"Development of an expert system for supporting the selection of robot grippers"

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CONTENT

ABSTRACT

The aim of this thesis is to lay the basis for the development of an expert system for the selection of robot grippers. This work has started with a review of the literature of the grasping principles, of releasing strategies and of the main problems concerning the automatic assembly or, more in general, the handling.

Later, we have studied a set of parameters constituting the input of the expert system, together with a set of rules aimed at choosing the appropriate gripper. The work ends with a series of tests, with a focus on the food industry, reporting the results and discussing the possibility of future developments.

SOMMARIO

Lo scopo di questa tesi è porre le basi per la realizzazione di un sistema esperto per la selezione dei gripper. Il lavoro è partito dallo studio in letteratura dei principi di grasping, delle strategie di releasing e dei principali problemi che riguardano l'assemblaggio automatico o, più in generale, l'handling.

Successivamente è stato studiato un set di parametri, che costituiscono l'input del sistema esperto, insieme a un set di regole necessarie per effettuare la scelta del gripper appropriato. Il lavoro si conclude con l'esecuzione di alcuni test, focalizzati sul settore alimentare, riportandone i risultati e discutendo la possibilità di sviluppi futuri.

1 INTRODUCTION

1.1 GRIPPERS IN INDUSTRY AND THEIR MAIN APPLICATIONS

According to the definition of grippers given in the VDI Guideline 2860, a gripper is a robot end effector capable of temporary grasping, retaining and subsequently releasing an object of a particular geometrical shape.

Grippers are designed for industrial automation to give to robot arms versatility in handling a broad range of parts. Industrial robots are usually seen as a substitute for manpower, but, especially in the last years, their relevance has become stronger in applications which are very difficult for people, for instance the pick & place of micro objects, or even dangerous for the working men or the manipulated product itself (eg. hazardous or repetitive work).

Grippers can be designed to handle a large variety of objects in very different contexts and operations; initially, most grippers were designed for dedicated tasks and could not manage different shapes from the ones they were designed for, relegating their use to large scale productions and, in case of changes into the production line, making possible redesigns expensive and difficult. Later, grippers started to be designed in order to be more and more flexible, making them an economically viable choice even in different contexts for agile, fast and safe work pieces handling.

These days, thanks to the continuous research, grippers has started to be a real human work alternative in many different applications, involving not only mechanical components but even textiles, leather, meat or fish.

Furthermore, miniaturized grippers have been developed to handle fragile components in micro assembly. This has been possible thanks to the research of many novel prehension methods that have increased the use of grippers in nonindustrial areas such as in civil engineering, space research, handicraft, medical and pharmaceutical engineering.

1.2 ISSUES WITH THE SELECTION OF THE PROPER GRIPPER

In automatic assembly or production operations, grippers represent the direct interface between the automation devices and the object to be grasped. Therefore, the selection of the proper gripper involves a deep analysis of the characteristics of the object and of the context in which the operation takes place. In some cases, there will no available grippers which are fully reliable to perform the selected operation, making the design of a specific gripper highly recommended.

At the moment there are no guidelines or algorithms that suggest how to select the proper gripper, and usually companies rely on their previous experience, or in particular cases on the advice of a consultant or a gripper manufacturer, making the choice often slower, more expensive and restricted.

The choice is even harder when the selected gripper has to be flexible in order to be able to handle objects with different characteristics.

Furthermore, it should be considered that the work of a gripper is not just focused on ensuring a grasp basing onto the object characteristics; indeed, the choice of the gripper type is always determined by many parameters which can be briefly summarized in:

- Object characteristics;
- Feeding characteristics;
- Handling operation characteristics;
- Placing and releasing;

As we will discuss in the following chapters, all those operations are strictly linked between each other. One gripper that could excel in the grasping of the selected object may, for instance, not be able to pick it with the actual feeding system.

Therefore, even if a gripper is designed to be fully capable to ensure a safe grasp, it may be not capable to do the operation required. This represents a significant issue.

When selecting the proper gripper it should also be considered that there are many different ways to achieve a grasp. An object could perhaps be grasped by its sides with a frictional gripper, or by its surface with a vacuum gripper, or even with an internal grasp that could be done both with a frictional or an expansion gripper; all those different methods imply different requirements.

1.3 THESIS PURPOSE

As stated before, the selection of the proper gripper is not an easy task, and it requires high expertise to avoid inappropriate choices. Actually, there is not a system that guides through the selection of the appropriate gripper, partly because it is a sector still under deep development, partly because the parameters to be evaluated are too many and their connections are hard to establish. It is possible to find in literature software that guides the user to the selection of the gripper, relying on strong initial conditions and working only with one selected grasping principle (usually friction grippers), other than still requiring very high expertise from the user (as described in 3.1).

This thesis work aims to lay the basis of an expert system which, starting from both qualitative and quantitative parameters, should help users to understand which grasping principle is capable to handle the work piece they prompted. The requirements on the user's side are just basic engineering skills.

The work starts with a study of the current grasping principles, in order to establish how they ensure the grasp, and then it focuses on their object and environmental requirements, so as to define their field of application and limits. All the grasping principles and the gripper characteristics are described in chapter 2.

Later, feeding, handling and releasing issues have been analyzed to determine the most valuable parameters and their possible values.

2 STATE OF THE ART

2.1 FEEDING, GRASPING AND HANDLING

2.1.1 The grasping process

The grasping process, in a standard pick and place operation, can be divided into 6 steps, as showed in Figure .

For an easier understanding we used a scheme that represents a common jaw gripper, but the steps can be easily adapted to any other kind of gripper, even if contactless.
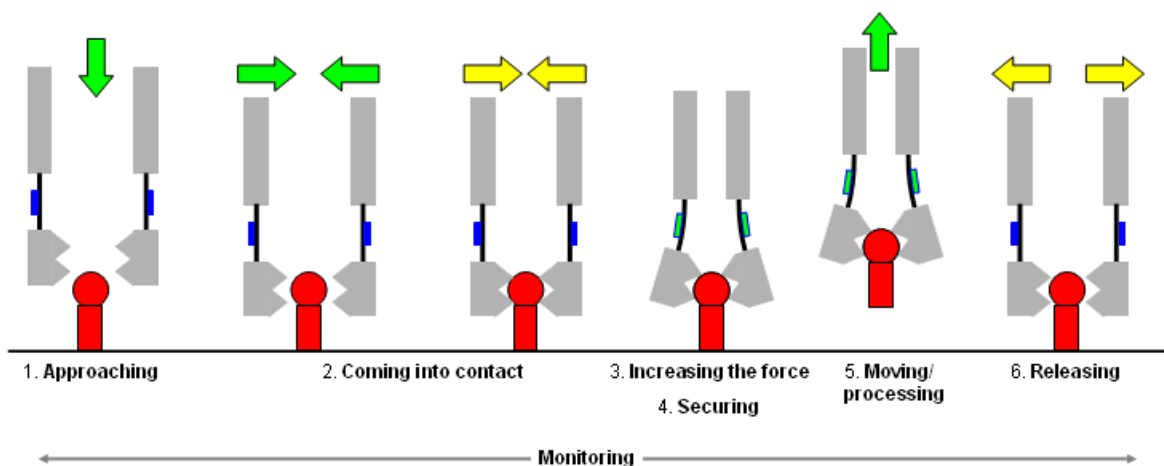
Figure 1 - Grasping process in a standard pick and place operation [50]

- **Approaching**: the gripper moves towards the object and then slows down to align as precise as possible.

- **Coming into contact**: the gripper goes nearby the object and comes into contact with the object surface;

- **Increasing the force and securing**: the gripper closes its fingers (in the case of a jaw gripper) until it ensured enough grasping force (a force sensor increases precision);

- **Moving/processing**: the gripper moves the part from its initial position to the destination; during the manipulation more or less acceleration can be used, according to the requirements: the more acceleration, the more grasping force is required;

- **Releasing process**: as discussed in the previous paragraph, the releasing could be achieved following different strategies that are mainly divided in the ones that can be applied in micro scale and the ones that can be applied in macro scale.

2.1.2 Feeding

Reliable feeding is a key factor in automatic handling of work pieces. How an object is fed will determine the quality, the reliability and even the feasibility of the grasp.
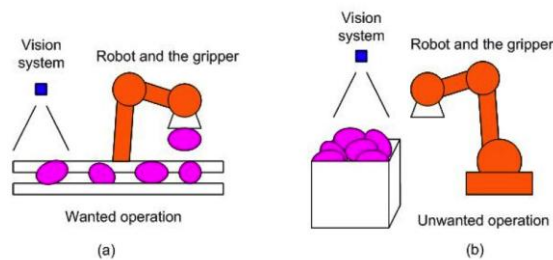
Figure 2 - Different feeding scenarios [75]

As shown in Figure , a work piece fed by an automatic feeder is much easier to pick, compared to picking it inside a box with other pieces. Therefore the factors that are influenced by feeding can be summarized in:

- Orientation: which could be random or predetermined;
- Distance from other pieces: an object too close to another can make the grasp harder;
- Relation with other pieces: the object, for instance, could be tangled with other work pieces;

In general, during assembly, work pieces, in order to be easily grasped, should be fed by an automatic feeder but, parts that present particular automatic feeding problems, are unlikely to be candidates for automatic feeding and will probably represent a harder grasp. For example, if parts tend to tangle or nest when in bulk, they will need a special-purpose feeding system to be handled [8] or a redesign in order to avoid the problem of tangling or nesting [9].

However, there can be other problems when dealing with mixed non-rigid objects which are less suitable for automatic feeding, for example thin flexible lines can easily lead to entanglement.

2.1.3 Cross issues

A very significant issue in the grasping process is, as stated before, that is strictly linked with how the work piece is fed, how it has to be handled and how it has to be positioned and released as shown in figure 3.
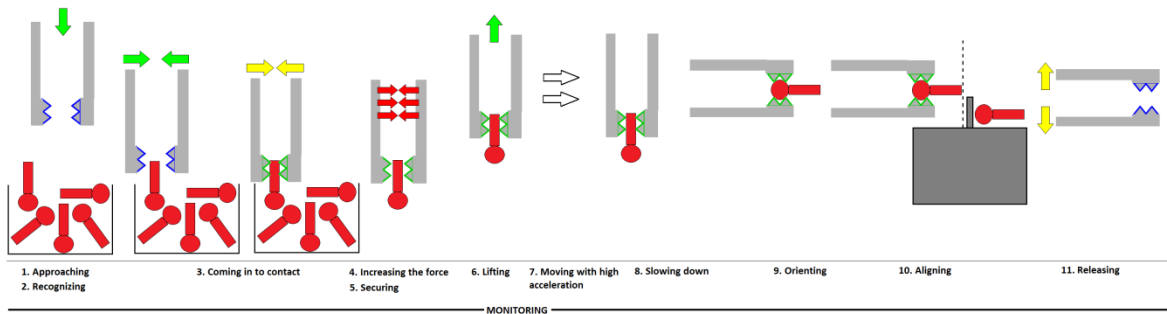
Figure 3 - Cross issues

Figure 3 clearly shows how the grasping process becomes harder when the operation is not a simple pick and place and includes other variables, such as:

- Picking from random position: the gripper has to be equipped with a visual system that helps the object, and its orientation state, recognition;

- Increasing the acceleration: higher acceleration requires higher grasping force and may exclude some grasping strategies;

- Aligning: the gripper, and the robot which manages it, must have sufficient positioning precision;

- Orienting: the gripper must be capable of orienting a work piece, and the work piece itself has to be easily adjustable;

Phase	Description	Gripper	Robot	Monitoring
1	*Approaching*	✓	✓	
2	*Recognizing*			✓
3	*Coming into contact*	✓		✓
4	*Increasing the force*	✓		✓
5	*Securing*	✓		
6	*Lifting*	✓	✓	
7	*Moving with high acc.*	✓	✓	
8	*Slowing down*		✓	
9	*Orienting*	✓	✓	✓
10	*Aligning*	✓		✓
11	*Releasing*	✓		

Figure 4 - Phases details

Figure 4 resumes how not only the gripper is involved in the operation, but even the robot and the monitoring system affect the capability to efficiently complete the operation. A tick represents when the gripper, the robot or the monitoring system are involved in the corresponding phase of the operation.

In order to clearly show the implications of what has just being discussed on the different grasping principles, a further example has been proposed.

If we consider three different grippers, based on three different grasping principles (Bernoulli, magnetic and vacuum), they are all capable to manage the operation of a standard pick and place of a common thin sheet of metal, but if the feeding and the positioning are changed, not every gripper will be able to manage the operation.

In this paragraph different scenarios will be described:
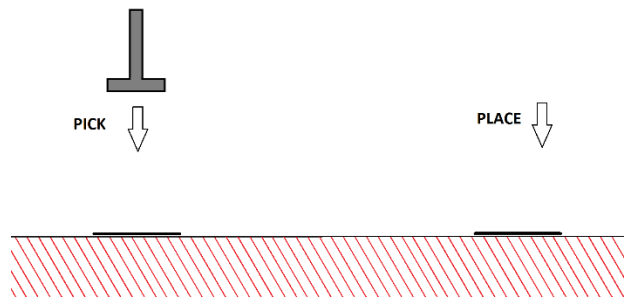
Figure 5 - CASE 1 - pick and place

In this scenario, all three grippers are able to complete the operation.
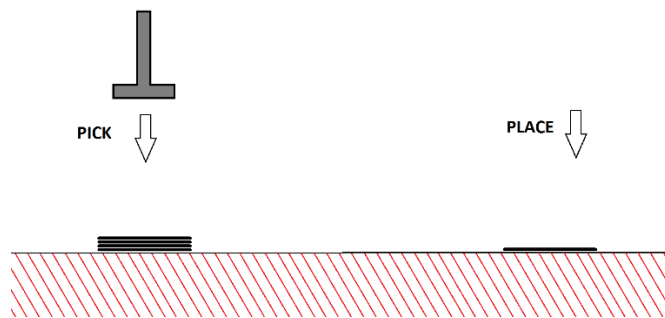
Figure 6 - CASE 2 - pick from a stack and then place

In case 2, the feeding system has been changed, the sheets of metal are stacked. In this case the magnetic gripper will have troubles in picking just one sheet of metal, and the same would happen for the other two grippers (Bernoulli and vacuum) in case of porous work pieces.
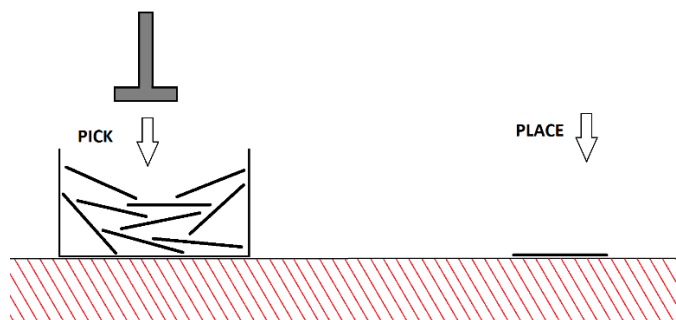
Figure 7 - CASE 3 - pick unoriented work piece and then place

This is a clearly atypical situation for a sheet of metal, but it could be likely for a part such as a gear. In this case a magnetic gripper would have difficulty in picking just one sheet, the Bernoulli gripper would be able to pick only horizontal pieces, the vacuum gripper would be able to grasp the sheet only if it is not blocked by others. In any case, a sensor that helps the gripper to find the right coordinates to pick the object will be needed, since the object is in a random position. In this case the feeding played a key role since it reduced the number of available grippers and it implied a new requirement: a monitoring sensor.
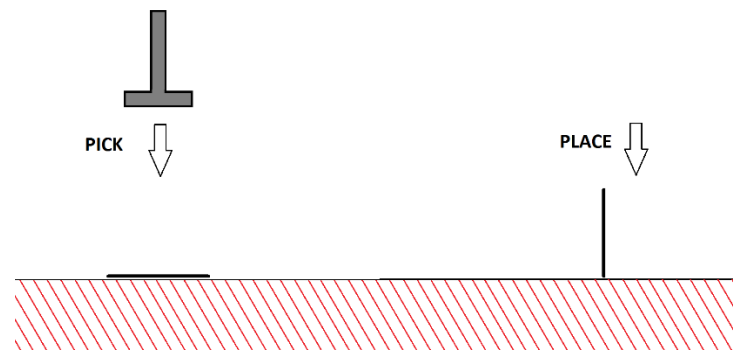
Figure 8 - CASE 4 - pick, orient and then place in vertical position

In this last case the object needs to be oriented during the manipulation. The Bernoulli gripper is not able to orient it since the horizontal forces will drop down the object.

