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# Active connection mechanism for space exploration on Mars with modular robots

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# 1 Abstract

Reconfigurable modular robots are robots composed of modules tied together using a connection mechanism. Only self-reconfigurable one can do that autonomously to achieve different task by changing their morphology or adding a specialized module (wheels, camera). The goal of this project is to design an Active Connection Mechanism (ACM) that works in Mars environment. The principal problem on Mars will be the dust and the temperature. The dust causes alignment problem between modules. To avoid this misalignment, we designed a mechanism inspired by a concept of underwater electrical connector used in petrol fields. The final mechanism creates a physical latch between the two modules without misalignment. However, the mechanism is quite complex and its volume is maybe too big to be implemented on real modular robots.

# 2 Introduction

In reconfigurable modular robotics, robots are composed of multiple modules that can attach and detach to each other, either actively or passively. An active connection is a connection that can be done by the robot itself whereas a passive connection is a connection that needs an operator. The modules are robots with only few Degrees Of Freedom (DOF) that have limited possibilities of movement.

The goal of modular robotics is to have a robot that can adapt itself to achieve different tasks. An active connection has the advantage that the robot can reconfigure itself during the task in real time without the help of a human.

In most of modular robots, all the modules are the same because it is the first vision of modular robotics. The idea is that modules can do everything only with a good arrangement between them.

Some researches show that special module lead to an easier morphology with less module [1]. In this paper, the robots have general-purpose modules and specialized modules like wheel modules or camera modules. The specialized modules are designed with the same connection so they can connect with other modules in the same way that general modules do.

The goal of this project is to design an Active Connection Mechanism (ACM) for space exploration on Mars. An ACM is the mechanism that connects two modules so that there is no misalignment between them. If there is a misalignment, the kinematic model of the robot become wrong and therefor its positioning. Moreover, the kinematic model cannot be compensated using sensors. The ACM have to resist to torques and force that pass through the connection due to the movement of the robot and still guarantee the alignment.

A constraint of this project is the environment. On Mars, the ground is covered by dust and the temperature is always under zero degrees Celsius. There is also dust storm so that the dust is both in the atmosphere and on the ground. The ACM have to be « dustproof ».

The ACM is designed so that it can be mounted on a snake modular robot Lola-OP (fig 1). The Lola-OP is composed of very simple module with one DOF (one rotation). The modules are linked to each other with a 90° rotation so that the robot can move in three dimensions.

Figure 1: Lola-OP with 8 modules [11]

A Lola-OP metamodule composed of four modules and two ACM should be able to move on-grid. On-grid is opposed to off-grid where the robot moves in free space. The grid is composed off multiple passive connectors spaced with a known distance. We choose four modules because this is the minimum for moving in 3D space and being able to reach the next passive connector. The metamodule should be able to reach any location on-grid with multiple movements.

With the goal of the project, the specifications can be done by studying the constraints of an ACM. Besides the environment constraints, an ACM have to correct a misalignment between two modules. The Lola-OP, like most of modular robots is controlled in open loop, so the position of modules is not right due to bending effect and motor error positioning. The ACM needs to connect even if the modules are not exactly face-to-face.

In order to understand the different ways to connect two modules, we conducted a study on existing ACM. The goal was to investigate already used mean of connection such as physical latch (Roombots [2], Singo [3] and I-Cubes [4]), vacuum (Shady [5]), magnet fields (Smores [6]) and melting material (Soldar Cubes [7]).

This study revealed that none of the existing ACM is dustproof. However we found a promising idea when studying electric connection under sea for petrol field. In this domain, an electric connection is done at high depth (more than

1000m), placed by an underwater robot. The connection is called Wet-mate connector [8].

Our final design is based on a wet mate connector. This connection solves the dust problem and allows a connection without misalignment.

# 3 Constraints

## 3.1 Alignment

It is necessary that modules be centered relative to each other. This ensures the metamodule positioning that is controlled in open loop. If a module was to be misaligning, many areas could not be reached on-grid. The grid is composed of passive connectors spaced with a known distance so that the metamodule can reach each of them with multiple movements.

A set of variable is needed to describe the alignment of two modules (fig 2). To simplify, we assume that one module is fixed and all variables are defined in comparison to the center of the first one. The face of the ACM is on the plane (**x**,**y**) and **z** goes out the ACM.

$$(x, y, z, \alpha, \theta, \gamma)$$

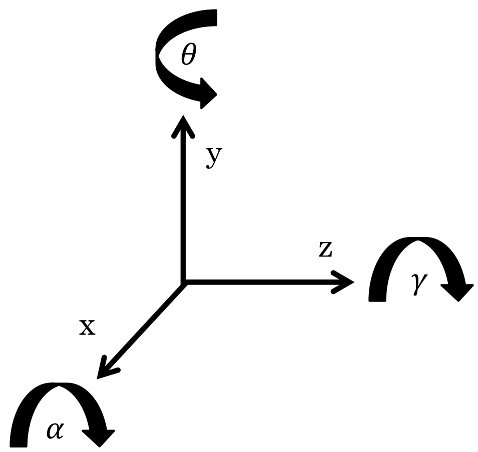


**Figure 2: Definition of the alignment variables**

Indeed, Lola-OP has alignment issues due to several factors:
- Positioning servomotor error ($\pm$ 0,3°)
- Bending effect
- Misalignment in the connection with previous modules

The misalignment in the connection with previous modules is neglected because the connection is supposed rigid in the chain of modules.

For all calculations, Lola-OP metamodule is composed of four modules and two ACM at each end. We decide to use four modules because this is the minimum for moving in 3D space and being able to reach the next passive connector even if it is after a corner. In order to calculate the bending effect, the robot is simulated with the help of SolidWorks simulation [9]. To find the maximum value of variables, the robot needs to be simulating in the worst position. The horizontal position is chosen (fig 3) with positioning servomotor error equal to +0,3°.

We were not able to simulate the bending effect because of the complexity of servomotor 3D model. Thus, the given values are only due positioning servomotor error plus a margin of 50%.

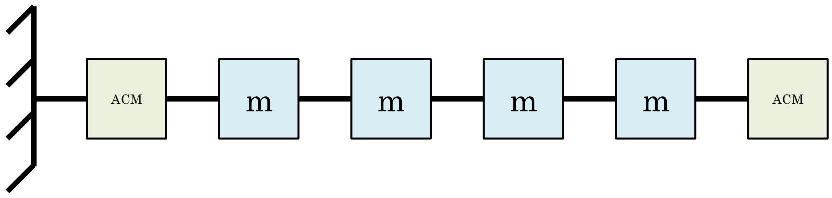


**Figure 3: Horizontal position of a metamodule composed of 4 modules**

$$x = 3{,}84mm$$
$$y = -2{,}77mm$$
$$z = 0{,}03mm$$
$$\alpha = \theta = 0{,}9°$$
$$\gamma = 0°$$

The yaw $\gamma$ is equal to zero because the bending effect was not taken into account. The other values are quite small. The bending effect maybe lead to an higher margin than 50%.

### 3.2 Payload

ACM should be able to hold the metamodule. Besides the fact that ACM can be broken, it's necessary that the system assure maximum rigidity to avoid bending of the metamodule under its own weight.

Another set of variables is needed to define payload. The forces and torques are defined in the same way as alignment variables.

$$(F_x, F_y, F_z, T_x, T_y, T_z)$$

In order to guarantee the same dynamic motion of Lola-OP, the mass of the ACM is equal to one module with a certain margin. A module is composed of a servomotor, 2 connections plastics and screws.

$$m_{module} = m_{servomotor\ AX-} + m_{cp1} + m_{cp2} + m_{screws} \quad (1)$$
$$m_{module} = 70\ g$$

$$m_{ACM,max} = m_{module} + \pm 20\% = 85\ g \quad (2)$$

To compute the variables, the worst static case is chosen for each variable according to the figure 4. A margin of 20% is added to be sure that the ACM resist to dynamic motion.

