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Introduction

To complete my training in engineer's profession, I think it was indispensable to have an internship within a research laboratory. Having it in a North American university, a continent on which I had never visited, was a great pleasure.

This training took place at Ryerson's polytechnic University, at Toronto in Canada, and the training was within the Department of Mechanical, Industrial Engineering and Aerospace. The intent of my project was to develop a study in a domain not pursued before by my supervisor "Doctor Filippo Salustri". The project that I have decided to do is the connection for the modules of reconfigurable robot.

Nowadays, products proposed by the manufacturers are more and more varied, so that to answer in best to the exact demand of each customer or consumer. The flexibility thus became more and more important within the production workshops.

That is why this becomes useful to design production systems, which can quickly adapt themselves to these varied demands. The automated systems also belong to theses modern production tools. The Research and Development department tries to develop reconfigurables robots constituted by modules.

One of the main points allowing the application of this technology is the connection system. To assure a precise piloting of the active part of the robot (tool, crowbar, etc.), it is necessary that the connections are the most precise. Each error of location between modules adds on to the other connections.

Current developments concerning reconfigurables robots mainly study systems of small sizes. These ones appear most of time with the shape of snake or of spider. Their utility is mainly to adapt themselves to an unknown ground and to move there. For that purpose, these robots can change their shape configuration to climb obstacles. Its applications are to investigate in inaccessible or dangerous grounds (searching for victims in rubble, investigation of caves, on grounds undermined, etc.). Thus this is about robots, which one could more exactly qualify as self-reconfigurable. On no account, are these robots, able to fulfill any tasks of production. That is the reason of this project.

I. To understand the design problem

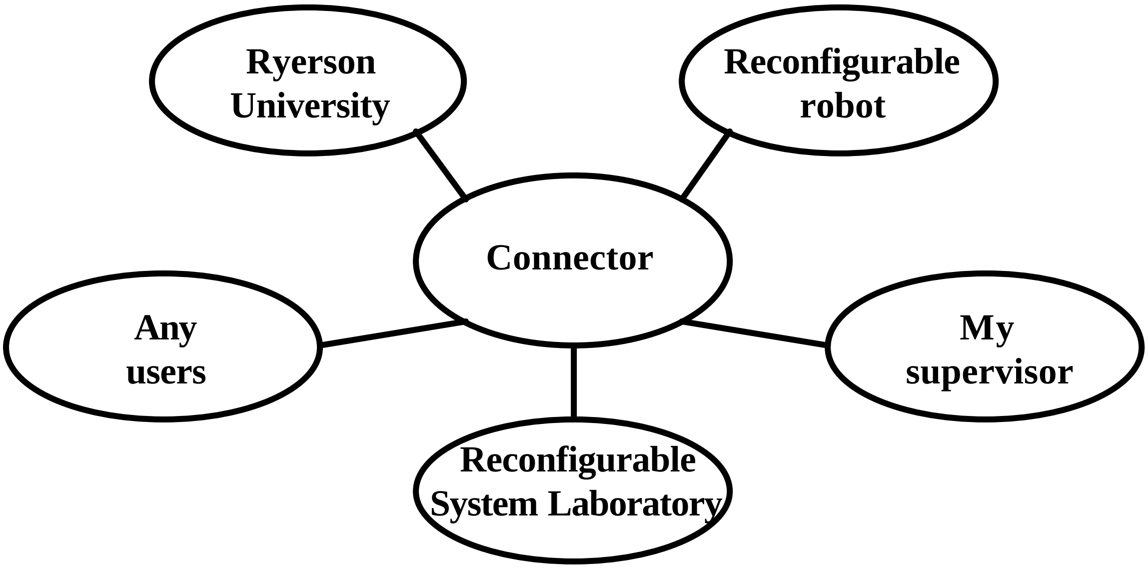
I'm using the Quality Function Deployment (QFD) method in order to settle the basement of our design methodology.

I.1. Step 1: Identify the customers

The purpose of the understanding of the design problem is to translate the demands of the customer into a technical description of what should be designed. It is thus necessary to determine exactly who are the customers.

In this case, the first customer is my supervisor, Dr. Filippo Salustri, who wants to create a quick connector for a reconfigurable robot. This connector would be used by anybody in the Department of Mechanical, Aerospace and Industrial Engineering of Ryerson University.

The following scheme shows the various actors of this design project:



The users will be mainly students and professors from Ryerson University. In the future, any skilled personal in industrial applications would be using this connector.

The reconfigurable robot is a modular robot, composed a little like "Lego"(a block toy). Each module has a connector in order to be assembled to another one.

My tutor, Filippo A. Salustri, Ph. D., P.Eng., Assistant Professor of Mechanical Engineering at Ryerson University, is the initiator of this project.

The Reconfigurable System Laboratory (RSL) is the place where students could make researches and studies on the robot . Professor Fengfeng (Jeff) Xi, Ph.D., P.Eng., manages this area. Research carried out in the laboratory is in the area of mechatronics and manufacturing, with support from NSERC (Natural Sciences and Engineering Research Council of Canada), from MMO (Materials and Manufacturing Ontario) and from NRC (National Research Council of Canada).

Ryerson University is the university where is the RSL. It's a polytechnic university placed in Toronto, Ontario, Canada. Ryerson is working on this subject in collaboration with Queen's University, University of Toronto, The University of Western Ontario, University of Catania (Italy) as well as a number of companies.

I.2. Step 2: Determinate the specifications

We are now going to develop the list of all the needs that can affect the design. To do it, we alternately adopted the point of view of the customer and the investigator.