These examples have been made to demonstrate how feeding, grasping, handling and positioning are linked together. Another example could be made repeating the first case with higher acceleration; in such case every gripper will need an higher grasping force, but the Bernoulli would not be able to hold the piece because the inertia forces will make it slip away.

Therefore all those aspects must be evaluated separately and only once we have evaluated correctly the effects on the various grasping principles, will it be possible to choose the ones that can correctly pick, handle and place the work piece.

However, since this expert system is focused on supporting the decision process that leads to the choice of the appropriate gripper, starting from qualitative parameters, the system could manage this problem from the opposite perspective, recommending how to feed the work piece in relation to the grasping principle (for instance for frictional grippers the recommended grasping direction will be given, which influences how the work piece should be fed).

2.2 GRASPING PRINCIPLES: A REVIEW OF THE LITERATURE

Grippers are the end-effector of an industrial robot which provides temporary contact with the object to be grasped, ensuring its position and orientation. The grasp can be achieved in many different ways, depending mostly on the grasping principle.

Grippers belonging to the same category can be specifically designed to fit different pick and place operations, according to the properties of the object that has to be grasped. The reliability of the grasp is the main task and this is influenced from a significant number of parameters and their influence varies from grasping principle to grasping principle. Furthermore, when dealing with micro components[1], the focus is not only on the reliability of the grasp, which has still to be secure and robust, but even on the effectiveness of the release.

The figure summarizes the main grasping principles found in literature and the respective manageable object sizes.
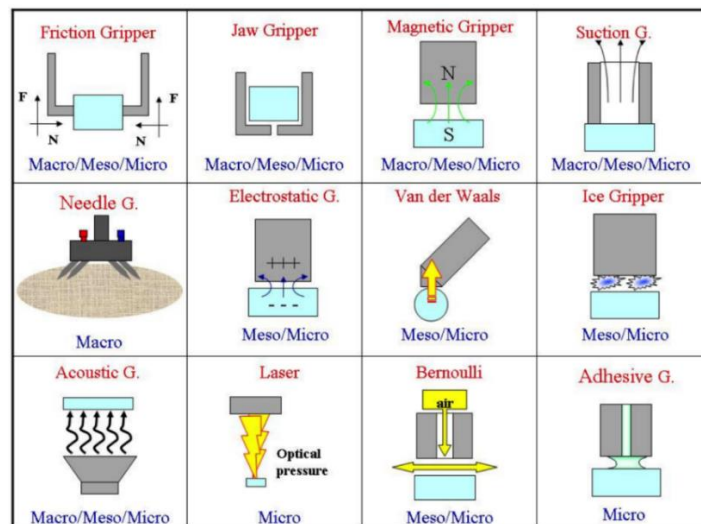
Figure 9 – Grasping principles (from http://www.roblog.eu/)

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[1] A work piece smaller than 10mm belongs to the micro category.

2.2.1 Friction and jaw gripper

Friction and jaw grippers, usually seen in the form of two or three-fingered mechanical grippers, are a simpler model of the human hand which uses a clamping jaw-like system to grasp objects. These grippers possess fingers which usually move synchronously allowing an automatic object centering and ensuring a correct positioning and orientation; however independent jaw motion is also possible. The movement of the fingers can be achieved with many different pneumatic and electromagnetic prime movers.

The holding of an object can be done following two different methods:

1. **Frictional grippers**: Friction grip jaws rely totally on the force of the gripper to hold the part, the fingers must be capable of supplying sufficient grasping force to hold the work part. In order to avoid scratches on the work part and to improve the coefficient of friction, soft type pads are usually applied on the fingers;

2. **Jaw grippers**: jaws add stability and power by cradling the object, having the contact surfaces of the fingers designed according to the work part to adapt to the work part shape;

Furthermore, owing to the wide choice of available gear systems, there exists a very large diversity in design of such grippers in which translational or rotational motion is transformed into jaw motion as shown in *Figure 10* - Some typical gripper mechanism for jaw motion [20].
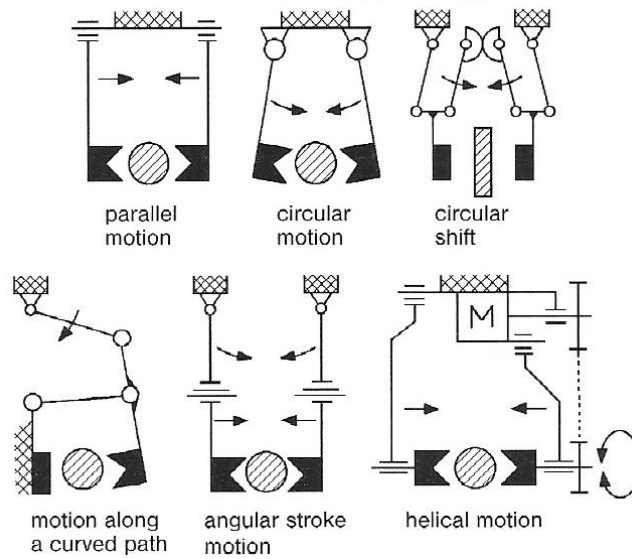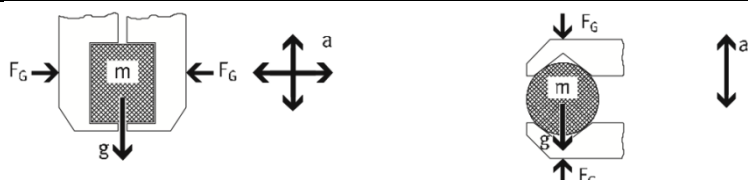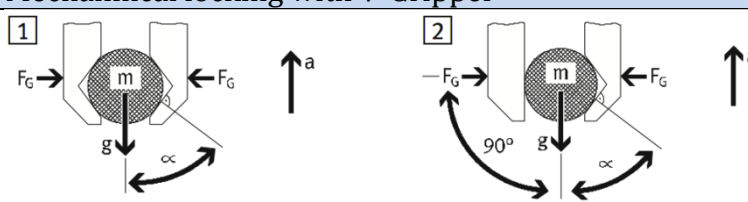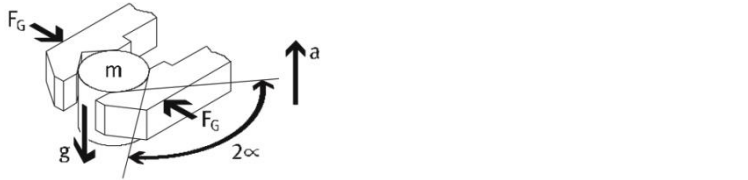
Figure 10 - Some typical gripper mechanism for jaw motion [20]
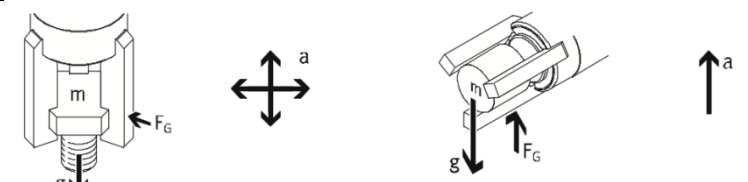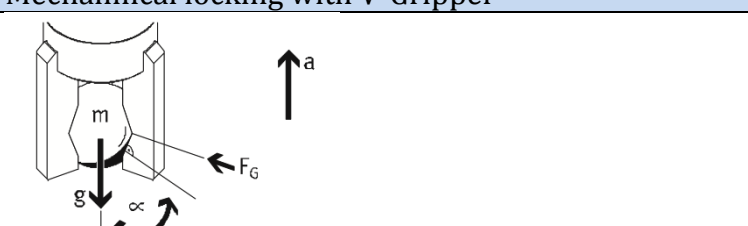
The kind of motion influences the characteristics of the gripper, for example a gripper with parallel motion will be able to grasp a more wide range of objects, in terms of object size, but with less grasping force compared to a similar gripper using circular motion.

As just described frictional and jaw grippers can hold the object respectively with a mechanical locking or a frictional locking between the gripping surface and the work piece surface. In the following table [23] is summarized how the gripping force act in case of 2-jaw and 3-jaw grippers.

2-jaw grippers:

Mechanical locking	
	$$F_G = K * m * (g + a)$$
Mechanincal locking with V-Gripper	
	1. $F_G = k * \dfrac{m*(g+a)}{2} * \tan \alpha$ 2. $F_G = k * m * (g + a) * \tan \alpha$
Frictional locking	
	$$F_G = k * \frac{m * (g + a)}{2 * \mu} * \sin \alpha$$

3-jaw grippers:

Mechanical locking	
	$$F_G = K * m * (g + a)$$
Mechanincal locking with V-Gripper	
	$$F_G = k * \frac{m * (g + a)}{3} * \tan \alpha$$
Frictional locking	

$$F_G = k * \frac{m * (g + a)}{3 * \mu}$$
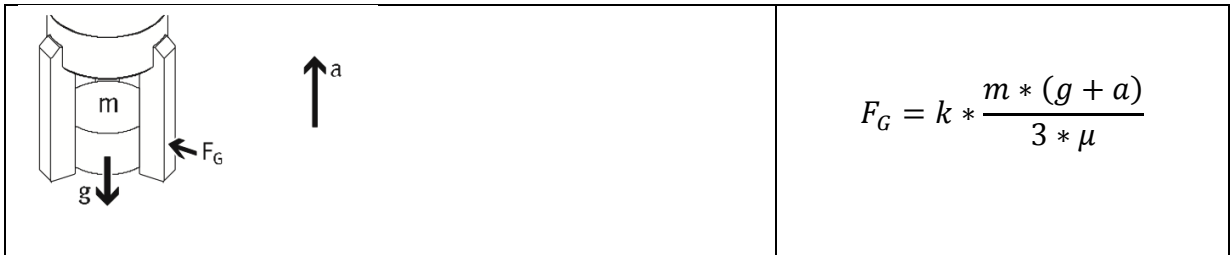
Where:

- F_G = Gripping force

- m = Mass

- g = Gravitational acceleration

- a = Gripper acceleration

- μ = Frictional coefficient

- K = safety factor (usually at least 2)

Frictional and jaw grippers, using appropriate grasping forces and fingers (with different shapes and properties), can grasp a really large variety of objects, from micro to macro components and from very low to very high weights.

Furthermore, when specifically designed, they can handle even fragile objects thanks to pneumatic actuation and compliant soft fingers. In figure 10-11-12 some examples are shown.
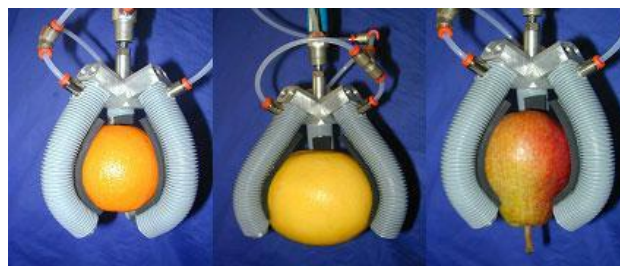
Figura 11 - Hand with flexible fingers (www.dimec.polito.it)
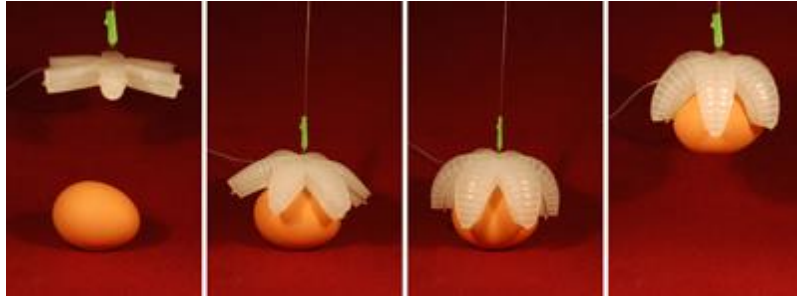
Figure 12 – Compliant pneumatic gripper (Danish Technological Institute, Robot Technology)

Figure 13 - Compliant mechanical gripper (www.schunk.com)

Benefits

- Stability: the grasp is very stable, the work piece once it is grasped cannot move between the fingers;

- Automatic centering;

- Low cost;

- Frictional and jaw grippers, relying on the kind of fingers they are equipped, can grasp a wide range of objects;

Drawbacks

- Friction grippers need at least 2 opposite surfaces to ensure a secure grasp;

- Slow material grasping: this kind of grippers needs to approach to the work piece slowly to avoid damages to the object, also the aperture and closure of the fingers has to be slow for the same reason;

- Heavy weight: this affects the whole robot load capacity;

- If not specifically designed to be compliant they can deform soft objects;

- Grippers need to be specifically designed to be capable of handling fragile objects;

- If not properly designed, since their grasping strategy is based on the contact with the object surface, there could be a risk of bacteria growth;

- Their shape and weight create problems when operating in narrow spaces;

- In case of jaw grippers a separate design is needed in order to handle different kind of objects.

This kind of gripper is also very common for many reasons such as ease of use, low cost, good dexterity and object stability.

2.2.2 Expansion gripper

Expansion grippers, which are also based on friction and form-fitting, ensure the grasp expanding an elastomer in the hole of objects having enough inside diameter. The expansion can be achieved in different way, depending on how the expansion gripper have been designed; usually is achieved through compressed air in the inner piston diameter of the elastomer which compresses increasing elastomer diameter and grasping the object thanks to the friction exercised on the inner walls of the work piece.
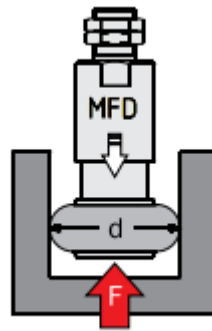
Figure 14 - Expansion gripper [50]

The grasped object has to be built specifically to be grasped with an expansion gripper, since every expansion gripper is designed to handle a very thin range of holes diameter with different grasping forces.

Furthermore the grasping force is controllable varying the pressure of the compressed air which is a must on this gripper since the force output depends on several other variables such as the diameter of the picked object, the surface finishing, friction and others.

The release is achieved by switching off the compressed air: the piston will return in its original position and the elastomer part to its original shape.

Benefits

- Comes in handy when the contact surface is too small for using vacuum cups or other kinds of gripper;

- It represent a very efficient solution for grasping small work pieces with holes;

- The grasping force can be controlled with the input pressure making the same gripper capable of handling objects with very different weights;

- The inflatable construction allows a multiple number of shapes to be handled with one model;

Drawbacks

- It works only with objects having compatible holes;

- The working range of a single gripper, in terms of dimension, is very limited since the grasping force is strictly linked to the diameter of the grasped object;

2.2.3 Magnetic gripper

The magnetic grippers, commonly used for grasping ferromagnetic materials, can be divided into two categories depending on the kind of magnet used.