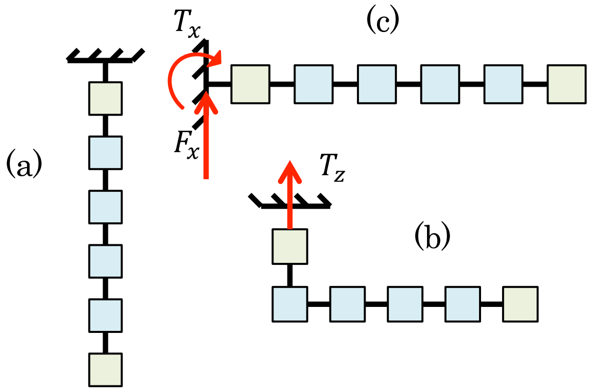


**Figure 4: Worst static case for each variable**

So $F_z$ is equal to the weight of a metamodule (fig 4a). $T_x$ and $F_x$ are compute in horizontal position (fig 4b). It is the same definition for $T_y$ and $F_y$ because of the symmetry. $T_z$ is compute like $T_x$ but with a module less because of the 90° angle (fig 4c). One can assume that the length of the ACM is approximately the same as a module (55mm)

$$F_x = F_y = F_z = 5{,}28N$$
$$T_x = T_y = 0{,}84N.m$$
$$T_z = 0{,}36N.m$$

### 3.3 Connection time

The connection/disconnection time needs to be low regardless of environment constraints. Self-reconfigurable modular robots change their morphologies to achieve goals, so time is the key to their success. It should be kept under 30s.

### 3.4 Energetic

ACM should not consume energy when it connected (or disengaged). Moreover, consumption during transitions must be kept low to be realistic considering the embedded battery.

### 3.5 Environment

Our ACM is designed to be used in space exploration missions. The two main problems in space are the transport and the exploration. Our ACM needs to withstand transportation (vibration, temperature, cosmic radiation). During transport, one can used an external device to protect Lola-OP modules. One can assume that Lola-OP supports the transport thanks to an external device so that the transport constraints don't need to be taken into account in the specifications.

During the exploration phase, our ACM needs to withstand large temperature range (day/night), dust and chemical substance.

On Mars, the main problem is dust. Average diameter is around $1\mu m$ and it is present both in the air and on the ground because of permanent sandstorms [9].

Temperature could also be a problem, especially during night. The robot needs to be sterilized to avoid bringing bacterial infection on Mars. As a consequence, the operating range of temperature for our mechanism should be:

$$T°_{min} = -130\ °C$$
$$T°_{max} = +130\ °C$$

### 3.6 Electrical

Modules need to communicate and transfer power between them and probably with a master station. To do that, the transfer device should be included in the ACM so its volume can't be neglected.

### 3.7 Lola-OP

Some constraints come from strategic choices. The ACM is hermaphrodite. It means that the ACM can connect with an identical one, so the shape of the ACM need to be flat. It is important that one module can disconnect if the other is defective. Thus, the active part is only on one side of the connection. The goal is to reduce active part in modules and be able to connect with passive module (empty module, wall, table). The ACM needs also to be 4-way symmetrical in order to connect the metamodule with different angles on the passive connectors of the grid.

## 4 Qualitative comparison of existing ACM

In order to understand the field of ACM, a qualitative study was done on existing ACM. We considered five points of comparison: tolerance to misalignment, maximum force that can pass through the ACM, hermaphroditism, dustproof and connection time.

ACM can be classified based on the physical mean of connection: physical lock, magnetism, vacuum and melting material.

For the physical lock, three main different methods have been studied.

1. The first one is the hook mechanism used for example on Roombots [2]. The ACM is a 4-way symmetric, hermaphrodite connector based on four retractable hooks that close synchronously on a passive part of other module.

2. The second one is the double centering hook used in Singo [3]. The ACM can open/close its four hooks linearly. One connector will come from outside in, while the other from inside out. The hooks meet in the middle of the process.

3. The third one is the lock and keys used in I-cubes [4]. The ACM uses a conical connector that fit into the female shape on the other module. The cone rotates to align a hole in face to a sliding bar that locks the connection.

For the magnetism, our study focused on the Smores robot [6]. The ACM is composed of four permanents magnets disposed in a cross shape with alternated polarity. To unlock the mechanism, the ACM uses a docking key that allows to do a 90° rotation that bring the same poles face to face. It leads to repulsive force that unlock the two modules.

The vacuum connector is used on the Shady robot [5]. Shady have a membrane that can lean on a flat surface and expands its volume to create a pressure force. Shady also has a hook mechanism to climb on windowsill but the study doesn't focus on this part.

A very different way to connect two objects is to melt a material on both sides to create a connection when it cools down. The Soldar cube [7] uses a resistive heater to melt the material and create a connection. The ACM is very simple. It only consists of a PCB.

| **Legend : L**ow, **M**iddle, **H**igh, **X** (out of subject) | **Hooks (Roombots V3)** | **Double centering hook (Singo)** | **Lock and Keys (I-Cubes)** | **Vacuum (Shady)** | **Permanent Magnets(Smores)** | **Melting (Soldar Cubes)** |
|---|---|---|---|---|---|---|
| **Planer misalignement max (x_max, y_max)** | **M** : depends on the shape of notches | **H** : Due to design of the hooks | **M** : depends on cone diameter | **X** : if we push the menbrane against the surface, the misalignment can be corrected by vacuum | **H** : With opposed magnets, they will tend to attract and correct the misalignment but magnets needs to be strong enough to move the module | **L** |
| **Offset max (z_max)** | **M** : depends on the size of hooks | **M** | **X/H** : there isn't moving parts for the cone but the shape can be pushed into female part. | | | **L** |
| **Tilt Max (α_max, γ_max)** | **L** | **L** | | | | **L** |
| **Yaw Max(β_max)** | **H** | **M** | **X** : only software, the hole needs to be directed to the pin | | | **L** |
| **Shear Force max (Fx_max, Fy_max)** | **H** : depends on the materiel breaking point (hook and support) | **H** | **H** | **L** | **L** : risk of dropping out if there isn't a complenentary shape | **L** |
| **Axial Force max (Fz_max)** | | **H** | **H** | **M** : depends on the pressure and the surface | **M** | **M** |
| **Dustproof** | **L** : Many moving parts | **L** | **M** : if there is sand in the female part, cone can't be pushed into it | **M** : menbrane protects the mecanism when it's connected | **H** : magnets don't need to be exposed to the surface | **L** |
| **Connection time** | **L** | **M** | **M** | **M** | **L** | **M** |
| **Hermaphroditism** | **Yes** | **Yes** | **No** | **X** | **Yes** with a 90° rotation | **Yes** |

Table 1: Study of existing ACMs

The study (table 1) shows that physical latching is the best way to share heavy payload. Indeed, breaking point of physical latching depends on the material breaking point. Right now, most of mechanical systems are manufactured in plastics but for a final prototype, they will be made of metal.

The misalignment problem can be corrected by an electromagnetic field created by permanent magnets or electro magnets. Electromagnetic field tends to align each other if they are strong enough to move the metamodule. One can also assume that the software can move the module in the alignment zone to help electromagnetic fields.

The connection time is under 30 seconds on all the studied mechanism. For modular robotics, this value is acceptable.

One of the main problems in the conception of this ACM is the dustproof constraint since none of the studied systems are taking this aspect into account. However the magnets on the Smores could be a good idea to start with because they can be mounted inside the module with no interaction with the dust environment.

# 5 Concept

## 5.1 Origin of the concept

The main challenge we have to overcome is the dust present in the environment of Mars. It is very difficult to create a perfect connection as described in the study that is dustproof. There are three lines of thought that we can considered to tackle this issue:

- The system can resist dust by its own without an external device.
- ACMs have a cleaning device such as a brush or an ultrasound device that is used before every connection. This supposes that the dust is only on specific spots and that it can be easily cleaned.
- A membrane protects the ACM. When the two membranes are in contact and sealed on their perimeter, a system clean the dust between the membranes. After, the membranes can open and the mechanism can connect. This solution ensures that the mechanism is never in contact with dust.

The first idea cannot be implemented with a physical device because of the moving parts. And the study shows that the ACM needs a physical lock to share heavy payload. This idea can only be used with a magnetic link between modules because with other physical connection means, a cleaning is needed.

The last idea is complex and only moves the dust problem to the membrane level. This membrane needs to open and creates a seal on its perimeter. It will be a very complex part.

Most of the considered solutions need at one point a cleaning device to ensure that there is no misalignment in the connection. Very few fields use active connection in difficult environments. Most of the time the connection is mounted in a clean area, so all the parts can be cleaned by hands.

Petrol fields use wet-mate connector [8] in order to do an electric connection under water at high depth. Wet-mate connector is a gender connector composed of cylinder that comes into the female part. The female part is also a cylinder of the same size so that when the two cylinders are in touch, they come into the female part without breaking the sealing. Figure 5 shows the operation of one cylinder but this kind of connector can transfer up to 40 channels, so 40 cylinders in the same connector.