For the user, the purpose is that the product can allow the fast assembly and the fast disassembly between two modules of one robot. This mechanism would allow the robot to re-configure itself, in an autonomous way. The connector would allow modules to attach to one another easily, and would provide data/power as well as physical connectivity between modules. To satisfy completely the user, the design is greatly emphases to the safety as well as the appearance of the product.

For the investigator, the system would allow modules to attach one to another with extremely high reliability, and would provide data/power as well as physical connectivity between modules. The investigator is also looking for a system that could follow the development of such new technology. And would also imposes on delivery time and industry standards.

This study have made appeared several main specifications:

- Minimum cost
- Dimensions
- Low weight
- Safety
- Small connection time
- Delivery time < 5 months
- Mainly mechanical system
- Precision
- Secure connection
- Quick connection

- Data/power transmission
- Project ended before January 2003
- Autonomous connection and disconnection
- Standards
- Recyclable

Remark: these specifications have been written for the customer's vocabulary. Later, these requirements will be translated in technical specifications.

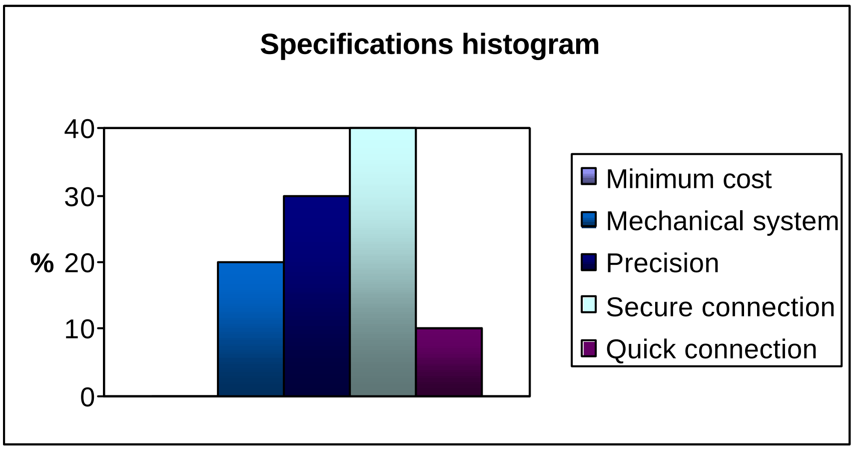
I.3 Step 3: Organize the specifications

Some specifications of this list presented above are considered as absolutely necessary: if we do not take them into account, the design is obsolete. Five specifications appeared as necessities:

- Low weight
- Dimensions
- Safety
- Delivery time < 5 months
- Project ended before January
- Standards
- Recyclable
- Data/power transmission
- Autonomous

The other specifications should be balanced; we are thus going to use a technique of pair wise comparison to determine the relative importance of each of them.

Minimum cost	0	0	0	0							**0**	**0**
Mechanical system	1				0	0	1				**2**	**20**
Precision		1			1			0	1		**3**	**30**
Secure connection			1			1		1		1	**4**	**40**
Quick connection				1			0		0	0	**1**	**10**
											/10	**%**



This analysis shows that the design should be particularly attentive in the precision of the location and the preservation of the position and also and the system to be mostly mechanical. On the other hand, it shows here that the cost is not really important; we thus decided to ignore it in the following.

Remark: the values presented in the table of dichotomous comparison are the result of group.

I.4. Step 4: Competitors analysis

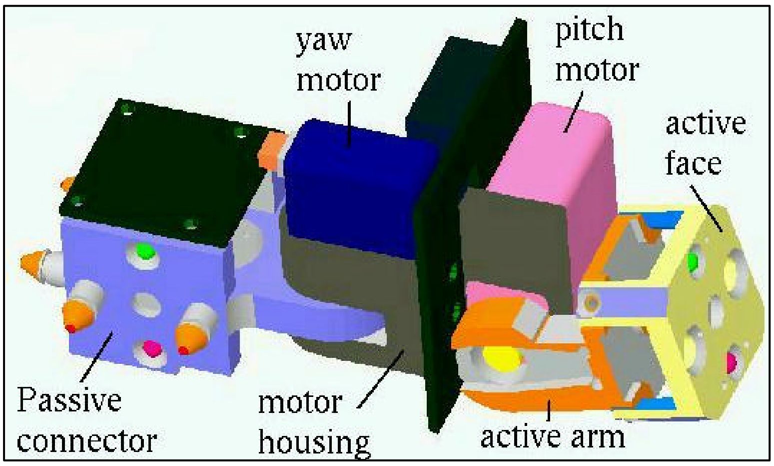
The purpose of this step is to determine how the customers perceive competitors capacities to deal with the specifications.

Searches on Internet have been made to list the various existing systems.

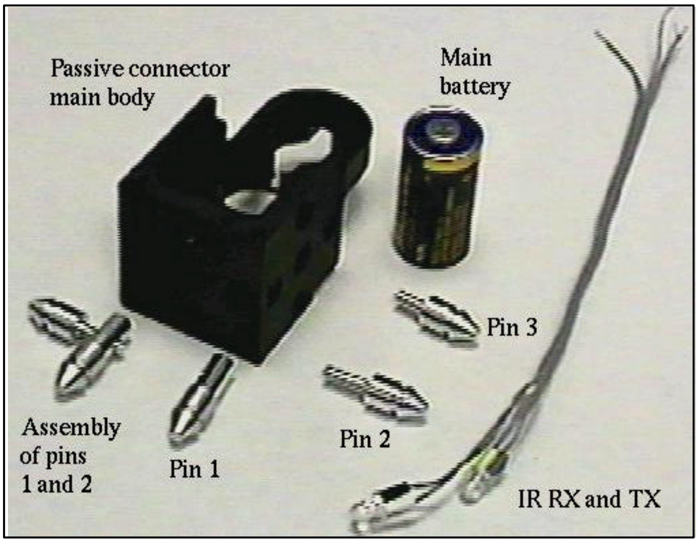
- The **CONRO** Project has a goal of providing the Warfighter with a miniature reconfigurable robot that can be tasked to perform reconnaissance and search and identification tasks in urban, seashore and other field environments. CONRO will be a miniature and is to be made from identical modules that can be programmed to alter its topology in order to respond to environmental challenges such as obstacles.