Magnetic grippers with electromagnets

This kind of magnetic grippers needs a DC power in order to be activated and safely manipulate the object, this makes them more easy in controlling and releasing the object than magnetic grippers, mainly because they do not need an additional mechanism to release the object and the can be turned on and off. Anyway, if they do not implement an adequate safety system, they are more subject to unexpected object release in case of failure of the power source.

The magnetic field is generated by a wire wounded into a coil, when the electricity is passing through the wire the magnetic field becomes active and it deactivates when the electricity is gone.
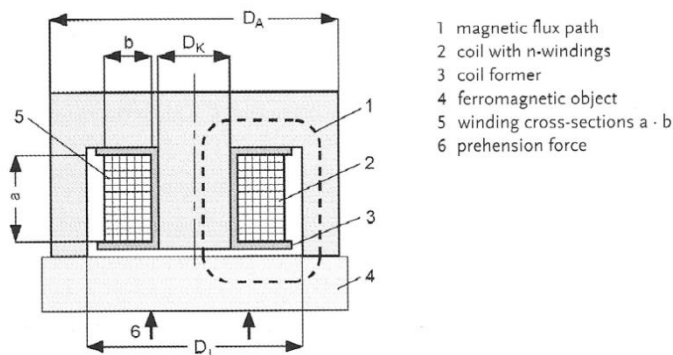
Figure 15 - Electromagnetic gripper [20]

The grasping force can be calculated using the conventional electromagnetic formula:

$$F = B * I * l$$

Where:

- B = Magnetic flux density;

- I = Current trough conductor;

- l = length of conductor

Magnetic grippers with permanent magnets
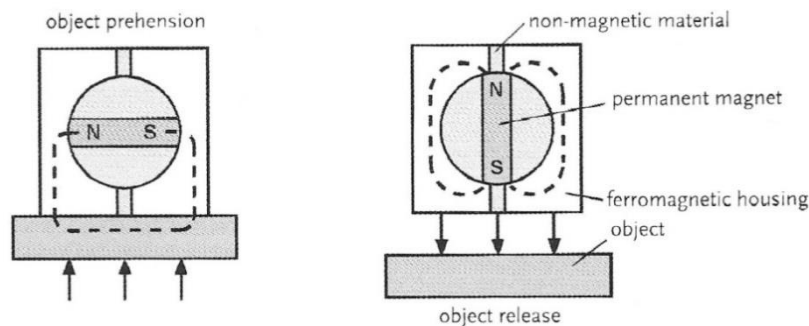
Figura 16 - grasping and releasing with a permanent magnet [20]

This kind of gripper does not require any sort of external power, as happens with the electromagnets, for handling the materials. After this gripper grasps an object, since it is not possible to turn off the grasping force, an appropriate releasing strategy is needed; usually the release is achieved through a mechanical switch (in the figure above: mechanical control of the magnetic flow), through air pressure or a specifically designed device.

Most of the magnetic grippers, using permanent magnets, which are currently available on the market are pneumatically actuated, but the most efficient are electrically actuated. It works similar to the electromagnets, where for activation and deactivation is necessary just a short electric pulse, but in this case the workpiece can be securely held in an emergency stop situations because it needs no DC power.

For specifically designed permanent magnets, typical retention pressure can be as high as 200kN/m² [20].

A particular problem exists when a magnetic gripper has to grasp a single thin and flat object from a stack. Recently has been developed a magnetic array tool (Magswitch® patented) that uses multiple permanent magnets with different magnetic fields to create a very shallow depth of field to destack sheets up to 0.7 mm.

Benefits

- It only requires one surface to ensure an effective grasp;
- The grasping is done very quickly;
- No power losses due to friction;
- It does not require separate designs for handling different size of materials;
- It is capable of grasping materials with very high porosity;
- Usable with a wide range of object sizes and shapes;

Drawbacks

- The gripper works only with ferromagnetic materials;
- The grasped work piece has the chance of slipping out when it is moving quickly;
- In case of electromagnetic gripper a failure of the power supply could lead to an almost immediate object release;
- A permanent magnet gripper requires an additional release system which may lead to other problems (for example scratches or damages to the workpiece);
- Sometimes oil in the surface can reduce the strength of the gripper;

- Due to permeating effects of the magnetic field, separation of thin objects may be very difficult even though recent studies showed a resolution of 0,7mm;

- Magnetic chips may stick to the gripper during unloading.

2.2.4 Vacuum gripper

Vacuum grippers are constituted by one or more cups inside which a vacuum level is created. The suction cups are connected through tubes with under pressure devices (like vacuum pumps, ejectors, suction bellows, pneumatic cylinders) for picking up items, for releasing items air is pumped out into the suction cups.

The following figure shows the most important functions and properties of a suction gripper.

1 Vacuum line
2 Pressure switch
3 Angular freedom
4 Quick exhaust
5 Vertical freedom
6 Quick interchangeability
7 Generation of holding force
8 Workpiece contact sensor
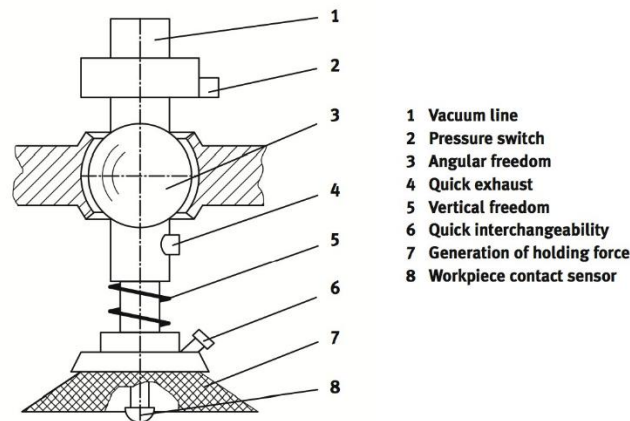
Figura 17 - Properties of a suction gripper [23]

Generally, the suction cups are round shaped and usually developed by means of rubber or other elastic materials or soft plastics and can be used at temperatures between -40 and 200 °C depending on the material used. Moreover, the vacuum cups can be prepared of hard materials when dealing with the handling of soft material objects. Thereby vacuum cups designs vary upon specific object characteristics, such as surface roughness, toughness and shape.

The suction cup can be categorized into four different types as shown in *Figure 18 - Different types of suction cups [7]-*
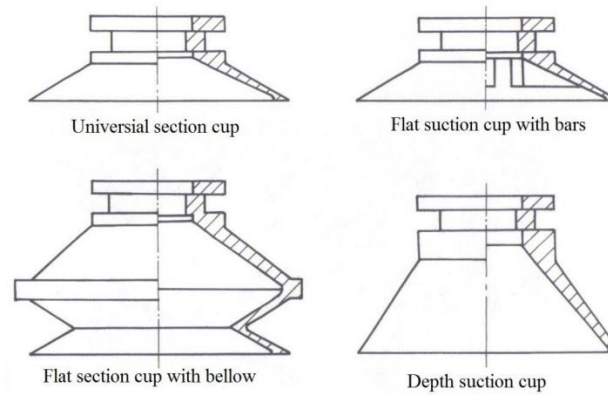
Figure 18 - Different types of suction cups [7]

The vacuum can be created in two ways trough two different devices: venture device or vacuum pump, the first is a simpler device and it is also more reliable and inexpensive. Both devices can provide high vacuum if there with a sufficient supply of air pressure.

The following formula helps with the definition of the suction chamber and the size of the suction area in order to ensure a safe grasp.

$$F = (p_0 - p_u) * A * n_3 * \eta * z * \frac{1}{S}$$

Where:

- A = Area of the suction cup;

- F = Load;

- n_3 = coefficient of deformation of the cup;

- p_0 = atmospheric pressure;

- p_u = pressure in seal suction chamber;

- S = safety factor;

- z = number of suction cups;

- η = efficiency of system.

Vacuum grippers are largely diffused for moving objects of various natures (glass, marble, sacks, etc.). Vacuum suction is used extensively throughout the packaging industry, as well as most other fields of robotics. In addition to the advantage of producing an attraction force, vacuum grippers have a soft grasp even on large and heavy objects. Grippers based on vacuum forces also demonstrated their effectiveness in managing deformable and lightweight parts [86][87] without distortion, deformation or damage.

Vacuum grippers can grasp objects spacing from micro objects [61][65], which is still under development for rounded surfaces, to very large and heavy work pieces [62]. The constraint of this grasping principle is the need for a flat surface available for grasping, limit which has been recently overcome with a specific self-selecting Grasper [60] which is capable to handle regular rounded surfaces.

As happens with frictional grippers even vacuum grippers can be specifically designed to handle fragile objects; since the first limit in handling such object is the impossibility to use strong pressure on low contact area, recently such problems have been solved recurring to more than one cups with lower pressure or one bigger compliant cup such as the one showed in the figure above:

Figura 19 – Compliant vacuum gripper

Benefits

- Can grasp very fragile objects, such as glass;

- Very fast grasping and placing;

- Configurable for variable geometries;

Drawbacks

- Low precision;

- For high grasping forces it needs a large grasping surface available;

- It cannot grasp objects with high porosity;

- Object with low porosity can still be grasped, but the grasp is not energy efficient;

- Needs a flat surface to ensure a safe grasp;

- Very loud;

- Needs specific and premade configurations for non-flat or variable geometries;

2.2.5 Electrostatic gripper

Electrostatic fields, like their magnetic counterparts, can be used to provide an astrictive force, known as electroadhesion. Such grippers are mainly used to grasp micro objects where the surface related forces start to dominate over the volume related.

Electrostatic micro grippers consist of electrodes where an applied voltage generates an electric field. Dependent on the material properties of the objects to be handled either a homogeneous or an inhomogeneous field distribution is needed to generate a grasping force.

Electrostatic forces in parallel plates can be described as in the following equation:

$$F = \frac{1}{2} * \frac{\varepsilon_0 \varepsilon_r * S * V^2}{d^2}$$

Where:

- S = Contact area;

- V = Applied potential;

- d = separation distance;

- ε_0 = free space permittivity;

- ε_r = dielectric constant.

DC electric fields have been used for handling micro parts [55], aligning optical fibers [56], positioning and aligning micro components [57], feeding mini flat plates [58] or micro parts [21], moving a microprobe, and even transporting bubbles in microgravity

[59]. Furthermore recent searches have shown a highly flexible electrostatic gripper systemwhich has been developed at Fraunhofer IPT.

Figura 20 - Electrostatic gripper developed at IPT.

It is capable of lifting semi-finished textile products made of carbon fibers and other materials and putting them down again with pin-point accuracy, without damaging them.

In particular, electrostatic forces comes in handy when traditional contact approaches fail in handling fragile, polished, or coated optical micro parts. Such parts can be damaged, for example, by friction-based grippers or could present features that can be broken by contact pressure or might have to be manipulated in particular environments where suction grippers cannot be applied (for example, in vacuum) [21].

Benefits

- Works in particular environment (such as vacuum);

- Does not damage or scratch fragile objects;

- Works with high porosity objects;

- Can handle all metals, whether ferrous or non-ferrous.

Drawbacks

- Low grasping force;

- Very sensible to the humidity changing of the environment [63], not very reliable with an high humidity rate[1];

- Requires dust-free environment;

- Can't grasp wet objects;

- Not suitable for the manipulation of charge-sensitive devices;

2.2.6 Bernoulli Gripper

Bernoulli gripper relies on the Bernoulli airflow principle which states that when the speed of a moving fluid, which can be liquid or gas, increases, the pressure within the fluid decreases.

A Bernoulli gripper can grasp an object with the under pressure made by the high velocity airflow from the noodle to the surface of the object. If the force created by the under pressure exceeds the weight of the object it will be grasped by the gripper.
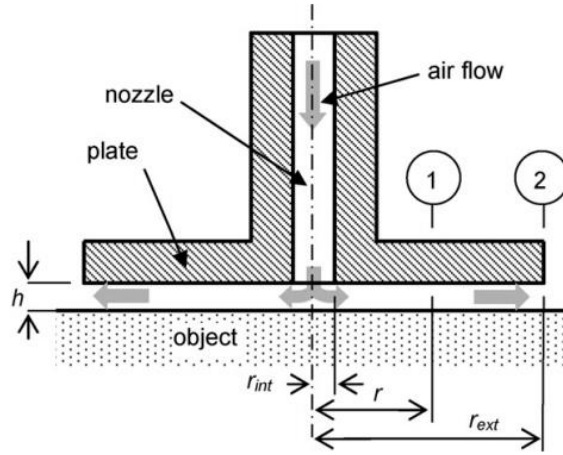
Figure 21- Bernoulli gripper[13]

The grasping force can be described by the formula below.

$$F_g = F_l - F_r$$

$$F_l = \frac{1}{2}\rho \frac{Q^2}{2\pi h^2}\left[\ln\frac{r_{ext}}{r_{int}} - \frac{1}{2}\frac{(r_{ext}^2 - r_{int}^2)}{r_{ext}^2}\right]$$

$$F_r = \rho \frac{Q^2}{\pi r_{int}^2}$$

Where:

- F_l = lifting force;

- F_r = repulsion force;

- Q = volumetric flow rate;

- ρ = air density;

- h, r_{int}, r_{ext} are shown in Figure 21- Bernoulli gripper[13];

Such grippers are typically used with small and light rigid products such as silicon wafers and circuit boards, recent studies also demonstrates their effectiveness in grasping leather plies [13] and sliced fruit and vegetables [38].

When high speed operations are involved the grasped object needs to touch the gripper slightly to overcome inertia forces with static friction [65].

Benefits

- No imprinting on delicate surfaces;

- Contactless handling;

- No contamination of and from the gripper;

- In sliced fruit and vegetables it can remove surface moisture produced during slicing [22];

Drawbacks

- The gripper will drop the work piece if significant lateral force is applied;

- Loose effectiveness and reliability when dealing with porous surfaces;

- Very high noise level when working;

2.2.7 Van der Waals gripper

A Van der Waals gripper is based on the Van der Waals forces which are short range forces, acting when surfaces are sufficiently close together, and are due to spontaneous electrical and magnetic polarizations that cause a fluctuating electromagnetic field within the medium and the gap between the surfaces[73][74].

This kind of gripper is used especially in micro-manufacturing because of its relatively low gripping forces but since this grasping principle is based on one of the predominant forces which act on micro components[2], this introduces problems in releasing [27]. The challenge is then how to release the micro-material since the Van der Waals forces have an adhesive effect when particles are in contact, many studies have addressed this problem in different ways (it can be a separate device, mechanism or a specific physical design) with different benefits and drawbacks [26][72][31]. Even if this grasping principle is mainly adopted in micro-manufacturing, recent studies demonstrates its effectiveness even when heavy loads are involved.