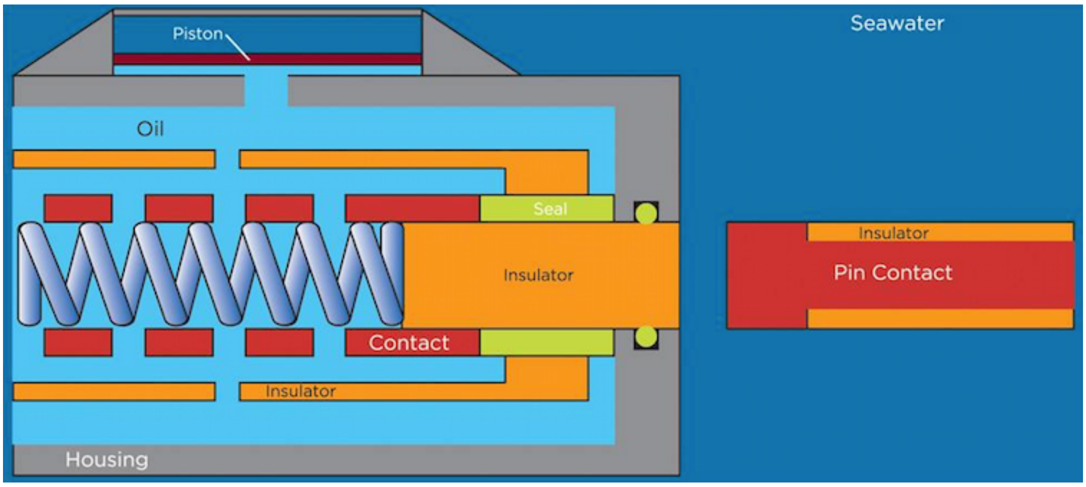


Figure 5: Wet-mat connector [13]

Even if this idea is an electric connector, the concept can be used to do a mechanical connection with few modifications.

The cylinders need to come into the other module, so they need a motor to do the translation. The decision is taken to have only one cylinder because multiple cylinders lead to multiple motors or a gear system.

The first problem is the alignment of the cylinder. The wet-mate connector uses its cone shape to align the male cylinder with the female one. However, one constraint is the hermaphroditism so this idea cannot be used. To solve the alignment problem, our ACM will use electromagnetic field created by electromagnets at the end of the cylinder.

The use of permanent magnets raises several problems. The first one is the hermaphroditism.  With only one magnet in the center, the connection is gendered. However this problem can be solved by placing an even number of magnets on a circle with alternated polarity. The magnets should be placed with an offset from the axis of symmetry to ensure hermaphroditism.
The second problem is the magnetic dust [10]. The magnetic material can be attracted by the permanent magnets and be stuck here forever. To avoid this, the magnet should be coupled with an electromagnet to cancel the magnetic field

before connection. The magnetic dust will fall down and the connection can be done.

For this last reason, the decision is taken to have one electromagnet in the center. Especially in the case of this ACM, the magnetic link is only needed during the connection time. At the end, the alignment will be guarantee by a seals and pins system.

One can assume that the dust between the faces of the two cylinders is distributed homogeneously so that the dust creates only a little offset on z between the two faces. Therefore during the connection, the electromagnet allows to cancel the misalignment (fig 6b) expect for the yaw angle and offset z. The yaw angle is due to deformation of the metamodule and the offset z.

In contrary of wet-mat connector, the ACM is hermaphrodite, so the two modules can be active. A passive connector will be design later.

Now that the two cylinders are in touch, they move synchronously into one of them (fig 6c). At this moment, the cylinder passes trough a lip seal that clean its surface. A second seal is used as a plan bearing to avoid translation and rotation on **x** and **y** after the connection. The cylinder had henceforth two DOF: translation and rotation on **z**.

In order to lock the system, pins are added inside the cylinder. The pins come out to lock the cylinder into the other module with the help of cavities (fig 6d). The cavity had a chamfer to correct the yaw angle. When the pins go out, they rely on the chamfer until the yaw angle is zero. The chamfer is also useful in z direction to be sure that the offset z doesn't create trouble in the connection of the pins.

The connection is lock and all the misalignment problems are solved.

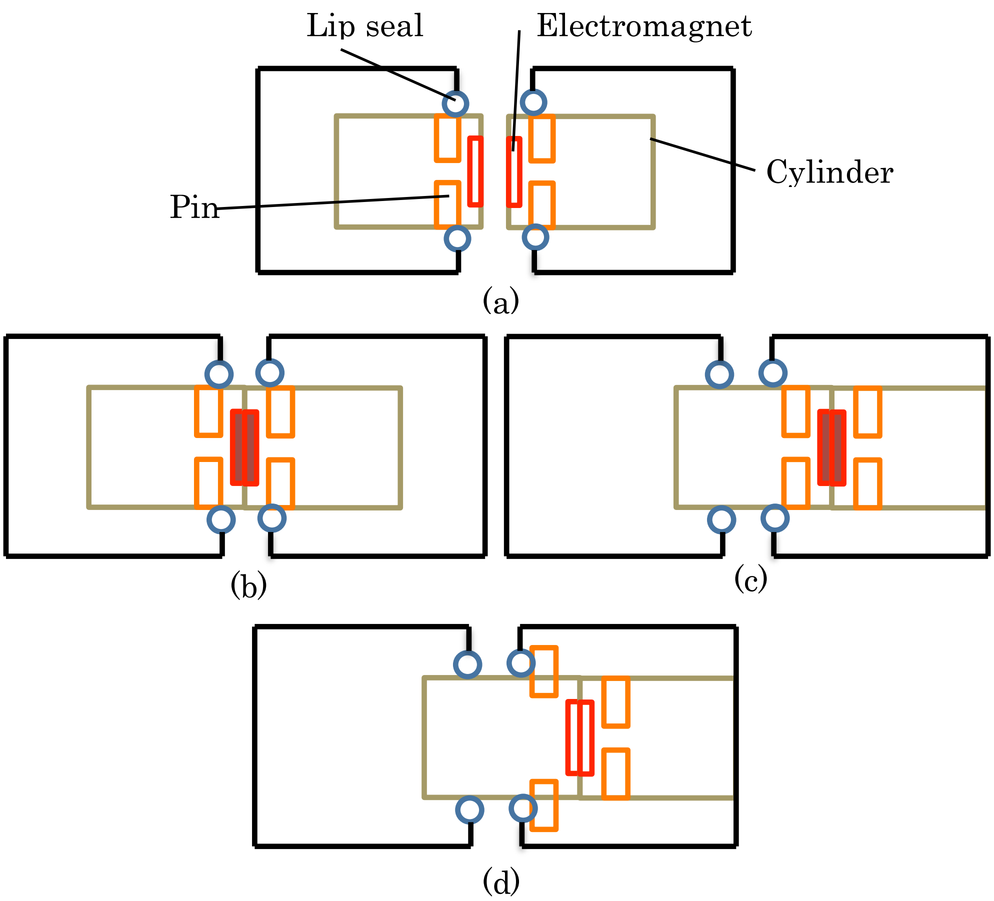


Figure 3: Connection step. (a) Before connection, electromagnet (EM) Off (b) EM On (c) Cylinders movement (d) EM Off, pins out.

### 5.2 Pin mechanism

In order to have pins that come out from the cylinder, two solutions were considered.

The first one is an electromagnet that keeps the pins in when it is switch on. In this method, there are two pins mounted on springs. When the electromagnet is off, the pins come out with the help of a spring.

The second one is a crank slide (fig 7). This is a mechanism that transformed a rotation into a translation. The advantage is that one movement can move multiple pins. Our ACM is 4-ways symmetrical so we need at least two pins. In order to have a greater payload distribution, four pins are used.

The first idea needs a second electromagnet perpendicular to the first one. The problem with electromagnet in this configuration is that the force is very small after few millimeters. So the springs need to be weak so that the electromagnet can bring the pins in. Consequently, the force on the pins will be too small to correct the yaw angle or even the offset z.

On the other side the crank slide has a lever that allows transferring a bigger force. Furthermore when the arms are collinear, the force on the pins tends to be very high. It could be very useful to lock the pins into the cavity. The last advantage of the crank slide is the irreversibility of the system when the arms pass the flat position. The arm has an end stop created by the other arm. This is also the reason why the mechanism has four pins. This idea is coming from the Roombot ACM as shown on figure 7.