The base topology is simply connected, as in a snake, but the system can reconfigure itself in order to grow a set of legs or other specialized appendages. Each module will consist of a CPU, some memory, a battery, and a micro-motor plus a variety of other sensors and functionality, including vision and wireless connection and docking sensors. Major challenges include packaging, power and cooling as well as the major issue of programming and program control.

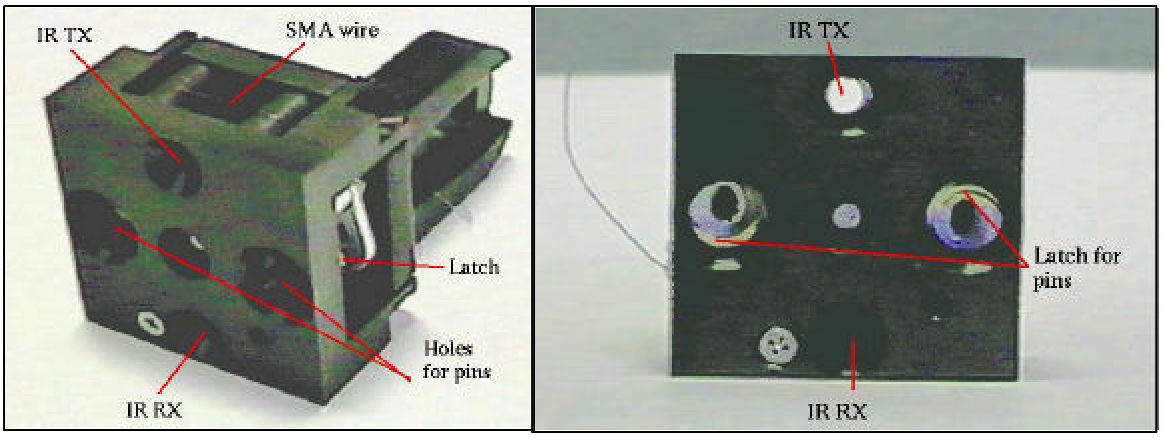
The module has three main parts: a passive connector that has pins to allow the module to connect to other modules, a motor housing that supports the servos of the module and, an active connector that contains the connection/disconnection mechanism that allows other modules to attach to it. The active connector has two subparts: an active arm that is connected directly to the pitch motor and an active face that actually holds the connection/disconnection mechanism.



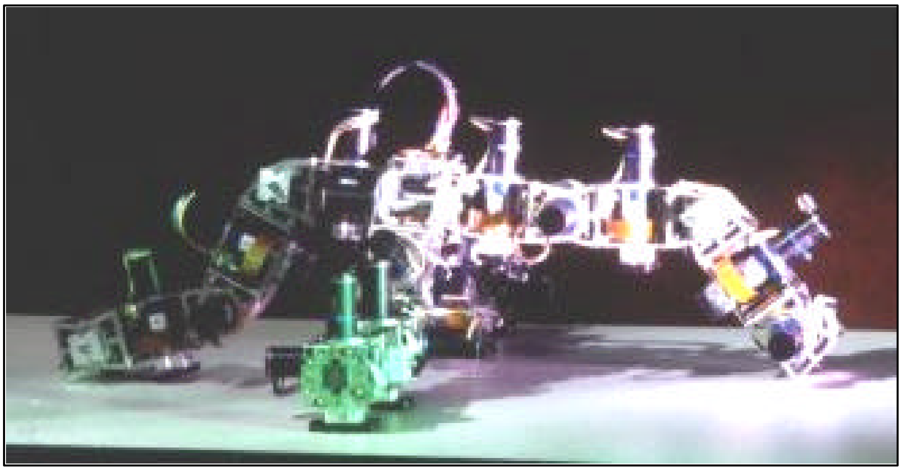
The main part of the passive connector, its body, it's a cube with a tail that is used to attach the passive connector to the yaw motor. On three faces of the cube an infrared pair and 2 pins are installed. Due to space constraints, the three pins are different. Pins 1 and 2 actually intersect inside the cube and thus, pin 1 has a hole that screws pin 2 into, as shown in the figure. The pins are made out of aluminum. The body of the active connector also serves as the main battery holder.



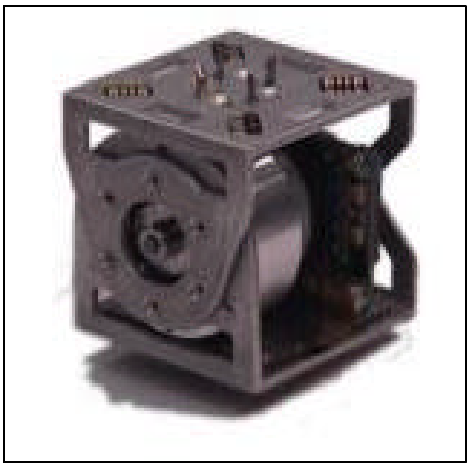
The active connector is under a constant process of improvement. The version shown in the image is already functional, though, but it is not 100% reliable. The active connector has 4 holes in its face. Two of the holes are for infrared the receiver and transmitter. The other two holes are receptacles for the pins of other modules. When the pins of another module are inserted into the active face, the latch engages groves on the pins and secures them. To release the pins, a SMA (Shape Memory Alloy) wire is contracted pulling the latch back and freeing the pins. Seen from the front you can observe the two small yellow arcs formed by the edges of the latch that engages the pins. When the SMA is activated, the arcs retract away from the pins releasing them. When the SMA is deactivated, a spring brings the latch back to the close position, ready to engage a new set of pins.