A gripper, relying on Van der Waals forces, can pick an object when the surfaces of the gripper and of the work piece are sufficiently close together to generate enough gripping force following this equation [28]:

$$F = \frac{A_H Y^X}{6 D^n}$$

Where:

---

[2] *Gravity dominates in macroscale but, when dealing with micro-components, forces like Van der Walls forces, capillary forces and electrostatic forces are predominant [24][25][26].*

- A_H = Hamaker coefficient, which depends on the kind of material;

- D = shortest surface distance;

- n and X are two exponent, greater than zero, that vary with the geometry of the grasped object;

- Y = dimensional parameter of the micro-material under consideration;

Van der Waals forces are also dependent on the shape or geometry of the interacting substances [29][30] , making this kind of gripper not suitable without a planar surface available, as shown in the following table:

Geometry	Force
Two flat surfaces	$f = -\dfrac{A_H}{6\pi D^3} \; per \; unit \; area$
Two spheres	$F = -\dfrac{A_H}{6D^2}\dfrac{R_1 R_2}{R_1 + R_2}$
Sphere-flat surface	$F = -\dfrac{A_H R}{6D^2}$
Cone-flat surface	$F = -\dfrac{A_H \tan^2 \phi}{6D}$
Cylinder-flat surface	$F = -\dfrac{A_H R^2}{6D^3}$

Where:

- R = radius of the sphere or the cylinder;

- ϕ = half cone angle.

The table also clearly shows how the Van der Waals forces are not only depending on the distance between two surfaces, but also on the surface area available.

Recent studies also demonstrated how the surface roughness of the work piece can influence the manipulation capability of this kind of gripper: surfaces with higher

roughness were found to be suitable for the pick-up position, and those with low roughness for the placement position in an effective material handling system[26].
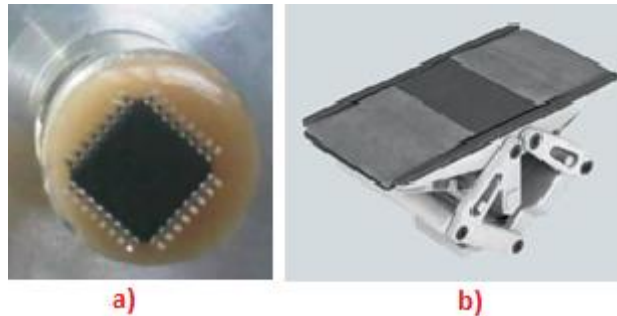
Figura 22 - Van der Waals grippers - a) Polyurethane gripper [72] b) Festo – Nano Force Gripper

Benefits

- It needs a very low amount of energy for grasping and no energy for holding;
- It is very suitable for fragile objects;

Drawbacks

- It is greatly influenced by the superficial treatment of the object surface;
- Depending on the gripper geometry it may require an additional release system;
- It is not suitable with very rough surfaces[26];
- It needs a planar surface available for grasping;

2.2.8 Needle gripper

This kind of grippers are very suitable for the handling of tissues or food. Their structure is quite simple and they can manage to grab a tissue very well without leaving significant traces on it.

In particular in fish industry a needle gripper is very suitable since others, like frictional, to avoid damages to the grasped objects needs a soft grip which requires tactile sensing which still is slow in action, expensive and not suitable for the demanding environment in the fish processing industry [75].
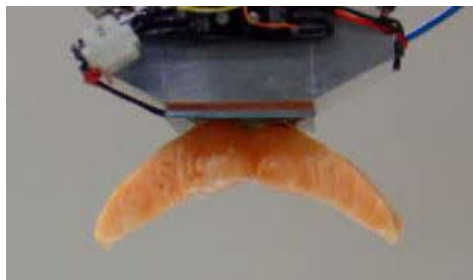
Figure 23 - Gjerstad needle gripper

The grasping elements are the needles, which can be classified into two groups depending on which are rigid, or flexible depending on the requirements of the grasp. In particular, during the movement of the gripper, rigid needles are not subjected to deform, while flexible needles deform because of their low relative stiffness, compared to that longitudinal axis of the tissue that is grasped.
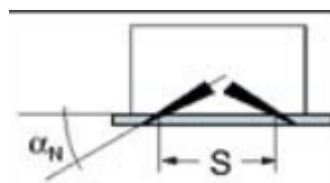
Figure 24- Needle gripper[12]

The holding force formula [12] of the needle gripper is the following:

$$F = \frac{E_{Z_x}\delta}{2Ssin\alpha_N}$$

Where:

- E_{Z_x} = Modulus of elasticity of a fabric with x% extension;

- α = penetrating angle;

- δ = layer thickness;

- S = distance of needles;

Benefits

- Can handle very flexible objects;

- Fast action;

- Variable geometry grip;

Drawbacks

- Pieces with soft texture require lower acceleration to maintain surface quality[75];

- Cannot be used with very fragile objects;

- The object has to be permeable;

- Punctures and may scratch object surface;

2.2.9 Capillary Gripper

A capillary gripper takes advantage of the surface tension forces provided by a liquid droplet used as an interface between two surfaces. Those forces, compared to gravity, are relevant in micro-component handling and the higher is the viscosity of the fluid, the higher will be the gripping force.

In micro assembly, surface tension gripping has been introduced in the late '90 for the purpose of gripping millimetric silicon chips and from then it has found many applications to grasp various kind of objects of different size and have been used owing to their flexibility and reliability [34][36][85].
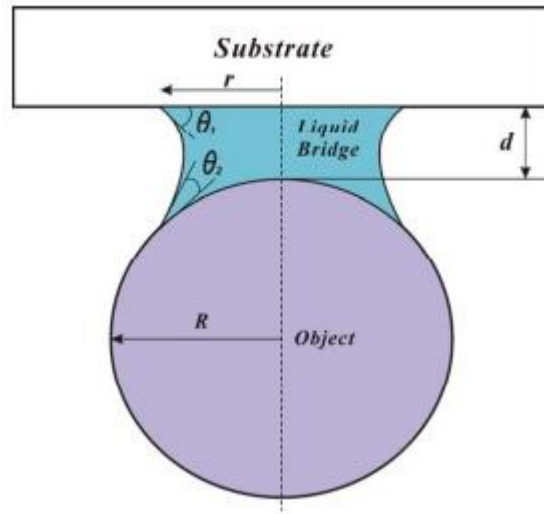
Figure 25 - Capillary micro gripper[37]

The grasp is achieved with a combination of capillary and cohesive forces [32] as shown in the following equation [20] of the lifting force:

$$F = p_k \pi a^2 \psi_0^2 + 2\pi\gamma a\psi_0$$

Where:

- γ = suface tension;

- p_k = capillary pressure;

- a = gap width;

- $a\psi_0$ = radius of the fluid bridge;
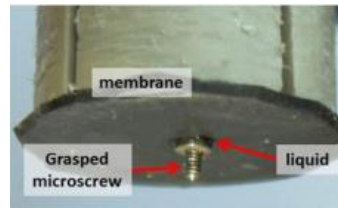
Figure 26 - example of capillary gripper [38]

In order to achieve the release, other than the general micro components releasing methods already discussed, many different strategies can be followed [33] as showed in the following table:
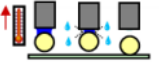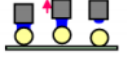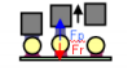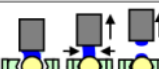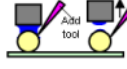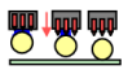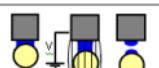
			Principle	Scheme	Problems/Difficulties	Advantages	Released compo-
RELEASING PRINCIPLES	Passive release	Gripper	Hydrophobic coating		-Manufacturing difficulties -Resistance of coating to few cycles	-Flexibility -Manufacturing by silicon technologies	Prevalently flat parts
		Envir.	Dry Atmosphere (heating the environment)		-Energy consumption -Long cycle time -Scarce reliability	-Easy to be realised	Probably all shapes
	Active releasing	Forces	Air pressure		-Precise control of the volume and pressure of air	-Precise if done in contact with the substrate	All parts
			Acceleration or vibration		-Lack of precision in releasing	-Easy to be realised -Reliable releasing	Parts with not too low mass
			Micro heater		-Reach exactly the drop -Risk to damage temperature sensitive parts	-Various types of heating source -Local action	-All parts except temperature sensitive ones
			Different adhesion force		-The precise control of the dispensed volume of liquid is difficult	-Self centering of the object on the releasing drop	All parts
			Engagement by the substrate/tool		-Often not precise -Releasing from other tool -Structured substrate -Damages on the part	-Reliable releasing	It can depend on substrate features
			Gluing on substrate		-Releasing precision depending on the glue -Glue volume control -Glue curing	-Self centering on the glue drop	All parts
			3D handling of the gripper		-Difficulties in the surface curvature control -Difficult to reach small radii of curvature	-Flexibility -Many actuation strategies are available	Prevalently flat parts
		Contact area	Additional tool		-Difficult to reach the part without wetting the tool -Damages on the part	-Precision	Probably all; better if flat parts
			Roughness change (increase gap)		-Manufacturing difficulties -Need for hydrophobic needles	-Flexibility	Probably all; better if flat parts
			Electrowetting		-Difficulties in meniscus curvature control -Charges induced both in liquid and component	-Direct control of the liquid meniscus (force)	Prevalently spherical parts

Figura 27- Releasing strategies related to capillary grasping [33]

Another possibility to achieve a release is using a solvent like ethanol, or it can be done waiting the liquid interface to evaporate, but it is a much slower release and its speed is usually unacceptable.

47

Furthermore recent studies [38] also shown a new releasing system where the work piece is released by squeezing the liquid bridge and obtaining a variation of the wetted surface which implies a drastic reduction of the gripping force.

Benefits

- Energy efficient;

- Can grasp components with only one upper free surface available;

- Needs only a small available grasping area;

- Has no limitations in terms of material and shape;

- compliant behavior and a self-centering effect due to surface tension;

- capability of grasping delicate components as the meniscus between the gripper and the object has a ''bumper'' effect;

Drawbacks

- It implies the use of liquid;

- Dust particles may stick to the liquid;

- Very porous objects cannot be grasped;

2.2.10 Acoustic gripper

The acoustic gripper overcomes the surface forces by levitating the handled component, being a contactless gripper it also avoids the release problems in micro manufacturing related to adhesion forces between the gripper and the work piece.

Two configurations can be found in literature [43]: standing wave levitation and near-field levitation.
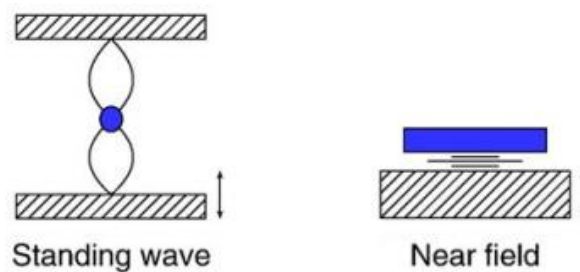
Figure 28 - Different configuration of acoustic levitation [44]

Standing wave levitation

In standing wave levitation the component stays, in the nodes of an acoustical standing wave, between a vibrating plate and a reflector. This configuration can lift particles with low weights (few grams) [44] which can be greatly increased if working in special environment (liquid or microgravity). A gripper based on this configuration can also achieve precise positioning and orientation by moving the reflector or changing the node position.

If a standing wave pattern is generated between the transducer and the reflector, by placing the reflector at an appropriate distance from the transducer, parts can be suspended in a stable position into the acoustic levitator. Positioning forces, acting in the direction of the pressure nodes, holds a part in balance below a node, as the axial

components of the levitation forces acting on all sides of the body compensate for the weight of the sample as shown in the following figure.
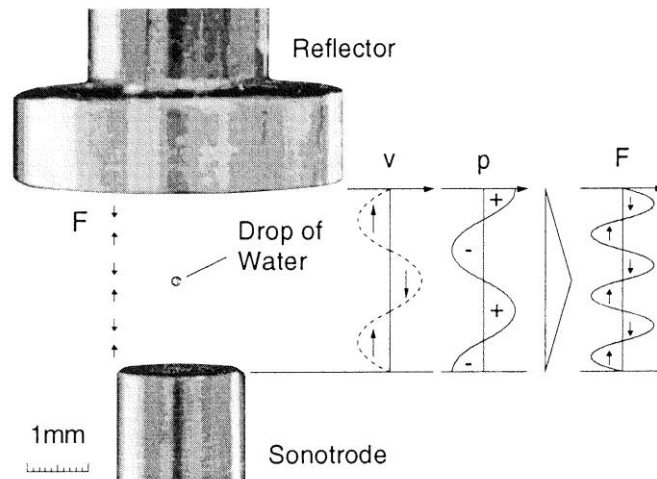
Figure 29 - Levitation of a water drop in a standing wave [47]

Near-field levitation

Near field levitations lifts flat planar objects through an high intensity ultrasonic transducer. The lifting height is quite small compared to the standing wave levitation but this configuration can reach much higher lifting forces and, depending on the transducer used and the gripper configuration, it can lift any weight if the separation distance is small enough and the shape, which has to be flat, offers enough planar surface available [47][48].
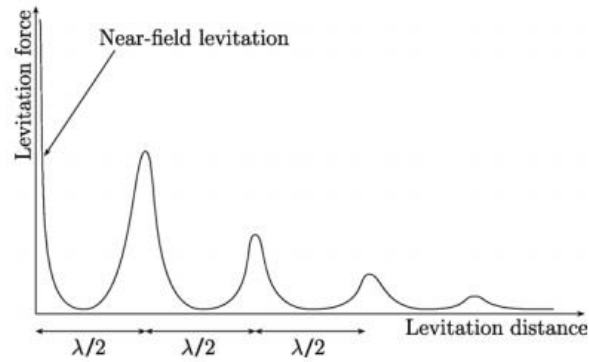
Figure 30 - Levitation force as a function of levitation distance [48]

Benefits

- Any kind of material can be lifted;

- Standing wave gripper can achieve precise positioning and orienting of the lifted object;

Drawbacks

- Slight asymmetries in the acoustically induced convective flow field can lead to imprecise positioning or uncontrolled object rotations[44];

- In near field levitation the object must be flat and preferably thin while standing wave can lift only small an light objects;

- Does not work in vacuum environment;

2.2.11 Solid-liquid state gripper

This kind of grippers are based on the principle that the adhesion power of an intermediate (which can be, for instance, water) in its solid state is greater than in its liquid state.

The grasping process starts with a liquid droplet between the gripper and the surface of the work piece, subsequently the droplet is frozen and its adhesive power will ensure the grasp.

The release, as well as the known releasing strategies of adhesive micro grippers, can also happen by breaking the frozen material that holds the object, one of the most common releasing strategies adopted with thermal grippers is the use of a micro heater; other strategies are discussed in 2.4.

The following images show two different kind of ice grippers, one based on thermoelectric effect [41] and the other based on the principle of the reversible thermal flow gripper achieved with a Peltier element [76].
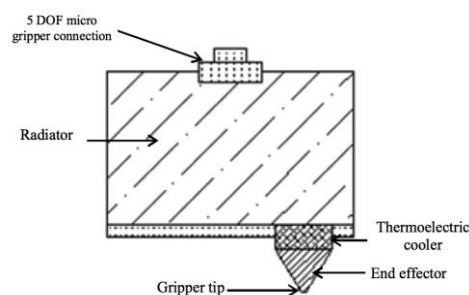
Figure 31 - Gripper configuration[41]
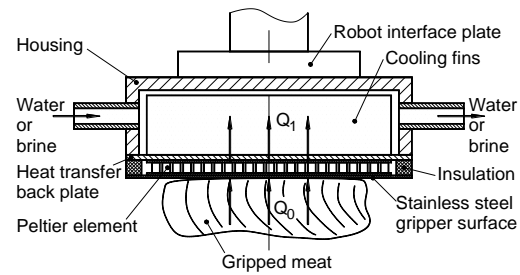
Figure 32 - Gripper configuration

Benefits

- Can hold different shapes;

- Can manage fragile objects;

Drawbacks

- Low grasping force;

- Does not work underwater;

- Low positioning precision when releasing micro objects;

- Can damage wet objects;

- Melting the object surface is not always feasible;

- Requires the object to be not sensitive to liquid;

2.2.12 Laser gripper

The optical (laser) gripper is a contactless gripper based on optical levitation [42] which states that particles can be freely suspended and accelerated by the forces of radiation pressure from visible laser light.