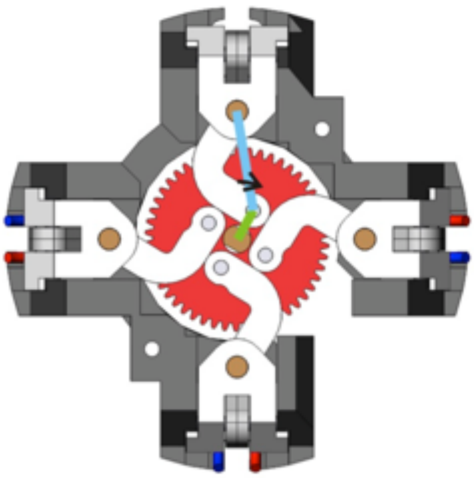

**Figure 7: Roombot crank slide with end stop [2]**

For those reasons, we decided to use a crank slide mechanism. The last thing to design is the driving of the crank slide.

## 5.3 Crank slide driving

In order to rotate the crank slide, two mains solutions were considered.

The first one is simply to have another motor in the cylinder. The only goal of this motor is to rotate the crank slide. With this solution, the final system has three actuators: two motors and an electromagnet.

The second one is to have a clutch driving by the electromagnet that brings the principal rotation to the crank slide (fig 8). The principal rotation is the rotation that creates the translation of the cylinder with the help of a screw/nut system. This system needs also a slide mechanism to transfer the principal rotation to the clutch. Indeed, the distance between the screw and the clutch changed because the screw is fixed and the clutch moves with the cylinder. In this idea, there are only two actuators: a motor and a linear electromagnet (solenoid).

The second solution has less actuators, so one can assume that it is more reliable even if the system of clutch and slide is more complex than a simple motor. The driving of the system is also simpler because it is only control by the

electromagnet. When the pins are close to the cavities, the electromagnet is switch off so that the principal rotation can rotate the crank slide.
When the pins come out, the cylinder still move a little because it is the same rotation that turn the crank slide and move the cylinder. The crank slide rotates less than a quarter turn to engage the pins into the cavities. One can assume that the translation of the cylinder created by this small rotation can be neglected, especially if small metric nuts are used.

We decided to use the second solution because it is a more reliable solution and it may be more easily miniaturized for further design.

## 5.4 Final design

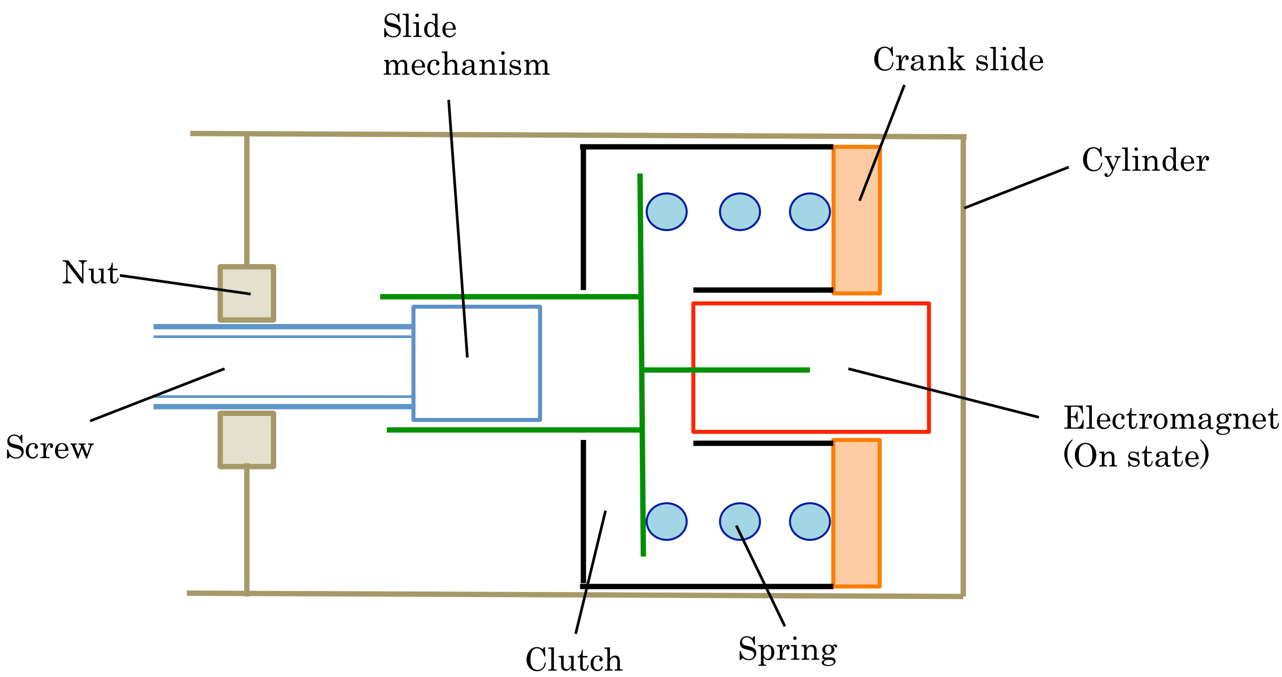


**Figure 8: Final design**

The mechanism is composed of four mechanical systems (fig 8):

- Screw/nut system for the translation of the cylinder
- A slide to transfer the rotation to the clutch
- A clutch driving by the electromagnet
- Crank slide attached to the clutch so that the rotation can be transferred to the crank slide

The screw/nut system allows translating the cylinder. When the pins are in front of the cavities, the electromagnet is switch off. The clutch is now connected and the rotation of the screw is transfer to the crank slide. The crank slide rotates in order to move the pins into the cavities.

The concept is quite complex but it has important characteristics:

hermaphroditism, physical latch and no misalignment even in dusty environment.

# 6 Design of the concept

Now that the concept is fixed, the goal is to design all the parts of the mechanism. First of all, a quantitative description of the mechanism will be done with all the variables that can be adjusted. All the design is made as if there is one pin because the number of pins doesn't change the results.

## 6.1 Chamfer

The goal of this mechanism is to correct the yaw misalignment $\gamma$ after the two cylinders are in contact. We assume that the maximum misalignment is 5° regardless of the yaw misalignment (before the contact of the cylinders) calculated in alignment constraint part. To rotate the cylinder, the pins needs to create a sufficient force $F_{ch}(\gamma)$ compared to the torque applied on the cylinder.

The torque $T_{ch}$ is composed of the friction torque created by the seals and the torsion torque. The torsion torque can be neglected because the motors of the modules have flexibility in their positioning so that the little rotation of the ACM doesn't create a torque. For the friction torque, it's very difficult to compute the friction force created by the preloading of the seals on the cylinder. A finite element study is needed to calculate this value. However, the complexity of lip seal (metal part, spring and elastomer) leads to a too complex study. In this report, one can assume that the friction torque is under 0,1N.m.

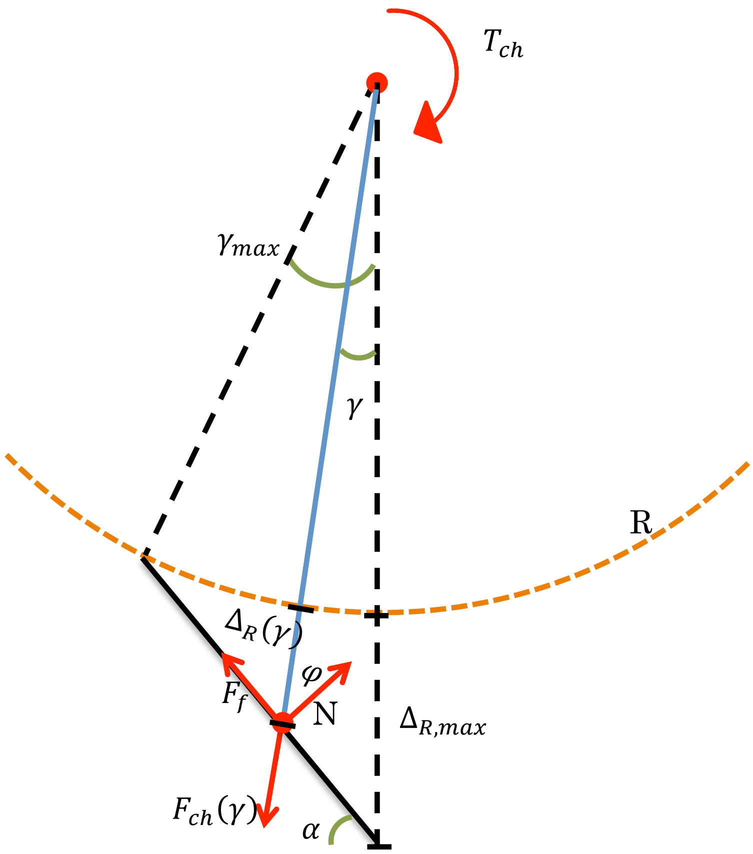




Figure 9: Chamfer definition. The orange circle represents the cylinder. The pin in blue relies on the chamfer in black.

$$F_{ch}(\gamma) = \frac{T_{ch}}{R + \Delta_R(\gamma)} * \frac{(\mu_{ch} * \sin(\varphi) + \cos(\varphi))}{(\sin(\varphi) - \mu * \cos(\varphi))} \; [N] \quad (3)$$

$$\Delta_R(\gamma) = R * \frac{(\cos(\alpha) - \cos(\varphi))}{\cos(\varphi)} + \Delta_{R,max} * \frac{\cos(\alpha)}{\cos(\varphi)} \; [m] \quad (4)$$

$$\varphi = \alpha - \gamma \; [rad] \quad (5)$$

In (3), R represents the radius of the cylinder and $\mu_{ch}$ the static frictional coefficient between the pin and the chamfer. The pins are made of stainless steel and the chamfer in PTFE in order to have a small friction coefficient ($\mu_{ch} = 0{,}1$). $\Delta_R(\gamma)$ is the distance at which the pin needs to come out and $\alpha$ is the angle of the chamfer.