➢ **PolyBot**, a project developed by XEROX PARC, is made up of many repeated modules. Each module is virtually a robot in and of itself having a computer, a motor, sensors and the ability to attach to other modules. In some cases, power is supplied off board and passed from module to module. These modules attach together to form chains, which can be used like an arm or a leg or a finger depending on the task at hand.

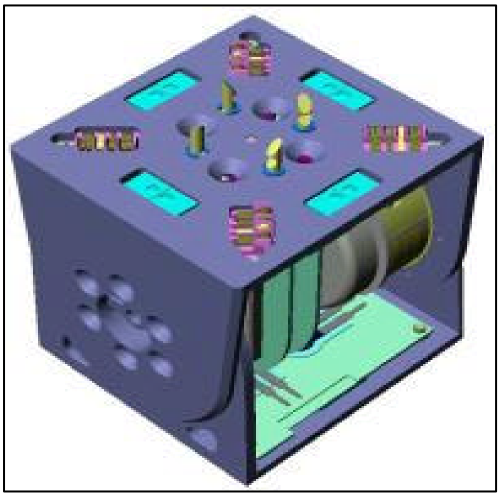


The third generation of PolyBot is currently under construction. Much of the mechanical hardware for 180 segments and 20 nodes has been built. Electronics have been designed and prototyped and software is in development. The goals for this large batch of modules are to demonstrate locomotion with large configurations and reconfiguration between configurations.



The target form factor for G3 was a 5-centimeter cube. The G3 module is actually a bit smaller at 50 x 50 x 45mm. It uses a modified Maxon 32mm diameter brushless pancake motor as the source with a 3.75:1 planetary gear stage between the motor and the size 8 100:1 harmonic output stage. This new main drive weighs only 70 grams bringing the total module weight down from 450 grams to about 200 grams. The G3 drive should deliver 1 Nm of torque and the machined aluminum frame has a range of motion of +90 to -90 degrees. In addition, an actuated roller ratchet will provide 10-15 Nm of braking in either direction.

The two connection plates on either side of the module are identical, hermaphroditic and have a 4 way rotational symmetry. That is, any two connection-plates may be attached together at 90-degree increments. To connect the plates four grooved pins enter four holes on the opposing plate and are grabbed by a latching mechanism that can be later released by a shape memory alloy actuator. Each face has 4 times redundant custom made hermaphroditic electric connectors to enable power and communications to be passed from module to module. Each face also has four IR LEDS and sensors for face to face docking during reconfiguration and rudimentary module-to-module communication. This communication is used during initialization by the robot to discover its configuration.



Each module contains a Motorola PowerPC 555 embedded processor with 1 megabyte of external RAM. This is a relatively powerful processor to have on every module and its full processing power has not yet been utilized. The final goal of full autonomy may require the use of these processors and memory. Each module communicates over a local bus within chains of segments using the (controller area network) CAN bus standard. The six-sided nodes will have switching and routing capability to pass messages from segment chain to segment chain.

In G3, the sensing includes the hall-effect sensors built into the brushless DC motors serving both for commutation as well as joint position with a resolution of 0.04 degrees, an absolute joint angle sensor (custom potentiometer), four accelerometers (one redundant, but can frequently be used for joint angle sensing) for measuring orientation relative to gravity and potentially contact bumps, contact whiskers, and low resolution force sensors on the interface pins. In addition, due to the placement of the IR components on the G3 interface plates, these components may also be used for proximity sensing.

For each of the specifications which we determined during the "step 3", we noted the existing designs (CORON and PolyBot) on a scale from 1 to 5 where:

1 = the design completely fails the specification.
2 = the design barely fails the specification.
3 = the design barely meets the specification.
4 = the design barely exceeds the specification.
5 = the design really exceeds the specification.

- Mechanical system:

CORON: the design barely fails the specification ? **2**
PolyBot: the design completely fails the specification ? **1**

- Precision:

CORON: the design barely meets the specification ? **3**
PolyBot: the design barely exceeds the specification ? **4**

- Position preservation:

CORON: the design barely fails the specification ? **2**
PolyBot: the design barely meets the specification ? **3**

- Connection duration:

CORON: the design barely meets the specification ? **3**
PolyBot: the design barely exceeds the specification ? **4**

I.5. Step 5: Translation of the customer specifications in measurable and technical specifications

The purpose is to develop a set of technical specifications (often named design specifications), which are measurable to allow an evaluation of the product design.

- Mechanical system: that means the connection system must be as much mechanical as possible. The systems include in the connection are the way to guide the module to the connection, how the fixation system is activated, how the connection is maintained, and how the disconnection is activated. In order to measure this specification, the **percentage (in %)** of mechanical solutions is the only indicator.

- Position precision: the precision could be translated into several technical specifications. The first of all is the **number** of available positions. The second one is the **precision required(in mm)** to be able to connect two modules. The last technical specification is the **position precision (in mm)** when the modules are connected.