Figure 33 - Force components of a laser beam

The focused laser source can produce enough pressure to lift only very small micro components since the gripping force hardly reaches $1nN$ [45]. Anyway, to compensate the small grasping force, the operation may take place in a liquid

Benefits

- Contactless gripping;

- Very suitable for nano parts;

Drawbacks

- Thermal effects on the work piece;

- Very low gripping forces relegate this gripper only to very low weight component grasping;

- The material needs to have an higher refractive index than that of the surrounding medium;

- Stability is also conditioned by the refractive index ratio;

2.3   HYBRID GRIPPERS

In the last years have been developed some grippers which does not fit in just one of the category described above and are called "hybrid grippers".

In this paragraph are described some examples of such grippers.

Jamming gripper

It is an extremely flexible gripper since it can grasp almost every kind of object, such as objects with strange shapes, fragile, with high porosity, without any flat surface suitable for grasping etc…

Figure 34 - Jamming gripper (from http://www.roblog.eu/)

The grasp is made taking advantage of friction, vacuum, compliant gripper shape and it can be soft thanks to the distributed and not localized pressure on the grasped object.

Anyway, this gripper has its drawbacks since it cannot center the object and the positioning is very inaccurate.

Electro adhesive frictional gripper

The gripper developed by SRI international is based on several principles: electroadhesion, friction and compliancy.

Figure 35 - SRI gripper (http://www.sri.com)

SRI electroadhesion technology allows electrically controlled reversible adhesion to most surfaces thanks to the compliance of the gripper fingers.

When alternate positive and negative charges are induced on adjacent electrodes, the electric field sets up opposite charges on the substrate and thus causes electrostatic adhesion between the electrodes and the induced charges on the substrate; thanks to the compliance the distance between the electrodes and the grasped object is extremely reduced and this results in more grasping force.

Experiments demonstrated how this gripper can adhere to numerous surfaces such as wood, drywall, paper, glass, concrete, and metals.

Contact Bernoulli gripper

This gripper, which is still under development, is not properly a hybrid gripper, since does not belong to more than one grasping principle, but it is not even a just a Bernoulli gripper since it is not contactless.

*Figure 36 - Contact Bernoulli gripper **Errore. L'origine riferimento non è stata trovata.***

Standard Bernoulli grippers would not be able to grasp an object which has not a flat surface available for grasping, while the one showed in the figure above can thanks to its capability to conform its shape on the object surface.

In this case deformable surface has been used to reduce the mean distance between the gripper and the object. The air is pumped through a series of needles and the lift force generated, thanks to the compliance of the gripper's shape, on non-flat surfaces has a significant increment.

Anyway there are still significant drawbacks since it cannot handle fragile or flexible objects due to the necessity to conform its shape through the contact with the object surface.

2.4   RELEASING STRATEGIES: A REVIEW OF THE LITERATURE

Since the most valuable parameter in releasing is the object dimension, releasing strategies can be divided into two categories: releasing strategies in macro scale and releasing strategies in micro scale.

2.4.1 Macro scale

In macro scale the release is mostly achieved through switching off the grasping forces and letting the gravity forces release the object.

However, this is not always possible and in some cases (e.g. a magnetic gripper which uses a permanent magnet) a separate device or mechanism is needed. The mechanism dedicated to the release has to be compatible not only with the gripper itself, but with the object characteristics as well. In particular, when an object is fragile, pushing it down with a separate device could damage the object, or could smear it if the part is sensitive to stain. Other than the object characteristics, another parameter that influences the choice of the appropriate releasing strategy is the positioning precision needed.

Since in macro scale there is not enough literature concerning releasing strategies, probably because other releasing strategies beside gravity represent a rare task (with the exception of permanent magnet), it is hard to suggest with sufficient reliability any specific releasing strategy; however, it is still possible to suggest when a dedicated mechanism is required and highlight when it should be compatible when particular object characteristics.

2.4.2 Micro scale

In micro scale, with the exception of a few contactless grippers (e.g.: Bernoulli, laser and standing waves acoustic grippers), the literature shows how the main problem of the contact ones (friction and jaw grippers, vacuum gripper, Van der Waals etc.) concerns the releasing task [33].

Following the work of Fantoni and Porta, which reviews the releasing strategies in micro parts handling, the releasing strategies can be mainly divided into two groups [33]:

1. **Passive releasing strategies**: where the reduction of the surface forces is obtained without the use of external forces. In this case environmental conditions can reduce the principal forces acting at micro scale (electrostatic, adhesion, Van der Waals) or the strategy could be focused on exploiting some micro gripper features (in terms of shape, surface coating and material);

2. **Active releasing strategies**: where an additional action allows the gripper to release the object. These additional actions can be forces able to overcome the adhesive ones between gripper and object, or means to reduce the contact area;

The following tables report more details about the releasing strategies, providing the corresponding link with literature, a brief description, a scheme and the kind of forces involved.
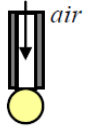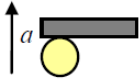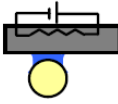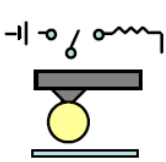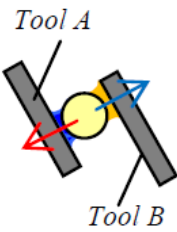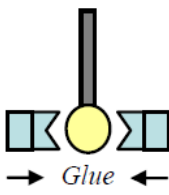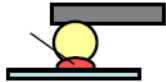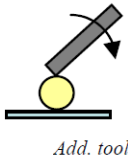
Type	Principle	Scheme	Description	Force
Gripper	Condutive material/coatings –grounded gripper		Conductive materials or coatings (which do not form insulating oxides) reduce static charges. Grounded grippers prevent the charge storage. [79][19]	electrostatic
	Low difference of EV potential		Gripper and object made of materials with a small potential difference reduce "contact interaction" forces. [19]	electrostatic
	Hydrophobic coating		Hydrophobic coating reduces surface tension effects; it prevents the adsorption of moisture. [102]	surface tension
	Low Hamaker constant coating		Low Hamaker constant coating reduces Van der Waals forces. [79]	Van der Waals
	Hard materials		Contact pressure causes deformations, increasing the contact area between gripper and object: grippers made of hard material have to be preferred. [19]	Van der Waals, electrostatic
	Rough surface – Micro pyramids		The gripper roughness reduces the contact area and sharp edges induce the self discharge effect. [19] [102]	Van der Waals, electrostatic
	Spherical fingers		Spherical fingers reduce the contact area in comparison with planar ones. [19]	Van der Waals, surface tension
Environment	Dry atmosphere		a dry atmosphere reduces surface tension effects (but increases the risk of triboelectrification and the generation of electrostatic force) [19] [79]	surface tension
	Vacuum		if no moisture affects the contact, there is no liquid bridge and so surface tension is reduced (but with risk of triboelectrification) [19]	surface tension
	No O2 in the environment		if there is no oxygen, native oxide cannot arise on the surface of the gripper/handled objects [19]	electrostatic
	in fluid releasing		Assembly in fluid eliminates surface tension effects and reduces electrostatic forces [19] [101]	electrostatic, surface tension
	Ionized air		Ionized air can neutralize free charges on the surfaces and so it reduces electrostatic forces [6]	electrostatic

Figure 38 – Passive releasing strategies [33]

Type	Principle	Scheme	Description	Problems	Released components
Forces	Air pressure 1.Direct 2.Indirect (Adsorption force)	*air*	1. An air pressure flow [6][10]overcomes adhesion forces; 2. By heating a suitable end effector the object is released thanks to the ad-sorption force [103]	Possible lack of precision in the re-leasing place	1. 50-300µm parts [6]; square silicon chips (4.2*4.2*0.5mm³) of 20.5mg; [104]; 2. Max. adsorption force 0.22µN [103]
	Acceleration Or vibration	*a*	An acceleration or a vibration given to the gripper support allows the object to be detached thanks to inertial forces [105][106]	Possible lack of precision in the re-leasing place [106]	40µm pollen micro spheres [105]; 400µm spherical and 900µm half spherical lenses [106]
	Micro heater 1.Evaporating moisture/liquid 2.Melting ice		1. A micro heater reduces the moisture-liquid (so surface tension-capillary forces) [79]; 2. Melting of ice (ice gripper) [77][82]	Temperature sensitive parts can be damaged by heat	SMD plastic elements, small copper coils for telecommunication [77]
	Electrostatic force control 1.Shorting the gripper 2.Voltage tuning 3.Inverting polarity		Parts are released by the electrostatic force control: 1. Shorting down the gripper electrodes [79]; 2. Tuning the electrostatic force between gripper and substrate [107] ; 3. Inverting the polarity [108][21]	Problem in releasing conductive components [18]	2. Metallic spheres of d=30µm [107]; 3. Spheres of d=100-800µm and cubic valve (l=l80µm) [108]; Spheres, cylinders of 300-1000µm [18]
	Different adhesion force 1.Adhesion on substrate 2.Different adhesion tools 3.Different volume of liquid	*Tool A* *Tool B*	Objects pass from a tool A to a tool B exploiting the difference in adhesion force between the tools and the object. The tool B can be: 1. A substrate [108]; 2. A gripper [105]; 3. The force difference can be given by different volume of the same liquid [109]	The object has to be detached from the tool B (if the releasing place on tool B is not the final place)	1. Glass spheres with d=100-800µm and cubic valve flap with edge l80µm [108]; 2. 40µm pollen microspheres [105]
	Engagement by the substrate/ tool 1.Snap 2.Against edge 3.Scraping 4.Rolling 5.Needle	*Glue*	The object is released by its mechanical engagement on the substrate [104] or an-other tool. This strategy includes: 1. The use of snaps [110]; 2. Part against an edge [111]; 3. Scraping [105]; 4. Rolling [105]; 5. Use of needle [104]	Often additional features on the substrate are required	2. Metallic/non metallic parts of 50-300µm [6]; 4. 40µm pollen microspheres [105]; 5. Square silicon chips (4.2*4.2*0.5mm³) of 20.5mg; [104]
	Gluing on substrate		Parts are released by gluing them on the deposal place [104]	Not suit-able for moving parts	Square silicon chips (4.2*4.2*0.5mm³) of 20.5mg; [104]
	3D handling of the gripper 1.Variation the curvature 2.Tilting	*Add. tool*	A decreasing of the contact area through: 1. Varying the gripper curvature from a flat shape to a curved one [112]; 2. Tilting the gripper [113]; 3. Parallel motion of the gripper respect to the substrate [114]	Complex 3D handling of the gripper. Many DOF required.	1. Minimum object weight 98mg [112]; 2. Metallic spheres of d=20-30µm [113]; 3. 40µm
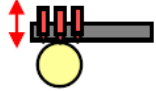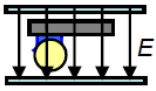
				pollen microspheres [105]
Additional tool		An additional tool (with little contact area with the object) allows the object to be first detached from the gripper [113], then released on the substrate by removing the tool	Many devices in a small space	Metallic spheres with diameter of 20-30µm [113]
Roughness change		The roughness change reduces adhesion forces al-lowing the part to be released [79]	Difficulties in realization	
Electrowetting		The modification of the liquid drop by an electro-static field reduces the contact area	Difficulties in meniscus control	

Figure 39 - Active releasing strategies [33]

The tables classify one by one the releasing strategies in micro scale, however it is not uncommon that releasing strategies use more than one approach at the same time.

This classification scheme is necessary to verify the matching couples of releasing strategies and grasping principles.

In the following table the compatible couples are listed.

Grasping P.	Passive releasing strategies									Active Releasing strategies										
	Gripper							Env		Forces							Contact area r.			
	Cond. mat/coat - grounded gr.	Low difference of EV potential	Hydrophobic coating	Low Hamaker constant coating	Hard materials	Rough surface	Spherical fingers	Dry atmosphere	Ionized air	Air pressure (direct/indirect)	Acceleration or vibration	Micro heater	Electrostatic force control	Different adhesion force	Engagement by substrate/tool	Gluing on the substrate	3D handling of the gripper	Additional tool	Roughness change	Electrowetting
Friction	■	■			■	■	■	■											■	
Ice												■								
Van der Waals	■			■		■											■			
Electrostatic	■								■				■	■			■			
Capillary			■							■	■			■	■	■	■	■		■
Suction										■	■				■					

Figura 41 - Releasing strategies available for grasping strategies [33]

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Therefore choosing the appropriate releasing strategy is a matter of compatibility between grasping principles and releasing strategies; the selection of the available grasping principles is achieved according to the object characteristics and the kind of operation in which the work piece is involved; the same happens with the choice of the available releasing strategies.

Fantoni and Porta list which object characteristics make a releasing principle or a releasing strategy not available. Their work has been integrated in relation with the object characteristics identified in 3.4 and then translated as exclusion rules (3.5).

2.5 GRIPPERS CHARACTERISTICS

The technical properties of a gripper and its price are the basis for an assessment of its suitability for a given application and a comparison with other makers' products.

The suitability of a gripper is then defined by how it satisfies the requirements of the operation. Every gripper has a "range" of acceptability for its technical characteristics (e.g. a range of manageable dimensions, manageable weights, shapes etc...).

The choice of the proper gripper must start with a study of the planned application, as discussed before this involves object characteristics, feeding system, environmental characteristics and handling characteristics.

Hence, the choice of the right gripper can be made when gripper technical characteristics are adequately defined; Festo, one of the major manufacturers, summarizes the fundamental technical data that defines the specifics of a gripper as shown in Figure 42 - Festo - Characteristic data for grippersfigure 42.

Festo divides into three steps the examination of the gripper suitability:

1. Assign to every characteristic a weight[3];
2. Check the primary characteristics;
3. Use the secondary data to make a final selection.

---

[3] For every given application a determinate characteristic could have different relief, one example is the closing and opening times, when speed is not a requirement their weight should be less compared to more important characteristics.

Characteristic data for grippers	
• Type designation • Design • Size	
Primary characteristic data	**Secondary characteristic data**

• Operating principle
  - mechanical
  - fluidic
  - magnetic
  - adhesive
• Gripping force in N
• Gripping force pattern
  (Gripping force diagram)
• Gripper stroke per jaw in mm
  or opening angle in degrees
• Gripping width adjustment
• Load capacity max. in N
• Closing (gripping time) in s
• Opening (release time) in s
• Load limit values
  - Forces
  - Torques
  - Finger length
• Number of gripper components
• Main dimensions in mm
• Dead weight in kg
	• Performance/mass ratio
	  in N/grams
	• Mass moment of inertia in kgcm²
	• Operating pressure range in bar
	• Maintenance cycles
	• Design of bearings and guides
	• Range of sizes
	• Repetition accuracy in mm
	• Operating temperature range
	  in degrees
	• Mode of operation
	  - Single acting
	  - Double acting
	• Working frequency max. in Hz
	• Mounting position
	• Energy type and consumption
	• Retention of gripping force in case
	  of power supply failure
	• Monitoring of gripping stroke
	• Material specifications
	• Service life
	• Interface data
	  - mechanical
	  - fluidic
	  - electrical
	• Environmental characteristics
	  - Clean-room class
	  - Exhaust air
	  - Abraided particles

Figure 42 - Festo - Characteristic data for grippers

Furthermore, the focus should not be only on which characteristics are fundamental for defining a gripper's field of application, but also how they are measured to be able to compare one gripper with another.