This mechanism have three variables that can be optimized: $R, \Delta_{R,max}$ and $\alpha$.

## 6.2 Crank slide

The crank slide is a mechanism that converts a rotational movement into a translation. It is composed of two arms linked together. One can assume that the friction between the lip joint and the pin is like a friction between two planer surfaces with a static frictional coefficient $\mu_{cs}$. It is as if the preloading of the seals is neglected. The lip seals must be made in PTFE because of the temperature constraints. It is the only elastomer that resist to -130°C in seal technology.

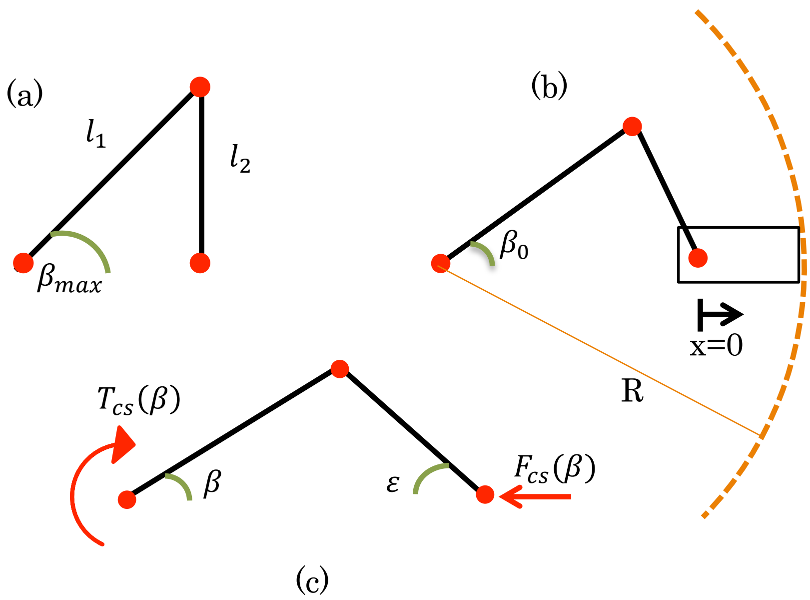


Figure 10: Crank slide definition. (a) Crank slide in maximum position (b) In starting position. The orange circle represents the cylinder and the rectangle the pin (c) In any position.

The equation (6) shows the force $F_{cs}(\beta)$ at the end of the crank slide created by a torque $T_{cs}$. $\beta$ is the angle between the first arm and the horizontal. $\varepsilon$ have the same definition but with the second arm (fig 10c). The lengths of the arms are noted $l_i$.

$$F_{cs}(\beta) = T_{cs} * \frac{(\cos(\varepsilon) - \mu_{cs} * \cos(\varepsilon))}{l_1 * \sin(\beta + \varepsilon)} \; [N] \quad (6)$$

$$\varepsilon = \arcsin\left(\frac{l_1}{l_2} * sin(\beta)\right) \; [rad] \quad (7)$$

The size of the first arm $l_1$depends on the radius of the electromagnet because the crank slide is around the electromagnet. It is very important that the pins are as close as possible to end of cylinder because the size of the ACM depends on this distance. Furthermore, $l_2$ is lower than $l_1$ because the diameter of the cylinder needs to be small. This decision leads to calculate the $\beta_{max}$ because a crank slide with a second arm smaller than the first one cannot rotate entirely (fig 10a).

$$\beta_{max} = \arcsin\left(\frac{l_1}{l_2}\right) \; [rad] \quad (8)$$

The crank slide cannot start at $\beta_{max}$ because in this position the output force $F_{cs}(\beta)$ is equal to zero. So the start angle $\beta_0$ should be a little lower than $\beta_{max}$. A margin $m_\beta$ is introduced.

$$\beta_0 = \beta_{max} * m_\beta \; [rad] \quad (9)$$

The equation (6) shows $F_{cs}(\beta)$ but the goal is to compare the force created by the crank slide with the force needed $F_{ch}(\gamma)$ to correct the yaw angle. So $F_{cs}(\beta)$ should be converted. First of all, with the help of numeric interpolation $F_{cs}(\beta)$ is converted in $F_{cs}(x)$ with x defined in the equation (10). $x$ is equal to zero when the end of the pins is at the level of the cylinder (fig 10b).

$$x(\beta) = l_1 * \cos(\beta) + l_2 * \cos(\varepsilon) - \; l_1 * \cos(\beta_0) + l_2 * \cos(\varepsilon_0) \; [m] \quad (10)$$

Then $F_{cs}(x)$ is converted into $F_{cs}(\gamma)$ with also numeric interpolation. In this design, $x$ is equal to $\Delta_R(\gamma)$ because the pin is always in touch with the chamfer.

To conclude, the crank slide have four variables that can be optimized: $l_1, l_2, T_{cs}$ and $m_\beta$.

## 6.3 Clutch

This ACM uses a flat frictional clutch to transfer the principal rotation to the crank slide. There are many different clutches but this clutch have several constraints that restricts the choice. A frictional clutch has the advantage that it

doesn't need synchronization in contrary of tooth clutches. The rotation of the crank slide is quite small so synchronization cannot be allowed.
The clutch is driving by an electromagnet that compressed a spring when it is switch on and releases it when the clutch needs to be activated (fig 11).

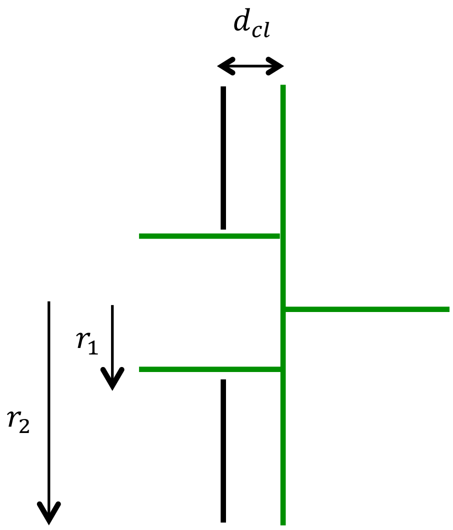


Figure 11: Clutch definition. The electromagnet is ON. The black part is the body driving by the skate in green.

The equation (11) shows the maximum torque $T_{cl,max}$ that the clutch can transfer. $\mu_{cl}$ is the static frictional coefficient between the two flat surface. It is maximized with the help of rubber on both sides ($\mu_{cl} = 1{,}16$). The frictional surface is defined by the internal radius $r_1$ and the external one $r_2$ .

$$T_{cl,max} = \frac{2}{3} * \mu_{cl} * F_s * \left(\frac{{r_1}^3 - {r_2}^3}{{r_1}^2 - {r_2}^2}\right) \left[\frac{N}{m}\right] \quad (11)$$

$F_s$ represents the force applied by the spring and it is determined by the force of the electromagnet $F_{em}$ when $x$ is equal to $d_{cl}$. $d_{cl}$ represents the distance between the two surface when the clutch is disengaged.

$$F_s = F_{em} * m_{cl} \, [N] \quad (12)$$

$m_{cl}$ is the safety factor between the force of the spring and the force that the electromagnet can does. According to the manufacturer of the electromagnet (Ledex), $m_{cl}$ should be equal to 0,66.