- Secure connection: this specification could be translated in the strength of the connection. The technical specification is the **maximal effort (in N)** the connecting can resist.

- Quick connection: this specification concerned the time needed to disconnect from a module and to connect another module. Thus the technical and measurable specification is the **time (in s)**

To end this step, the central part of the QFD table has to be completed. Every cell of the table expresses how every customer specification is connected with the various technical specifications.

In the following table are explained the symbols which appear in the central part of the matrix QFD.

◎	= High relation
?	= Average relation
?	= Low relation
Empty	= No relation

I.6. Step 6: Determinate the “target” values for design

At first is determining how competitor products perform the technical specifications. In the step 4, the rival products were compared with the customers’ specifications. In the step 6, the rival products are compared with the technical specifications. CORON and PolyBot supervisors couldn’t give these data. However some value could be approximated.

In the second time, the obtained values by testing the competition we shall give a base to establish the “target” values.

- Mechanical solutions:

CONRO: 50 %
PolyBot: 25 %

- Number of available position:

CONRO: 2
PolyBot: 4

- Precision required to connect:

CONRO: 5 mm
PolyBot: 2 mm

- Position precision:

CONRO: 2 mm
PolyBot: 1 mm

- Maximal effort:

CONRO: 200 N
PolyBot: 300 N

- Time needed to connect:

CONRO: about 10 seconds
PolyBot: about 5 seconds

We are going to establish the “target” values to obtain with the new product. The best "target" values are measured by a specific value.

- **Mechanical solutions:**

Both of competitors' products are very small and light. The product we want to design needs to be more resistant. That means that the connection must be able and preserved between two modules whatever the environment is (space, high radiation area, high magnetism area). Thus most of the systems needed to create this connection must be mechanical ones. . Furthermore we want this connection to be very secure. So the connection must be preserved in case of miss of electricity.

The “target” value is **75 % of mechanical solutions**.

- **Number of available positions:**

The number of available positions mainly depends on the kind of application the robots is design for. In our case, it is for a huge reconfigurable robot arm that could for instance move heavy parts in a workshop. The most important thing is to command the arm's extremity, thus the way of connection of the modules before the last module is not critical. We can consider 1 reliable position is enough. However, the module could have more.

The “target” value is **1 reliable position**.

- **Precision required to connect:**

Before the connection, the two modules are allowed not to be exactly in the perfect position. This is for several reasons.

The first one is because the precision of the active arm is not absolute. With the time, some gap could appear between the real position and the theoretical one. The second one is to assist the robot so in order to start trying to connect despite it is not in the perfect position. The last one is to avoid a jam between modules that are not really one in front of the other. This jam could damage or destroy parts (not only of the connectors).

The “target” value is **5 mm**.

- **Position precision:**

Position precision is a very significant specification. To command precisely a robot, we have to be sure the mistakes in connection precision are the smallest. In robotics, what is commanded is the extremity of the arm robot. Thus each mistake in the connection of each module is added to the other modules' one. At the extremity, the global mistake in precision could make the tool fixed on the robot arm not reliable or completely useless.

That the reason why, for such precise applications like moving parts in a workshop, the position precision has to be the highest.

The “target” value is **< 1 mm**.

- **Maximal effort:**

All the existing reconfigurable robots are composed of small modules and their purchase is mainly to move themselves in an unknown environment. Their connections are not solicited by strong efforts; usually less than the total weight of the robot.

In our study, the reliability and the strength of the connection are extremely important. The connector should support the heavy weight of the robot and also the efforts caused by the working extremity. We don't have any exact value, that's the reason why we have to approximate it. We can consider effort caused by the robot weight is 1 000 N and the effort of the working extremity is 1 000 N. These efforts could be also transferred through the connectors in torque.

The "target" value is **2 000 N**.

- **Time needed to connect:**

The time to disconnect a module and connect another one should be as short as possible. Nowadays, factories try to reduce the process time. The «changing tool » time is a useless time because the production has stop. This is a point, which reconfigurable robots would really improve and allow the production schedule a high flexibility.

Since the analysis of the existing products, we can assume that the time need to disconnect and reconnect would be about 5 seconds.

The «target value » is **5 seconds**.

I.7. Step 7: QFD matrix

The QFD matrix above is a way to summarize results that have been found in the last 6-step analysis:

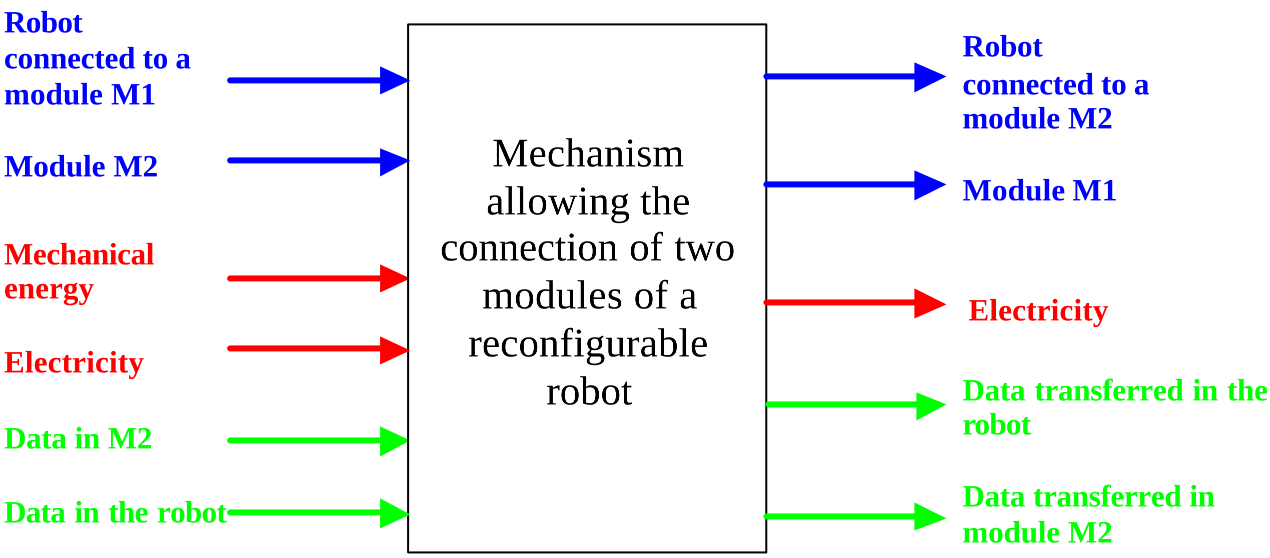
		Mechanical solutions	Number of available position	Precision required to connect	Position precision	Maximal effort	Time needed to connect	**CONRO**	**PolyBot**
Mechanical system	0.2	◎	?	?	?	?		2	1
Precision	0.30	?		◎	◎			3	4
Position preservation	0.50	◎			O	◎	?	2	3
Connection duration	0.10		◎	?			◎	3	4
Cost	*								
Low weight	*								
Dimension	*								
Safety	*								
Delivery	*								
Project end	*								
Standards	*								
Recyclable	*								
Data/power	*								
Autonomous	*								
		%	**Pos.**	**mm**	**mm**	**N**	**s**	**Unity**	
		50	**2**	**5**	**2**	**200**	**10**	**CONRO**	
		25	**4**	**2**	**1**	**300**	**5**	**PolyBot**	
		75	**^{3}1**	**5**	**£1**	**2 000**	**5**	**"Target" values**	

II. Functional decomposition

II.1. Step 1 : Global function

The objective of this project is to connect two modules of a reconfigurable robot.

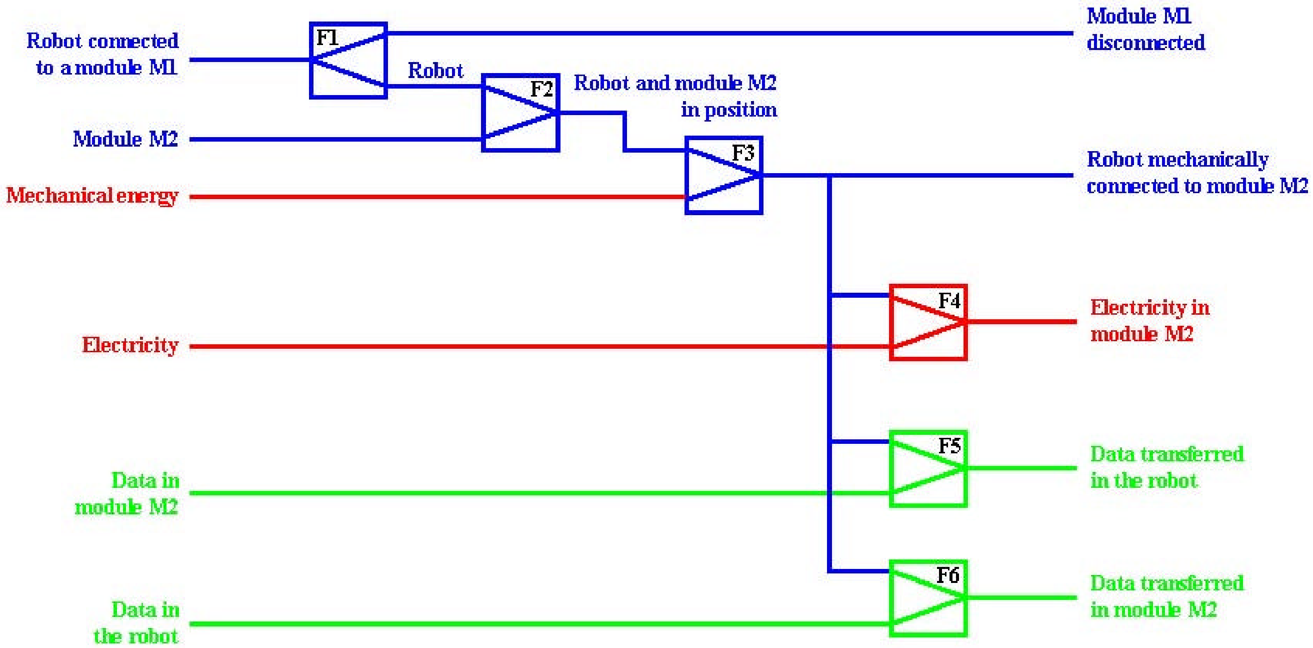
To realize the functional analysis of this connection mechanism, we had to apply a decomposition of the functions. The functions can be described in terms of logical streams of energy, material and information. We can then represent our system in the following way:



Legend: **Material stream**
Energy stream
Information stream

II.2. Step 2 : Decompose the global function in sub-functions

We proceed to the decomposition in sub-functions of the global function by using diagram-blocks.



Function 1: Disconnect a module from another one.
Function 2: Assure the good connection position.
Function 3: Secure the connection.
Function 4: Transmit electricity.
Function 5: Receive data.
Function 6: Transfer data.