Finally, if we take a closer look to the work of Festo, it is possible to notice that his characteristics parameters are particularly focused on frictional grippers and do not take in account the reliability of a gripper with specific object characteristics.

3   EXPERT SYSTEM

3.1 CURRENTLY AVAILABLE SUPPORT SYSTEMS

An expert system could be defined as a computerized system that emulates the decision-making ability of a human expert.

Actually, only some of the major grippers' manufacturers (e.g. Festo and Schunk) released a software that helps the user through the selection of the gripper, but this software is focused on just one grasping principle (usually frictional) and relies on strong initial conditions.

Recent studies [90][91] focused mostly on micro-components grasping, establishing a correlation between micro-assembly techniques and part features.

In this paragraph we summarize and analyze two very different approaches: the Festo gripper configurator and the work of Antonelli, Fantoni, Porta and Santochi about the selection of the appropriate micro-assembly technique.

FESTO
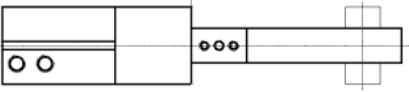
Festo developed a tool that helps the user to select the appropriate frictional gripper from their catalog.

It is articulated into 3 steps:

Figura 43 - FESTO - step 1 - information about object and gripper finger
(http://xdki.festo.com/xDKI/xDKI.asp)

In the first one the user is asked to define how balanced is the grasp and the weight of the object and the fingers that are supposed to be used.
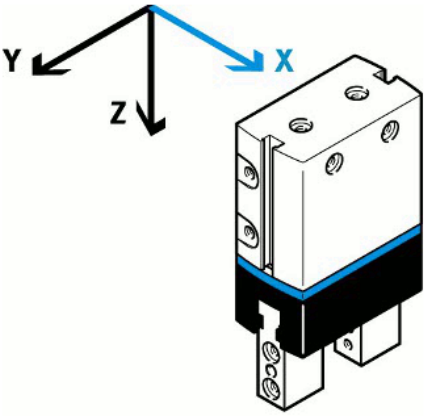
The software asks for purely quantitative parameters. The requirements from the user's point of view are:

- Knowing exactly where is the barycenter of the grasped object, and this is not always possible;

- Having already established which are the grasping points;

- Having already established the kind and weight of the fingers;

Figure 44 - FEST - step 2 - Further settings (http://xdki.festo.com/xDKI/xDKI.asp)

In the second step the system asks the user to define exactly the acceleration, the grasping direction, the coefficient of friction, the working pressure and the device temperature.

While the gripper position represents a parameter that is easy to establish, some of the information required is really hard to define:

- Acceleration: this is a parameter that may be known to the users, since they have already established the robot gripper, but this parameter also depends on other object characteristics that are not considered in this system;

- Other specifications: here are the parameters that the user will not define without difficulty, the coefficient of friction "for instance" is hard to establish without any preliminary test involving also the fingers of the gripper;

| Standard gripper | Robust Gripper | Long stroke gripper | Precision grippers | Low Price Gripper | Micro-gripper |

Part No.	Type	Total weight	Overall stroke:	Status
1254040	DHPS-10-A	0,37 kg	6 mm	OK
1254042	DHPS-10-A-NC	0,37 kg	6 mm	OK
1254041	DHPS-10-A-NO	0,37 kg	6 mm	OK
1254043	DHPS-16-A	0,48 kg	10 mm	OK
1254045	DHPS-16-A-NC	0,49 kg	10 mm	OK
1254044	DHPS-16-A-NO	0,49 kg	10 mm	OK

Type	Results				Max. possible	
Required static retention force	4.9	N		24%	20.21	N
Required dynamic retention force	5.9	N		29%	20.21	N
Intermediate distance of the pressure point	40	mm		100%	40	mm
Dynamic longitudinal force on the gripper fingers	1.47	N		1%	60	N
Dynamic lateral force Mx	0	Nm			3	Nm
Dynamic transversal force My	0.01	Nm			3	Nm
Dynamic lateral torque Mz	0	Nm			3	Nm

Product image

Options

- 2D/3D view
- Accessories
- Data sheet
- Documentation
- Add to basket

A usually ships same day/next day
Standard product

Back

Figura 45 - FESTO - step 3 - Degree of gripper utilization as a percentage
(http://xdki.festo.com/xDKI/xDKI.asp)

The third step is the output which precisely describes the forces that are needed and the required overall stroke of the gripper; these parameters will filter the gripper manufacturer database and define whether a gripper is capable or not to ensure a grasp; this step also shows the percentage of gripper utilization.

However further test showed how the gripper with highest value of overall stroke and total manageable weight is always flagged as "OK" regardless of the object characteristics (e.g. even if an object belongs to micro category the "biggest" gripper is flagged as "OK").

The following are the benefits and the drawbacks of this method.

Benefits:

- Gives a fully quantitative output;

- Searches through a big database of grippers;

Drawbacks:

- Works only with frictional 2-fingered grippers;

- Requires very strong initial conditions:

    o Object is always graspable by a 2-fingered frictional gripper;

    o It has a regular shape;

    o There are no troubles in the release;

    o It is correctly fed;

    o The operation is a simple pick and place;

- All kind of object characteristics, except the weight and the size, are ignored;

- Micro domain considerations on releasing strategies are ignored even if the output contains micro grippers;

- No exclusion are applied when a gripper is largely over dimensioned for grasping the workpiece, therefore the biggest gripper can grasp everything making the other grippers not preferable;

A methodology for the selection of micro-assembly techniques

This methodology is focused on addressing the problem of selecting the appropriate micro-assembly grasping principle and releasing strategy according to the micro-part features.

The system is works with an input that is based on qualitative data, since there is not sufficient structured knowledge about micro-assembly.

The methodology is based on different steps:

1. Defining a set of parameters which takes into account object characteristics;

2. Finding links between parameters and grasping principles;

3. Defining the implications of the parameters values on the releasing strategies;

4. The expert system chooses the best couple of grasping principle and releasing strategy.
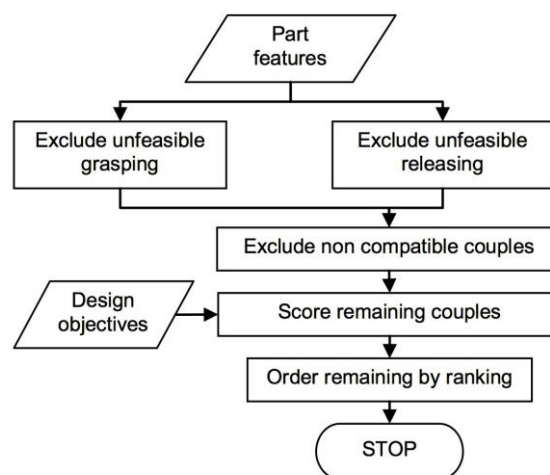
Figure 46 - Multistage model of the selection process [90]

This system is different from the one developed by Festo, the main differences are:

- It is focused on finding the grasping principle and the releasing strategy;

- It works with micro-components;

- It starts from qualitative parameters;

- It takes into consideration many object characteristics;

- The releasing strategy represents a main factor to

Therefore these methods focus on two different phases of the gripper selection: the Festo system chooses the exact gripper once the grasping principle is already defined, while the other methodology is focused for defining the best grasping principle according to the part characteristics.

So, a possible strategy to define the appropriate gripper, could be to articulate the selection into two different steps: the first step focuses on the grasping principle selection, the last step focuses on defining the required gripper characteristics of the specific grasping principle.

3.2 DFA AND DFH

Design for assembly (DFA) analyzes product designs with the aim to improve assembly efficiency and reduce assembly time, efforts and costs. This can be accomplished through different ways and, one of the most valuable, according to DFA techniques of Boothroyd and Dewhurst, is redesigning the product in order to reduce the number of individual parts that must be assembled and then ensure that the remaining parts are designed to be easily manufactured and assembled[9]. An example of DFMA is showed in the following figure.
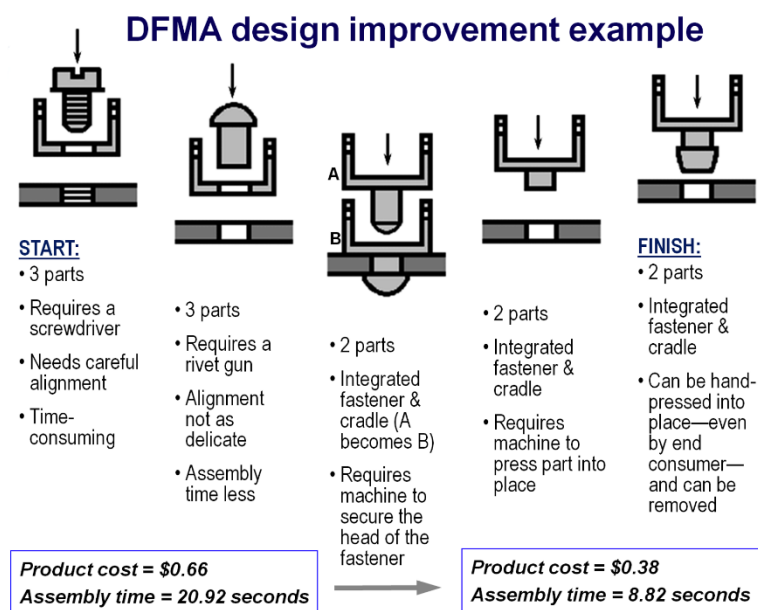
Figura 47 - Design for manual assembly improvement example

Assembly rationalization has to be looked as an optimization of the whole product and production system, emphasizing four main goals [92]:

- Improvement of the effectiveness of assembly: the productivity can be increased in relation to the manpower resources;

- Improvement of product quality: the value from the user can be increased in relation to the product price;

- Improvement of the assembly system profitability: it translates in increased utilization of equipment;

- Improvement of working environment within the assembly system.

In the last years DFA techniques helped much to reduce costs of manufacturing, both for manual and automatic assembly; when the automatic assembly involves the use of robots, and therefore grippers, the product should be designed for being easily manipulated by a robot (DFH – Design for handling).

Design for handling regards all those techniques of design which are focused on making easier the phase of grasping and handling of a work piece through a gripper. A workpiece, in order to be efficiently manipulated from a gripper, should be designed following some rules:

- Build in a way that makes it easier to ensure the grasp: the piece should be designed with features that helps the grasp in relation of the grasping principle utilized (e.g. a large flat surface for vacuum gripper, a hole designed for grasping for expansion grippers etc…);

- The piece should be auto aligned and auto centered easily: if the object, in order to be inserted, has to be oriented in a precise position, it is better if it is designed in a way that avoids unoriented states;

- Avoid object deformation or breaking: for instance, an object should not be too thin and deformable in the surfaces designed for grasping;

The selection of the most suitable assembly method (manual, automatic, robot) is a choice that should be made according to the value of the basic product, the production volume and other company parameters. The evolution of robot grippers, in terms of flexibility and cost reduction, allowed their utilize in contexts with lower volumes and higher work piece variability, other than in context that were not suitable for automatic assembly.

In recent years have been developed software that helps to determine the more efficient way, in terms of costs and time, to assembly and produce the product; this happens through a series of question made to the user and the analysis of the answers received. Furthermore those software give some advice to the user such as how to avoid difficult insertion, aligning, orienting etc…
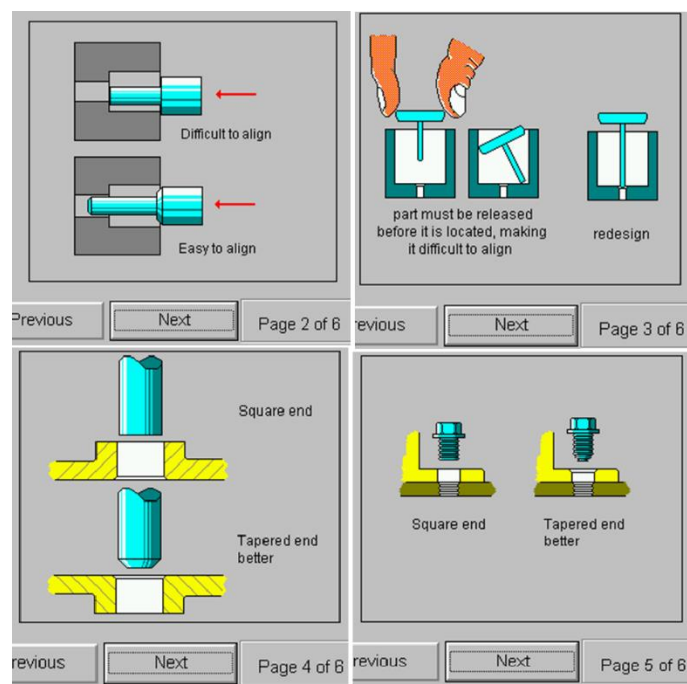
Figure 48 - Examples of DFA advices from Boothroyd and Dewhurs

Those software are usually focused on the quantified evaluation of assemblability in order to facilitate design improvements, this enable designers and engineers to measure the ease or difficulty with which components can be handled and assembled.

From the point of view of this thesis work the procedure of Lucas DFA technique is the most interesting.

DFA procedure – Lucas

The Lucas procedure come from the idea that a knowledge based approach, used together with a CAD system, was a possible step forward.

This technique shares with the Boothroyd and Dewhurst procedure the aim of reducing component numbers, without varying with the kind of assembly method (manual, automatic or robotic).

This method gains the necessary information through questioning the designer about component functions and their relationship with the product specification, the procedure is focused on avoiding crucial errors and providing a better starting-point for the design of assembly process.

The Lucas procedure is an iterative process structured into 7 steps:

- Product specification;
- Design: the questions are focused on establishing if each product is unique, or there are similarities in order to determine if there are the opportunities for standardization of components and assembly procedures;
- Functional analysis: the components of the product are reviewed mainly for their function in order to divide them into two different groups (Group A or B)

Parts belonging to group A are essential to the product's function, while the ones belonging to group B are not essential to the product's function (eg. Fastening, locating etc…). Once that the parts have been divided is possible to estimate the design efficiency:

$$E_d = \frac{A}{A + B} * 100\%$$

Typically, a design efficiency of 60% is targeted for initial designs;

- Feeding analysis: parts are scored from their suitability for automatic feeding, a feeding index is calculated for each part. This is made with the objective to ensure that the design of the individual component is compatible with the method of feeding;

- Gripping analysis: this analysis examines the ease with which each part can be grasped from a robot gripper, an index is calculated to represent the part's suitability;

- Insertion analysis: the user has to generate an assembly sequence flowchart and assign a cost index to every individual process. At this point the objective is to find the processes that are too expensive in relation to their value, and then suggest the necessity for redesign;

- Assessment: here are reported the results of the analysis

The last part is the manufacturing analysis which calculates the manufacturing cost of each component. This cost, even if does not represent the true cost of the part, can help the designers since it influences the choice of material and the process by which the part is made.

This method has also been implemented as an expert system, the software has been made with the aim of supporting, both analyzing the assembly process and making recommendations on eventual redesign of the process or the product. The system, following the procedure discussed above, includes a series of rules which has as input both textual data and drawing representation, and are applied through a decision model which searches through a knowledge base. This software is simple, easy to apply and update since a rule based structures is transparent and does not require any special programming skill to be updated.