To conclude, the clutch have four variables that can be optimized: $F_{em}, d_{cl}, r_1$ and $r_2$ .

## 6.4 Optimization

Now that all the parameters of the ACM are defined, they need to be correlated between them. The goal of the optimization is to reduce the diameter of the cylinder in order to have an ACM as small as possible.

The external radius of the cylinder R is equal to the sum of $l_1$and $l_2$ plus a margin that depends only on the lip seal of the pins. This margin is set to 10mm.
$\alpha$ is chosen so that $\Delta_{R,max}$ is equal to $x_{max}$ that depends on $l_1$and $l_2$ according to the equation (10). So all the parameters from the chamfer are correlated.

For the clutch, $r_1$ depends on the diameter of the transmission between the screw and the clutch, so $r_1$ is set to 10mm. $r_2$ should be maximised in order to transfer more torque. In this case, $r_2$ is equal to the sum of $l_1$and $l_2$ because the internal radius of the cylinder is defined when the crank slide is in flat position ($\beta = 0$). $d_{cl}$ needs to be as low as possible because the strength of the electromagnet decreases exponentially, so $d_{cl}$ is set to 1mm. The only parameter of the clutch that can be optimized is $F_{em}$.

For the crank slide, $T_{cs}$ is equal to $T_{cl,max}$. The length of the first arm $l_1$ depend of the diameter of the electromagnet plus a little margin to be sure that the second can rotate without touched the electromagnet. There are still two parameters to optimize: $l_2$ and $m_\beta$ for the crank slide.

In order to optimize the ACM, an electromagnet is chosen so that $F_{em}$ is fixed and $l_2$ and $m_\beta$ are changed. A comparison is done between the force needed to rotate the ACM $F_{ch}(\gamma)$ and the force created by the crank slide $F_{cs}(\gamma)$. $F_{cs}(\gamma)$ must be higher than $F_{ch}(\gamma)$ for every $\gamma$ between 0 and $\gamma_{max}$. A safety factor $sf$ is set equal to 1,5.

$$F_{cs}(\gamma) > F_{ch}(\gamma) * sf \text{ , } \forall\gamma \in [0; \gamma_{max}] \quad (12)$$

The 2ECM electromagnet from Ledex manufacturer is chosen. It is a low profile electromagnet with a conical face design that extends the useful range of the solenoid to provide higher force at 1mm. Its diameter is equal to 28,6mm. So $l_1$ is equal to 19,3mm with a margin of 5mm. Its $F_{em}$ is equal to 16N at 1mm when it is pulsed at a duty cycle of 50%.

| Diameter [mm] | 82,6 | 84,6 | 86,6 | 88,6 |
|---|---|---|---|---|
| l2[mm] / m_beta[] | 12 | 13 | 14 | 15 |
| 0,9 | 1,15 | 1,25 | 1,37 | 1,51 |
| 0,8 | 1,28 | 1,39 | 1,52 | 1,65 |
| 0,7 | 1,24 | 1,37 | 1,49 | 1,62 |
| 0,6 | 1,13 | 1,25 | 1,38 | 1,51 |

Table 1: Safety factor for $l_1 = 19,3mm$ with the diameter of the cylinder for each one.

The table 2 shows the safety factor for different $l_2$ and $m_\beta$. The minimum $l_2$ to have a safety factor of 1,5 is 14mm. Therefor the external diameter is equal to 86,6mm with a radius margin of 10mm. All the computation is done for $\gamma$ equal to $\gamma_{max}$ because it is the worst case. The figure 12 shows $F_{cs}(\gamma)$ and $F_{ch}(\gamma)$ for $l_2$ equal to 14mm and $m_\beta$ equal to 0,8.

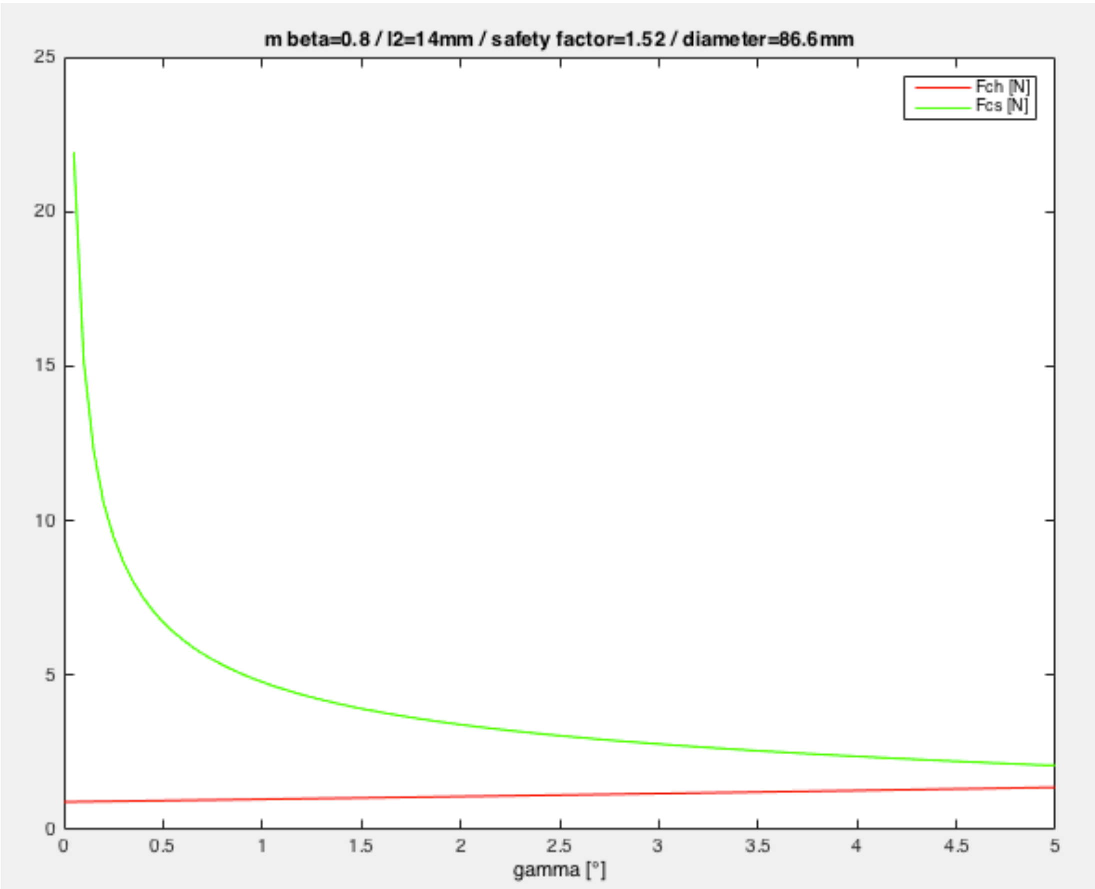

Figure 12: Comparison between $F_{cs}(\gamma)$ and $F_{ch}(\gamma)$

All the parameters of this ACM are set. The next step is to create a 3D model on SolidWorks to see if all the parts fit and to have the final characteristic of the ACM.