III. Concepts generation

III.1. Step 1 : Concepts development for each function

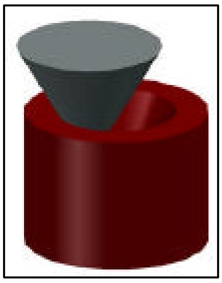
In the following part, we are going to develop concepts for each function.

- ✓ **Function 1:** This function is to separate or disconnect a module from another one.

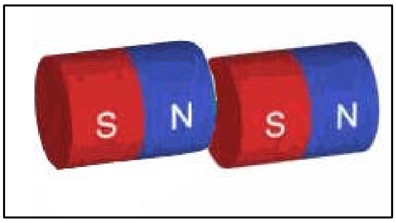
In order to follow a logical way, we do not develop concept for the «function 1» because the disconnection is dependant from the connection mechanism. In fact, the disconnection could be the reverse concept than the connection one.

- ✓ **Function 2:** This function is to assure that the positions of the two modules are good enough to allow the connection. This function is to guide the module.

The first concept we could use to guide the modules is a conic shape or an inclined plan. By this way, modules could fit the good position easily. Each module shape has to be the complementary than the other module one.



A second concept that could be used to guide the modules is the magnetism. The attraction of the iron by the magnet, baptized "magnetism", is the first physical phenomenon, which realized the idea of action at distance. Here the action would be to fit the modules. To realize it, at least one on the modules have to become a magnet (using ferromagnetism). If both are magnets, their polarities have to be opposed (one south and the other north).

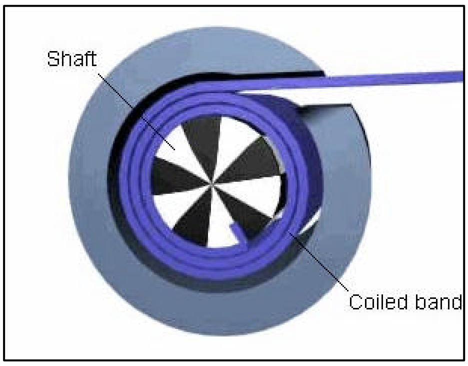


Concept 1 : Conic or inclined shapes.

Concept 2 : Magnetic parts.

✓ **Function 3:** This function is to secure the connection.

A first concept is the tightening. This one can be obtained by increasing the volume of an element inside another one. To do it, different mechanical systems are available: the movement cam (for example conic) moving other elements, the use of a coiled band (cf. Picture above).

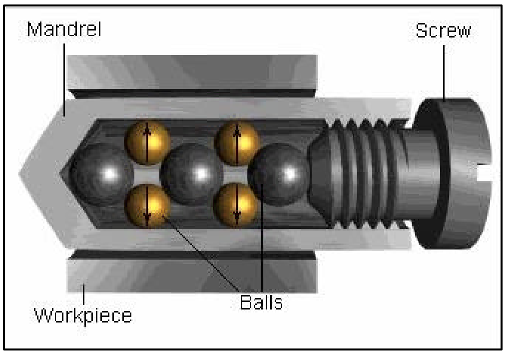


A second concept is the use of a handle (latch) allowing the locking. The latch is moved by the movement of the module and secure the connection by coming back to its position (using a spring for instance).

A third concept is the use of screwing. A screw would secure the connection.

A fourth concept is the lacing-up. This concept is used to get back a satellite by using an automated arm. Three cables wind around a part of the satellite.

The concept list is very long, there are plenty of other way to assembly two solids but we only reported the ones that seem to fit to our design. There are concepts we have difficulty in imagining at first sight but it does appears in some concepts libraries. The concept above is just reported to show another concept that could have been selected.



Concept 1 : Increasing diameter.

Concept 2 : Latch.

Concept 3 : Screw.

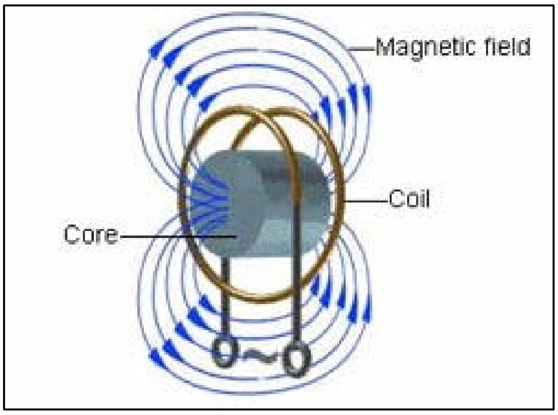
Concept 4 : Lacing.

- ✓ **Function 4:** This function is to transmit electricity from an active module to an isolated one. By this way, any module not connected is inactive and useless. The main use is to have only one electricity source.

The first concept is a mechanical connection like a plug that is design for this specific requirement.

The second concept is to use an existing plug that could be found on the industrial market. If this choice is the one, a more precise research have to be done.

The third concept is to transmit the power through coils. A coil crosses by an electric current create a magnetic field. This field could create a current in another coil that is closed to the first one.



Concept 1 : New plug connection design.

Concept 2 : Existing plug.

Concept 3 : Coils.

- ✓ **Function 5:** This function is to receive data from a module. We have to find the existing concepts that allow the reception of data.

The first concept is to use infrared. This invisible electromagnetic radiation could transmit data and be received by an IR receptor.

The second concept is to use radio waves. These waves could also transmit data and be received by a radio receptor.

The third concept is to use optical fibre. These very slender glass threads allow the transport of the information by light impulses. The main inconvenience of the optical fibre is its cost. The main interest is not to be sensitive to the electromagnetic interferences. Data could be encoded by the light impulses and received by a light receptor.

Concept 1 : Infrared.