3.3 SYSTEM LOGIC

The system logic is briefly displayed in the following figure.
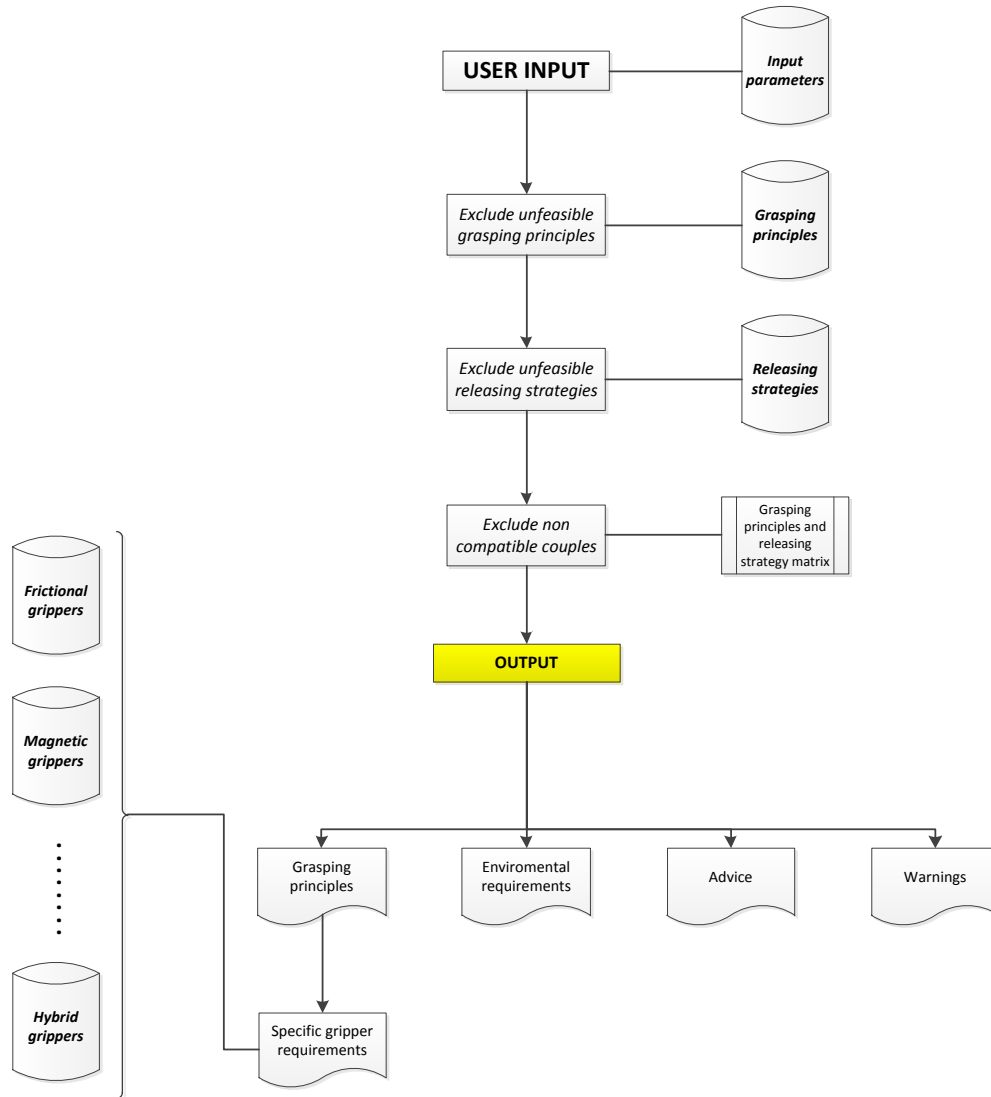
Figure 49 - Expert system logic

The logic of the expert system could be divided in different steps (3. and 4. only for micro objects). The set of rules is responsible to define the exclusion of grasping principles, releasing strategies and incompatible couples.

1. **Input:** the user answers to a series of questions to define the value of a predetermined set of parameters. The possible values of the parameters, with the exception of object size and weight, are predetermined and the user can select from one of those;

2. **Grasping principles exclusions:** the system, relying on a specific set of rules, based on the values of the parameters, excludes the unfeasible grasping principles;

3. **Unfeasible releasing strategies exclusions**: releasing principles that are not compatible with the object and operation characteristics are excluded.

4. **Compatibility check**: as discussed in 2.4 a compatibility check between grasping principles and releasing strategies is necessary. Only matching couples will not be excluded to prevent the use of grasping and releasing techniques that are in conflict with each other;

5. **Output**: the expert system gives as output the grasping principles capable of handling the work piece and a series of eventual warnings, advice and environmental requirements;

6. **Gripper requirements**: for every grasping principle in step 5 the system gives additional information that regards specific gripper requirements. This data could be used to search through specific gripper databases.

3.4 PARAMETERS SELECTION

The parameters selection has been made considering all the aspects involved in grasping and handling operations: feeding, handling, releasing.

The focus is mainly on the object characteristics, since they represents the main aspect and determines how to feed (e.g. thickness or shape), handle (e.g. toughness or roughness) and release (e.g. heat or water sensitivity) a determinate work piece.

Anyway, some parameters are hard to consider in the input phase, and therefore have been relocated as advices in the output (e.g. unbalanced grasp).

Aspects like inserting and aligning have been considerate but not yet implemented into the system logic.

This paragraph describes each parameter and briefly reports, through a table, the question that should be made to the user with the possible values that can be selected.

Part feeding and handling

In general, during assembly, work pieces, in order to be easily grasped, should be fed by an automatic feeder; parts that present particular automatic feeding problems are unlikely to be candidates for automatic grasping. For example, if parts tend to tangle or nest when in bulk, they will need a special-purpose feeding system[4] to be handled [9] or a redesign in order to avoid the problem of tangling or nesting [9]. There can be other problems when dealing with mixed non-rigid mixed objects which are less suitable for automatic feeding, for example thin flexible lines can easily lead to entanglements.

However this system evaluates the implication of not automatic feeding, taking into consideration the most common situations: stacked or tangled work pieces.

However, since it is difficult to give a precise output with just a Boolean variable as input and since this expert system is focused on supporting the decision process that lead to the choice of the appropriate gripper, the system could manage this problem from the opposite perspective, recommending how to feed the work piece in relation to the grasping principle (for instance for frictional grippers the recommended grasping direction will be given, which influences how the work piece should be fed).

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[4] Problems related with object orientation and identification has been solved by the use of vibratory automatic feeders.

Stacked work pieces

The separation of stacked objects, such as leather plies, requires special attention depending on the kind of material that is stacked and its shape, especially in the case of very thin and flexible items this could be a really hard problem to solve[11][12]. And that is not the only case, for example even when grasping stacked thin plate of ferromagnetic material: in this case the efficient use of a magnetic gripper can be much harder.

STACKED WORK PIECES		
	Question	**Possible answer**
1	*Are the work pieces stacked?*	Yes
		No

Tangled work pieces

This is one of the worst scenarios in part feeding and can be managed only by few grippers with precise requirements:

- Orienting: the gripper needs to be able to orient the object, this happens because it may be needed to untangle one work piece from another;

- Sensing: since the objects are in random order the gripper cannot be preconfigured with exact picking coordinates and needs to recognize the object and its orientation through an image sensor. Therefore it needs to be able to recognize when the object is correctly grasped and oriented through the use of force, presence and position sensors;

- Selective grasp of one work piece: for instance a magnetic gripper is not able to grasp just one work piece at time when the objects are really close or stacked.

However, with complex shapes and deep tangling a totally automatic grasp could be very hard to manage.

The system cannot give as output an exact solution, since it only knows that the objects are tangled, but can exclude the grippers that does not fit the requirements described above.

TANGLED WORK PIECES		
Question		**Possible answer**
1	*Are the work pieces tangled?*	Yes
		No

Acceleration

The acceleration imposed on the object directly influences not only the gripping force required making the operation more subject to unexpected object drops, but will enhance the chances to damage the object during the handling; Gjerstad demonstrated how, using a needle gripper, pieces with soft texture require lower acceleration to maintain surface quality[75].

Furthermore grippers based on Bernoulli grasping principle could not operate at medium or high acceleration since inertia forces will make the object slip away from the gripper. The same consequences are true in any other case where the grasping force applied is very close to the minimal necessary to grasp the work piece.

Even jaw grippers, since their grasp is not based on friction but on form-fitting, cannot operate at high accelerations.

Acceleration		
Question		**Possible answer**
1	*Choose the level of acceleration imposed to the work piece*	Low
		Medium
		High

In case of gripper based on friction, the system can apply a corrective factor to the necessary grasping force to hold the workpiece.

Unbalanced grasp

This is a parameters that, combined with others, can be heavy implications and cannot be simply a Boolean parameter, since there are different levels of unbalanced grasp.

Therefore its implications on flexible objects, grasping force required, higher chance of damaging fragile objects, higher difficulty in orientation all together with the difficulty in establish how unbalanced is the grasp with the different grasping principles, led to assume that the grasp is balanced, since is how it should be, and possibly evaluate its consequences separately with the different grasping principles.

Part characteristics

Following are reported the principal characteristics that can describe the object to be grasped from a geometrical and physical point of view. The choice of the parameters that are included into the list of characteristics has been made through the study of the grasping principles, analyzing their compatibility with different objects and situations.

Weight

The weight is the first aspect to consider since grippers have fixed lifting capabilities and are mainly divided by the weight they can sustain or the maximum available grasping force.

WEIGHT	
Question	**Possible answer**
1	*Enter the weight of the object [g]*	Exact weight [g]

This is, together with the object size, one of the few quantitative parameters used into this expert system.

Dimension

The object dimension is defined by its height, width and length; basing on the values entered by the user the object will be inserted in the corresponding category.

The first division aims to split the objects into two big categories for the different implications: in macroscale (>10mm) inertial forces, along with externally applied forces, are considered the dominant factors in developing dynamic models to predict the motion of an object, while in micro scale [10μm ; 10mm] adhesion forces are dominant. This does not affect only the grasp, which in microscale can be made even only through adhesion forces, but mainly the release which cannot be made anymore through gravity as happens in macroscale.

Anyway the dimension is not for sure the only parameter which defines when a grasp is feasible through adhesion forces or a release cannot be made through gravity, the weight, the shape, and the object density comes in handy to define a more reliable method to avoid improper grasping principle selection.

However is important, in order to avoid improper category selection[5], to establish a procedure:

1. The user enters the parameters width, length and height;

2. The greatest dimensional parameter will be discarded;

3. The object belongs to the category which fits the biggest parameter of the two remaining;

Then object greater than 10mm will be tagged as "macro" and object below 10mm as "micro", establishing a threshold and justifying the choice is not an easy task. A part belongs to micro category when the adhesion forces becomes dominating over gravity, as explained better in the next paragraph, but there is not an exact value of dimensional parameter that represents this transition even because there are other factors that concurs such as weight and shape; it would be interesting to establish, with further studies, an effective relation between those parameters in order to define a better threshold.

Micro [10µm ; 10mm]

In assembly dealing with micro-components (components with a size in the range between 10 µm and 10 mm) usually neglected adhesion forces (electrostatic, Van der Waals, surface tension and viscous forces) become dominating [18]. A quantitative comparison [64] of the interaction forces between bodies has demonstrated electrostatic to be the strongest, followed by Capillary forces, van der Waals.

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[5] *for instance lets imagine a long hair, which is surely an object that belongs to the micro category*
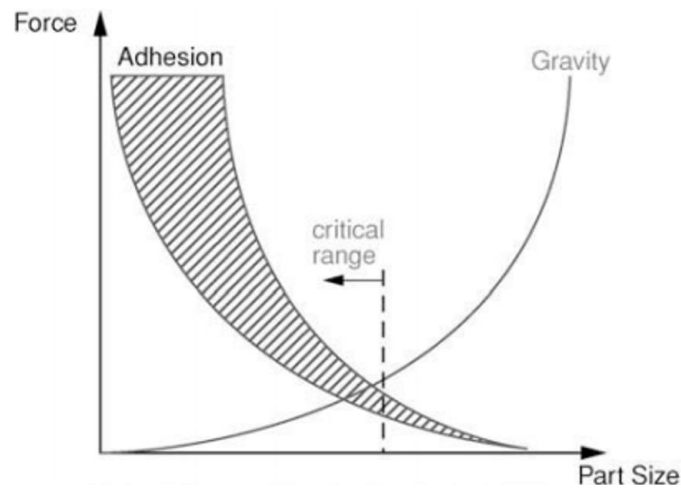
Figure 50 - Significant forces depending on part size [51]

This does not happen in macro manipulation where the main challenge concerns the picking of objects and then the development of sufficiently stiff tools to tackle the effects of gravity and inertial forces. At the micro scale, gravity and inertial forces are not so significant compared to surface forces, and release an object becomes a real challenge due to adhesion between the object and the tool[1].

In literature [34] are discussed four different strategies for threating the surface forces in micro scale.
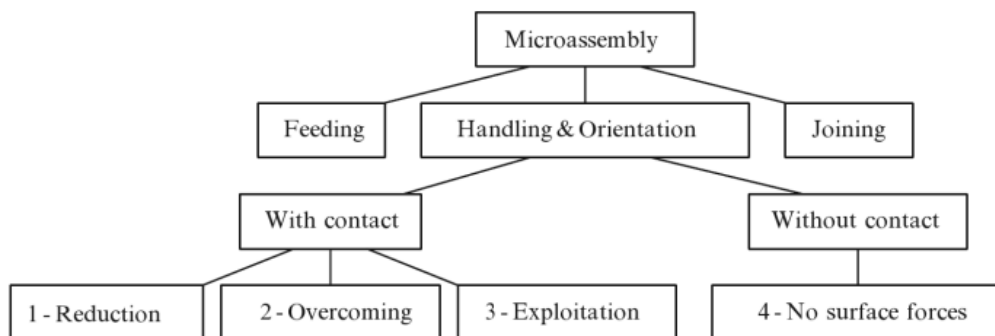
Figure 51 - Four different strategies

The first two strategies (reduction and overcoming) are focused on downscaling the grippers commonly used in macro context and proposing some solutions to overcome

the adhesion forces aspects. The last two solutions are focused on using grippers that are natively designed for micro components handling therefore based on strategies that takes advantage of the adhesion effects or that avoids any contact.

The system has a field of application that does not include the nano (<10μm) and mega (5m) categories because both require specific grasping systems, especially the ones belonging to the mega category that relies on custom systems with an intense use of pulleys.

Mega [>5m]

Dealing with objects which belongs to the mega category means working under particular conditions, involving different parameters both for what regards the context, which is mainly outdoors, and the gripper's structure.

The environment has strong implications on mega objects and gripper, for instance the wind influences a lot the requirements from the gripper sides since it makes the object fluctuate requiring much higher grasping force and structural strength.

From the gripper point of view it happens that most of the grippers are specifically designed for the desired operation and works through pulleys.

So, considered the totally different context and requirements from gripper side, the objects belonging to the mega category have been excluded from the field of application of this expert system.

DIMENSION	
Question	**Possible answer**
1	*Enter the length [mm]*	Exact length [mm]
2	*Enter the height [mm]*	Exact height [mm]
3	*Enter the width [mm]*	Exact width [mm]

Eventually, in future developments, the definition of the dimension could also help to automatically define other highly correlated characteristics such as shape.

Shape

The shape is essential in order to establish the correct grasping principle capable to ensure a safe grasp and release. For example a 2 finger friction gripper excels with prismatic objects while a suction gripper works best with flat surfaces.

The shape also influences the available grasping area for each gripper, and could be considered as corrective factor for the gripping force required.

Therefore the objects have been divided in 3 classes and corresponding subclasses.