# 7 3D model of the ACM

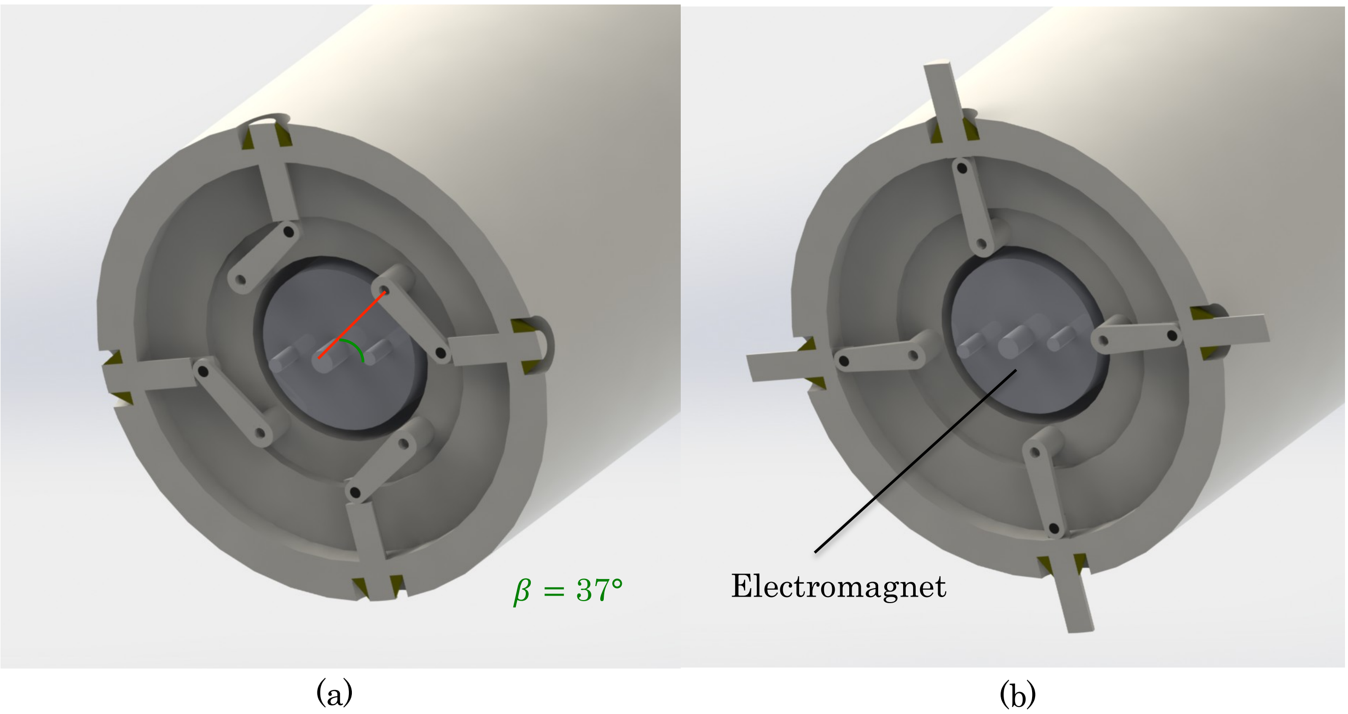


**Figure 13: Crank slide. (a) Pins In (b) Pins Out**

As mentioned in the design of the crank slide, the crank slide is around the electromagnet in order to have the pins as close as possible of the end of the cylinder (fig 13). It is very important because this distance influences the total length of the cylinder. Indeed, a high distance would lead to a higher distance of translation of the cylinder. Therefore the size of the ACM would be higher. In this ACM, the distance is equal to 9 mm.

The figure 13 shows the crank slide in its two modes. When the pins are inside the cylinder (fig 1a), the first arm of the crank slide has an angle $\beta$ equal to 37°. In out position (fig 1b), $\beta$ is equal to zero. The distance $x_{max}$ (eq 10) between the two positions of the pins is equal to 10mm.

In this design, the end stop of the arms is not designed but it could do easily with the help of the other arms like in Roombot crank slide (fig 7). In this case, $\beta$ in out position would be negative. It would lead to a lower $x_{max}$. The design of the cavities would need to be modified so that the difference of $x_{max}$ would not make problems during locking.

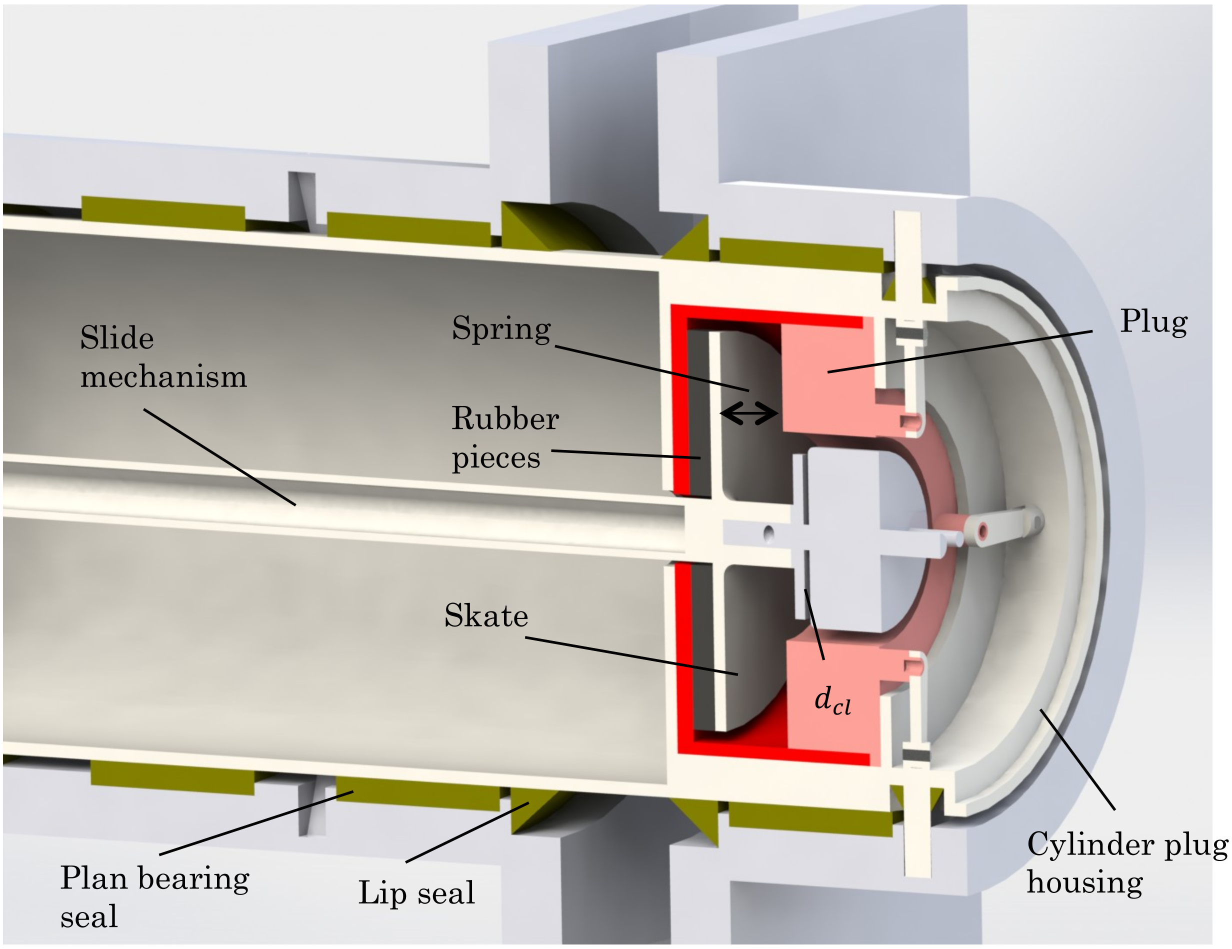

**Figure 14: Clutch in On position**

The figure 14 shows the clutch mechanism in on position. The electromagnet is switch off and the pieces of rubber are in touch with the help of the spring. The spring is not shown in figure 14 but it is between the clutch plug and the skate. The skate turns and drives the clutch with the help of the friction between the two rubber pieces. The skate rotates 37° clockwise to engage the pins into the cavities.

When the electromagnet is on, the skate moves about a distance $d_{cl}$ equal to 1mm. The spring is compressed. Thus the rubber pieces are not in touch and the rotation of the skate doesn't turn the clutch. In this case, the cylinder can translate without moving the pins. The electromagnet is mounted on the cylinder plug that closes the end of cylinder. In figure 14, the cylinder plug is hidden to see the crank slide mechanism.

The figure 14 also shows the seal system. The cylinder passes trough a lip seal to clean its surface and ensures no dust in the plan bearing seal. The plan bearing seals ensures the rigidity of the connection. Three plan bearing seals maintain the cylinder (two on its side and one on the other module). We choose to put two plan bearing seals at the back of the ACM. When the cylinder is pushed back like the right cylinder on figure 15, it needs to be maintaining by at least one plan bearing seal. We add on other one to be sure that there is not backslash between the cylinder and its built.

On the left of the figure 15, we can see the slide mechanism inside the skate. The slide mechanism is composed of a square with rounded corners mounted on the screw. A complementary shape is built into the skate so that the principal rotation can be transmitted to the skate. One can assume that the motor is strong enough to overcome the friction forces in the slide mechanism.