Concept 2 : Radio waves.

Concept 3 : Optical fibre.

- ✓ **Function 6:** This function is to transfer data to a module. This is the same concept that for the reception.

The first concept is to use infrared. This invisible electromagnetic radiation could transmit data by an IR transmitter.

The second concept is to use radio waves. These waves could also transmit data by a radio transmitter.

The third concept is to use optical fibre. These very slender glass threads allow the transport of the information by light impulses. The main inconvenience of the optical fibre is its cost. The main interest is not to be sensitive to the electromagnetic interferences. Data could be encoded by the light impulses and transmit by a light transmitter.

Concept 1 : Infrared.

Concept 2 : Radio waves.

Concept 3 : Optical fibre.

III.2. Step 2: Combine the concepts

In this table we report for each sub-function all their concepts.

	Concept 1	Concept 2	Concept 3	Concept 4
F2	Conic or inclined shape	Magnetism		
F3	Increasing diameter	Latch	Screw	Lacing
F4	New plug design	Existing plug	Coils	
F5	Infrared	Radio waves	Optical fiber	
F6	Infrared	Radio waves	Optical fiber	

To obtain new design solution, we simply have to combine the concepts of each sub functions. Many combinations drive to extravagant or not practicable solutions.

The table below presents the solutions that we retained:

	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5
F2	Conic or inclined shape	Conic or inclined shape	Conic or inclined shape	Conic or inclined shape	Magnetism
F3	Latch	Increasing diameter	Screw	Lacing	Lacing
F4	New plug design	New plug design	Existing plug	Coils	Coils
F5	Infrared	Infrared	Infrared	Radio waves	Optical fiber
F6	Infrared	Infrared	Infrared	Radio waves	Optical fiber

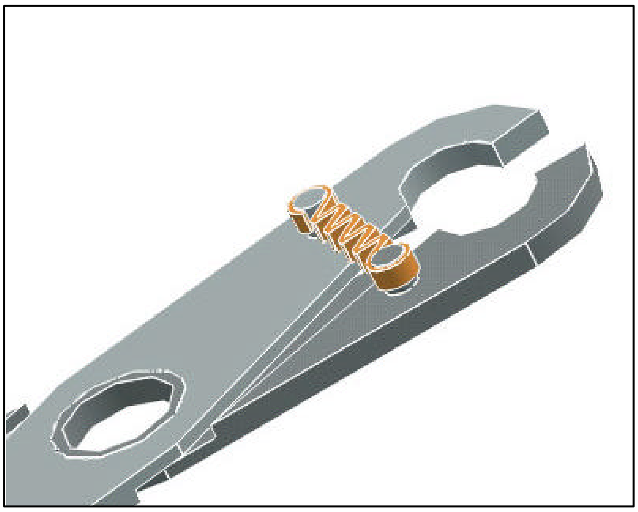
III. 3. Step 3: Design balanced by using a Pugh matrix

In the following table, we are going to estimate the various solutions according to the customer's specifications. The solution 1 is the one that we privilege, that is why it is going to serve as reference. Other solutions will be compared and noted with regard to this reference.

		Solution 1	Solution 2	Solution 3	Solution 4	Solution 5
Mechanical system	0.2	0	0	-	-	-
Precision	0.3	0	-	-	0	-
Secure connection	0.4	0	0	+	0	0
Quick connection	0.1	0	0	-	-	-
	Total	**0**	**-**	**-**	**-**	**-**
	Total balanced	**0**	**-0.30**	**-0.20**	**-0.30**	**-0.60**

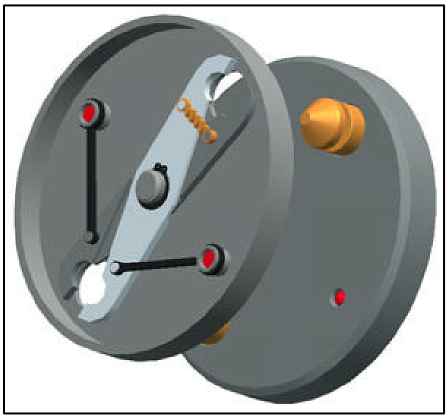
IV. Solution illustration

In order to achieve these design methodology, one of the solutions has to be illustrated. I've designed this assembly with the CAD software Solid Edge.



The male part have two pins, which allow the centering. These pins have a shape that could to be locked. The information transmission is made by infrared. The power transmission is not represented but could be done with contactors in the center of pins.

The female part is machined with two holes allowing the location of pins. Chamfers allow an easy guide of the parts. A spring maintains both fixation latches tightened. The opening of the system of locking is assured by two memory shape allow drivers (represented in black).



(Remark: the system of locking is represented opened. In this configuration, both latches should be tightened.)

Conclusion

My project was on a new subject from my supervisor, thus I tried to create a solid bases about reconfigurable robots, from the existing available systems on the market and more especially on the methodology of conception. This project thus was an opportunity to familiarize with design tools like QFD and TechOptimizer.

On the first hand, this training also allowed me to discover a domain of ultramodern technologies, which was until then ignored by me. Reconfigurables robots are indeed in phase of research and development. They should be more and more usually used as well on workshop, as on investigation sites.

On the other hand, I was disappointed by the fact of not working within a real laboratory. The fact of not having been integrated into a team is a criterion, which punished the quality of my results especially since these did not seem to interest the responsible of the laboratory of reconfigurables systems.

However, it was a very enriching experience on the human plan. During this semester, I discovered the North American university system from the outside but also from the inside by participating in some classes. I was also able to improve my linguistic level while discovering a beautiful country and its cultures.

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