 kN	159,5 kN	33,0 kN	17,5 kN	121,0 kN	77,0 kN
18	180 mm	171,0 kN	171,0 kN	35,0 kN	19,5 kN	128,0 kN	83,5 kN
19	190 mm	181,0 kN	180,5 kN	37,0 kN	21,0 kN	135,5 kN	90,5 kN
20	200 mm	191,0 kN	191,0 kN	39,5 kN	22,5 kN	142,5 kN	97,0 kN
21	210 mm	201,0 kN	201,0 kN	41,5 kN	24,5 kN	149,5 kN	104,0 kN
22	220 mm	211,0 kN	211,0 kN	43,5 kN	26,0 kN	156,5 kN	110,5 kN
23	230 mm	221,0 kN	221,0 kN	45,5 kN	27,5 kN	163,5 kN	117,0 kN
24	240 mm	231,0 kN	231,0 kN	47,5 kN	29,0 kN	165,0 kN	123,5 kN
25	250 mm	234,0 kN	234,0 kN	49,5 kN	31,0 kN	166,0 kN	130,0 kN

1) Auf Verfügbarkeit prüfen (Kapitel ZB) / check availability (chapter ZB)

Maximal zulässige Vorschubkräfte - Beschreibung siehe Seite ZB-36 / Maximum permissible feed forces – description see page ZB-36

Maße / Dimensions in mm

Figure 40: Pinion module and maximal feed force

References

[1] Atalanta. Rack and pinon. http://atlantagmbh.com/wp-content/uploads/2016/03/Servo_Deutsch.pdf consulted 6/12/2020.

[2] Cetic. Slewing ring. https://www.cetic.fr/product/couronnes-dorientation/ consulted 6/12/2020.

[3] Weihua Cranes. Bridge crane design calculation. http://www.craneus.com/Tech-Forum/Bridge_Crane_Design_Calculation_209.html consulted 10/12/2020.

[4] Demag. Guide rollers. https://www.demagcranes.com/fr/produits/technique-dentrainement consulted 6/12/2020.

[5] Lemmens. Straps. https://www.lemmens-cables.be/fr/catalogue/7-sangles-de-levage/ consulted 6/12/2020.

[6] Euro Norm Drive Systems. Documentation. https://www.euronormdrives.fr/documentation/documentation-produit/ consulted 6/12/2020.

[7] Euro Norm Drive Systems. Slewing ring with worm screw. https://www.euronormdrives.fr/produits/couronne-dorientation/entrainements-rotatifs/ consulted 6/12/2020.

[8] The Engineering ToolBox. Wire rope - strength. https://www.engineeringtoolbox.com/wire-rope-strength-d_1518.html consulted 10/12/2020.

[9] Vetter. Motor for turning loads. https://vettercranes.com/en/products/rotomaxr-load-turning-devices/basic-devices/rotomaxr-rve/ consulted 6/12/2020.