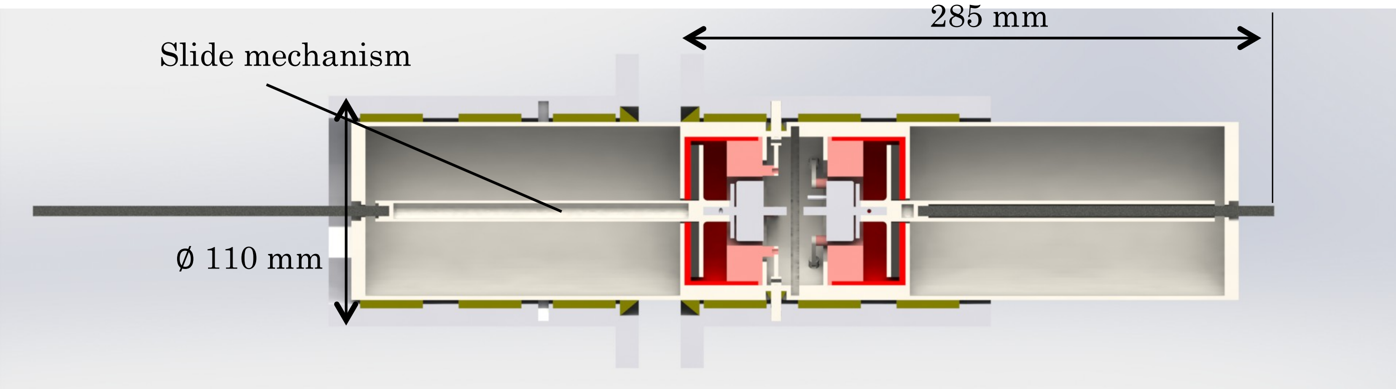


**Figure 15: Connection between ACM**

The figure 15 shows the connection of two ACM. The left ACM ("male" in this case) moves its cylinder into the other ACM ("female") and lock the connection with the pins. One thing is missing on the 3D model. We forgot to design a system that locks the rotation of the cylinder. However, it could do easily by adding a small cylinder right above the screw. This cylinder will be fixed on the built of the module and pass through the back plug of the main cylinder. With the screw and a sliding pivot created by the small cylinder, the rotation of the main cylinder is lock.

The final length of the ACM is 285mm and its diameter is equal to 110mm (fig 15). The motor that drives the translation of the cylinder is not included in the final length.

The final mass of the ACM is equal to 485g according to Solidworks [9]. Most of the parts are in ABS and could be printed with a 3D printer. For the calculation of the mass, we assume a filling rate of 30% so that the density of the ABS is equal to 305 $Kg/m^3$.

The constraints of mass and volume are really not respected. For the mass constraint, the target value was 85g. So the design is way to heavy. For the volume, the target was to have an ACM with approximately the same volume as a module. The volume of a module is about a 55mm square side. Therefore this constraint is also not respected.

However, this ACM can transfer high payload thanks to the physical lock with the pins and the plan bearing seals. It also ensures that there is no misalignment in the connection due to the dust. Thus the kinematic model is true.

This design is the first iteration of the concept. To see if this concept could be implemented on real modular robots, we need to see if the mechanism could be miniaturized.

To miniaturize, the problem is the translation of the cylinder. The cylinder needs to move about 160mm between its “female” position and its “male” one. So the slide mechanism in the cylinder takes at least the same length. The distance of translation depends on the length of the seals (lip seal and plan bearing seal) and the offset between the ACM at the beginning. Only the length of plan bearing seals could be optimized.

The diameter of the ACM could be more optimized by taking a cone shape clutch that allows transferring more torque to the crank slide. Thus, the crank slide could be a little smaller.

# 8 Passive connector

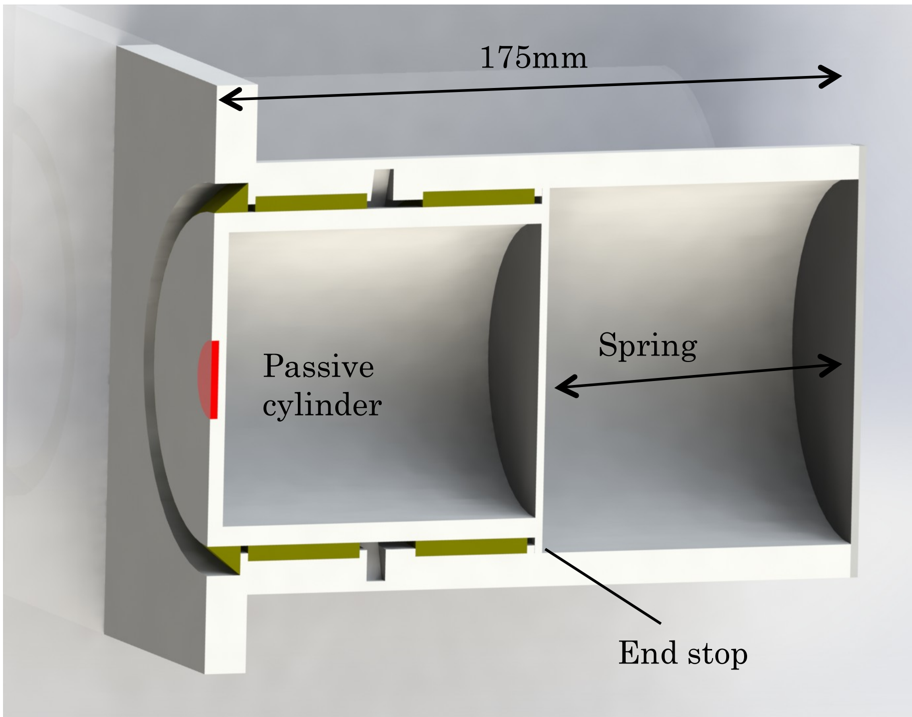


Figure 46: Passive connector

In order to create a passive connector, we took the same concept as the wet mat connector (fig 5). A spring pushes the passive cylinder against an end stop so that the cylinder closes the connector. When the ACM connects with the passive connector, the spring is compressed and the ACM can reach the cavities and lock the connection.

The spring needs to be designed so that the force is strong enough to push the cylinder during the disconnection. The spring force overcomes the friction force of the seals. However, if the spring is too strong, the ACM couldn't move the passive cylinder.

The red piece on figure 16 is a metal part. In order to correct the misalignment before moving the cylinders, the electromagnet of the ACM needs to align the two cylinders. We cannot put a magnet because of the magnetic dust problems [11]. The alignment will be way less good that between two active connectors because the magnetic field will push the ACM against the passive cylinder but the axis alignment of the cylinders will be less guaranteed.

The final length of the passive connector is equal to 175mm and the diameter is the same as the active one (110mm). By taking the same assumption on ABS density, the mass of the passive connector is equal to 330g.

# 9 Conclusion and future works

The design of a dustproof ACM for space exploration on Mars is very complex. None of the existing ACM studied (table 1) are taking into account the dust problem even on Earth. The dust creates misalignment in every connections studied.

In order to find a concept to solve this problem, we have looked into the petrol field that uses wet mate connector to create electrical connection at high depth. The idea was quite simple at the beginning but some constraints have made the concept way more complex.

First of all the hermaphroditism constraint doesn't allow to use any complementary shape for helping to correct the misalignment. This has led to the use of electromagnetic fields. However without a drive the surface, the alignment between the two cylinders axis is more difficult to guarantee and requires the use of stronger magnetic fields. Furthermore, the Mars environment contains magnetic dust [11] that forbid the use of permanents magnets. Thus, we decided to use electromagnet to correct the misalignment. The other advantage of electromagnet is that their magnetic field can be modified by pulsing it. This leads to a bigger electrical consumption but in last resort it could be useful.

Furthermore the choice of physical latching induced the pins mechanism. This leads a quite complex mechanism in order to move them. We decided to use a crank slide mechanism because it is the simplest mechanism that allows creating multiple translations with one rotation. A clutch is use to transfer the principal rotation that translate the cylinder to the crank slide. This allows us to have only two actuators (an electromagnet and a motor) instead of a second motor.

The design shows that this concept takes a lot of space. The ACM is too big and heavy to be implemented on the Lola-OP. Before trying to optimize the volume and the mass of the ACM, some studies are necessary. First of all, we need to know the right friction force between the seals and cylinders because the assumption made in this report could be wrong. Furthermore, we have made the assumption that the lip seal clean enough the dust so that the cavities will not be overload after few connections. This assumption needs a proof of concept with a real prototype and very fine dust. This prototype will also be used to confirm the assumption of alignment between two electromagnets. Indeed, if the misalignment between the cylinders axis is too high, the cylinders cannot pass trough the lip seal.

In the case of all those assumptions are verified, an optimization of the ACM could be done. First of all, the length of the plan bearing seals can be optimized in order to reduce the total length of the ACM. We can also reduce the diameter of the cylinder by using a more efficiency clutch that allows transferring more torque and therefore having a smaller crank slide.

To conclude, we think that even if our ACM were optimized, its size would be way too big to be implemented on modular robots. Moreover, modular robotic tends towards smaller modules making it unrealistic concept.

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