- **Bulk**:
    - o Cylinder;
    - o Prism;
    - o Sphere;
- **Flat**:
    - o Circular
    - o Square
    - o Amorphous
- **Line**
    - o Cylindrical section;
    - o Prismatic section;

SHAPE		
Question		**Possible answer**
1	*Define the shape of the work piece by choosing from the list below:*	Bulk
		Flat
		Line
2	*If bulk → define the kind of flat shape by choosing from the list below:*	Cylinder
		Prism
		Sphere
3	*If flat → define the kind of flat shape by choosing from the list below:*	Circular
		Square
		Amorphous
4	*If line → define the kind of linear shape by choosing from the list below:*	Cylindrical section
		Prismatic section

Furthermore, due to the difficulty for the user to understand when the object is line or bulk (cylinder/prism) and in order to avoid improper category selection, the "line" parameter will be set automatically, to the corresponding section, when one dimension is greater than the sum of other two multiplied for 3.

Defining the implications of the shape is not an easy task, the shape has different implications basing on the grasping principle used. Some grippers are capable to manage only certain shapes or are, at least, much more reliable.

Figure 52 reports the object shapes suitability for every grasping principle analyzed and, when available, the corresponding literature reference.

- Green: the grasping principle is reliable with the selected object shape;

- Yellow: the grasping principle does not perform at its best, with the selected object shape, if not specifically designed;

- Red: the grasping principle is not reliable with the selected object shape;

Grasping principle	Bulk			Flat			Line	
	Cylinder	Prism	Sphere	Circular	Square	Amorphous	Cylindrical section	Prismatic section
Frictional 2f								
Frictional 3f								
Frictional jaw[6]	[20]	[20]	[20]	[20]	[20]	[20]	[20]	[20]
Expansion								
Magnetic E								
Magnetic P								
Vacuum	[60]		[60][61][7]	[65]	[65]			
Electrostatic	[66]							
Bernoulli[8]		[67]		[65][68]	[65]			
Van der Waals					[72]			
Needle		[75]						
Capillary	[38]	[38]	[38]					
Acoustic SW			[69]					
Acoustic NF				[70]	[71]			
Ice	[41][76]	[41][76]				[41]		

Figure 52 – grasping principles and object shapes

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[6] *Jaw grippers need to be specifically designed to match the object shape.*

[7] *In macro context it has been developed an octopus gripper with grasping points [60] which works on very regular spherical or cylindrical shapes, when dealing with micro objects a needle or a noozle can sometimes ensure a safe grasp[61], but with troubles in releasing and when dealing with very little diameters due to higher possibilities to damage the work piece.*

[8] *Recent studies demonstrated how a deformable surface have been used to reduce the mean distance between the Bernoulli gripper and the object in order to ensure a grasp of object without flat surfaces available;*

Roughness

The level of roughness of the grasped object surface is an important parameter when dealing with micro objects since it significantly reduces Van der Waals forces [2] due to the reduced contact area.

The roughness of the surface has some implications even with acoustic grippers since it can influence the fluid flow around the part and slightly modify the acoustic field [1] and it is an important factor in defining the correct cups for the vacuum grippers [78].

Furthermore roughness together with the kind of surface treatment, the kind of material used, stickiness (and its opposite, slippery) is one of the main aspects that define the coefficient of friction of the surface of the objects.

In macro world, especially with frictional gripper, this can influence the grasping force needed to ensure an effective grasp.

Anyway in micro components manipulation the significance of roughness, in accurate evaluation of surface forces, is still very discussed and its importance repeatedly mentioned in the open literature where it is stressed that more research is needed towards the development of analytical models [17][18].

Roughness		
Question		**Possible answer**
1	*Define the level of roughness of the object surface*	Very low
		Low
		Medium
		High
		Very high

Hydrophobicity

Especially when dealing with micro components the hydrophobicity can have significant implications both in the available grasping principle [52], enabling the application of a grasping principle which could not have been applied otherwise, and in the available releasing strategies [33] since it could both lead to release problems due to too high surface forces or help the release by diminishing the grasping force.

When the object surface its hydrophobic this decreases the surface tension forces[9]; decreasing the tension force (capillary force) can also be performed using a dry atmosphere or adding hydrophobic coating [2][79]. Other ways to decrease such forces are: decreasing the contact area, increasing the roughness.

In such cases surface tension effects can be reduced with hydrophobic coatings, electrostatic forces can be reduced by using conductive materials or Van Der Waals forces can be neglected by increasing the roughness profile **Errore. L'origine riferimento non è stata trovata.**.

Hydrophobicity		
Question		**Possible answer**
1	*Define if the object surface is hydrophobic*	Y
		N

---

[9] *is a property of the surface of a liquid that causes it to behave as an elastic sheet allowing small insects, such as the water strider, to walk on water or small objects, even metal ones, to float on the surface of water, and it is the cause of capillary action. Substantially is the force used by capillary grippers to grasp micro objects [53] with mass of few grams, depending on the available contact area.*

Slippery

Slippery of the object surface, having low friction, often due to being covered in a non-viscous liquid, and therefore may be hard to grip depending on the grasping principle selected. Grippers based on friction have more difficulty than others, and can compensate the slippery of the object surface applying more grasping force, but this is feasible when the gripper has enough grasping forces and when the object is capable to sustain it without being damaged and/or scratched. Its importance is also increased in operations in which the load force of the grasped object varies.

SLIPPERY		
Question		**Possible answer**
1	*Define the level of slippery of the object*	Very Low
		Low
		Medium
		High
		Very high

Stickiness

If the work piece has an high level of stickiness a gripper with an additional releasing system may be required, especially when dealing with grippers in macro category where the adhesion forces are negligible and in most cases the standard releasing system is based on gravity.

On the other hand the stickiness may also come in help in some cases, for instance when dealing with a fragile object, if it has an high level of stickiness a frictional gripper will be able to ensure a grasp with less gripping force reducing the chances to damage the work piece.

Furthermore an object can be considered sticky in relation with the environment or the kind of operation the work piece is subject (eg. Inserting a ferromagnetic piece close to a magnet), but that kind stickiness is evaluated into the environmental parameters.

STICKINESS		
Question		**Possible answer**
1	*Define the level of stickiness of the object*	Very low
		Low
		Medium
		High
		Very high

Toughness

The toughness of an object is related to its compressive strength and its impact resistance so it influences the maximum grasping force that can be applied on a specific area of the object especially when using frictional grippers.

Since the user cannot know exactly the value of the toughness and since the toughness is highly correlated with the kind of material of the object, five levels of toughness have been defined:

TOUGHNESS		
Question		**Possible answer**
1	*Choose the level of toughness, in terms of impact and compression resistance*	Very low
		Low
		Medium
		High
		Very high

Naturally contactless grippers are much better in managing fragile objects but in literature we can find various examples that shows frictional grippers that, even if their

grasp is strongly based on contact, when specifically designed can handle very fragile objects like food[80][16].

Stiffness

Stiffness can be described as the capability of the grasped object of sustaining loads without too large deformations (known as "compliant displacements"). The deformation induced during a grasp can lead to transportation problems, damages on the work piece or placing difficulties.

Highly flexible materials (also called Non Rigid Materials "NRMs") have additional problems compared to rigid materials since they can deform significantly during handling and the system needs to manage these deformations which are mainly produced by the material's own weight and the dynamic and gripping forces during handling. A large percentage of flexible materials in manufacturing are flat like cloth, leather, food, biomedical materials etc…

This is why the handling of NRMs [12] implies high requirements for grasping and holding. Force fit, form fit, and material bond are basic principles that can be applied to attach work pieces to gripper surfaces:

- Force fit connections are realized by many grasping principles such as friction, magnetic, vacuum, electrostatic. Friction and jaw grippers ensure sufficient holding forces but might damage the surface. Suction grippers are restricted to airtight and low porosity materials. Magnetic grippers requires a ferromagnetic materials and electrostatic grippers can work only with low weights. Furthermore, when large and flexible materials are involved, multiple attachment points help to avoid deformations during the manipulation;

- Grippers based on form fit are needle and jaw grippers. Needle grippers puncture the work piece and can be adapted to different material properties. Jaw grippers can grasp the object with specifically designed fingers which matches the object shape. While jaw grippers can ensure a grasp without damaging the object, needle grippers can damage the surface of the material and are therefore limited to non-critical operations.

- Grippers based on material bond exploit molecular attraction by using active means and need an active release system. Adhesive tape grippers have the particular disadvantage that fibers and active means can be torn away while detaching the connection and therefore leave a bond remaining on the surface. An ice gripper has been developed that freezes water as active means for material bond. For attaching a non-rigid part, hydro adhesive grippers spray a little amount of water on the work piece surface. The gripper is equipped with a Peltier-Element that freezes the water immediately and builds up the attachment. After the handling operations, the work piece can be released with air pressure that warms up the ice and dries the piece back to initial state. Freezing grippers provide high holding forces without exerting additional stress to the work piece but requires a good wettable and not too glossy surface for a reliable gripping.

Furthermore recent studies [13] show a new way to grasp flexible and stacked work pieces, such as leather plies, with Bernoulli grippers without damaging or imprinting the surface.

Gripper based on vacuum or friction can increase their capability of handling fragile objects with multiple attachment points [81] achieved respectively with multiple couple of fingers or a larger number of cups.

STIFFNESS		Possible answer
		Very low
		Low
1	*Define the level of stiffness*	Medium
		High
		Very high

Object shape can change

During the first tests of the expert system another question regarding the stiffness came out: what happens when an object is very flexible and, when grasped, changes its shape? Is this always acceptable? It depends. A flexible object can change its shape without any consequences, but some may not; a large piece of fish fillet, which is very flexible and fragile at the same time, could be permanently damaged if its shape is changed during the handling or the grasp.

The need of another parameter does not come only from the fact that an object which is at the same time fragile and flexible can sometimes accept to change its shape (e.g. a sheet of paper), but even for handling requirements: an object could not change its shape because it may bump against an obstacle or tangle.

OBJECT SHAPE CAN CHANGE		Possible answer
1	*Can the object change its shape without incurring in any permanent damage during the handling operation?*	Yes
		No

Porosity

According to the grasping principle utilized, the porosity of the grasped object could be a critical factor, for example vacuum and Bernoulli grippers can only efficiently grasp object with very low porosity, can still grasp object with medium porosity but will require a lot more energy to hold the object, and a failure in the power source will almost immediately release the work piece.

The porosity affects even the grippers based on the capillary principle diminishing the surface tension effects and absorbing the water used as interface between the surfaces.

POROSITY		
	Question	**Possible answer**
1	*Define the level of porosity of the object*	Very low
		Low
		Medium
		High
		Very high

Sensitivity to stain

Some objects can be more or less sensible to stain and in some cases, such as food, clothing etc. it could be a significant issue.

For instance, since a capillary gripper works with liquid, it could smear the surface of the grasped object, the same happens for ice grippers.

The user does not define just if the object is sensible to stain or not, but if an eventual spot on the grasped object has to be considered an issue or not, this is done to avoid considering the staining an issue when it is not.

SENSITIVITY TO STAIN	
Question	**Possible answer**
1 *Is the object sensible to stain? And if yes, it has to be considered an issue?*	Yes
	No

Sensitivity to charge

A work piece can be sensible to charge, it happens, for example, in electronic field where some components can be damaged if subject to charge.

Since electrostatic grippers induce charges into the grasped object, the grippers based on that grasping principle will be excluded.

The sensitivity to charge not only affects the grasp, but even the release [33].

SENSITIVITY TO CHARGE	
Question	**Possible answer**
1 *Is the object sensible to charge?*	Yes
	No

Sensitivity to scratches and bruises

While grasping an object some grippers may scratch or bruise it, for example food products [16] can be easily bruised, making them difficult to handle for a common gripper. Another example may be a fragile glass plate, grasped with a vacuum gripper, which can be scratched if the grasp is not made in a dust-free environment.

There are many way to avoid such effect, depending on the other characteristics of the object. In the following table are resumed the implications, in terms of damage types, of different grasping principles in the grasping process of food and vegetables.

Strategy	Method		Damage type			
			Bruise	Tear	Break	Deformation
Air	Vacuum	Suction cups	Low	Low	Low	Low
		Pipes	Yes	Yes	Low	Low
	Pressure	Bernoulli	No	Yes	Low	Low
		Blow	No	No	Low	No
Contact	Gripper	Electric	Low	Low	Low	Low
		Pneumatic	Low	Low	Low	Low
		Hydraulic	Yes	Low	Yes	Yes
		Rubber	No	Low	No	Low
		Robot hands	Low	Low	No	No
	Multibody mechanism		Low	Low	No	Low
Ingressive	Needles		Yes	No	Yes	No
Fluid	Rheological change		Low	Low	No	Yes
Product properties	Gravity		Yes	Low	Yes	Yes
	Piling up, pushing		Yes	Low	Low	Yes
	Dynamic		Yes	Low	Yes	Yes
	Scooping up		Low	Yes	No	No
	Vibration		Yes	Yes	No	No

Figura 4- Damage types and grasping principles [9]

SENSITIVITY TO SCRATCHES AND BRUISES		
Question		**Possible answer**
1	*Is the object sensible to scratches or bruises?*	Yes
		No

Sensitivity to dust

Some operations, for instance the assembly process of microelectronic components, need to be dust-free.

The need of a dust-free environment does not come only from the object's sensitivity, but it is also a requirement for making available the grasping with an electrostatic gripper, since dust can dramatically reduce its performance both in the grasping and in the releasing phase[33].

Especially in micro manufacturing dust is recognized to be a factor that modifies adhesion forces and friction [2] and also dust particles may stick to the water droplet of capillary grippers [38].

SENSITIVITY TO DUST		
	Question	**Possible answer**
1	*Is the object sensible to dust?*	Yes
		No

Sensitivity to water

In some cases the use of water could represent an issue as it could damage the grasped object, since water damage describes a large number of possible losses caused by water intruding where it will enable attack of a material or system by destructive processes such as rotting of wood, growth, rusting of steel, de-laminating of materials such as plywood and many others. Water could also be responsible of staining the work piece.

Therefore grasping principles which uses water, if the work piece is sensible to water damage, have to be excluded.

Water is often used in object manipulation, for instance in the contactless manipulation of NRMs discussed before or in the manipulation of micro components in microelectronics, where it could be used water or ice to obtain the necessary grasping force.

SENSITIVITY TO WATER		
	Question	**Possible answer**
1	*Is the object sensible to water damages?*	Yes
		No

Sensitivity to liquid

Some objects, especially the ones belonging to micro category, may be sensible to any kind of liquid and not only to water.

For instance some operations can take place in oil, and electronic components are usually sensible to water and not to oil. This is just an example and, if more information will be found, maybe this parameter will be updated and will not be considered anymore a Y/N parameter but will include different liquid sensitivity.

Therefore the sensitivity to liquid in general has to be evaluated, when an object is sensitive to liquid it will be automatically sensitive to water, but the opposite, as shown before, is not always true.

LIQUID SENSITIVITY		
	Question	**Possible answer**
1	*Is the object sensible to liquid?*	Yes
		No

Magnetic sensitivity

Some objects may be sensible to magnetic forces, therefore grasping principle based on magnetic forces must be excluded.

For instance a magnetic field can damage an object that contains magnetic moving parts, or it could erase the content of a magnetic media (hard disk, memory cards etc…).

MAGNETIC SENSITIVITY		
	Question	**Possible answer**
1	*Is the object sensible to magnetic fields?*	Yes
		No

Heat sensitivity

When grasping with ice or capillary grippers one of the possible releasing strategies [33] is based on the use of a micro heater which, in case of capillary gripper, reduces the moisture-liquid (so surface tension or capillary forces) [2] or, in case of ice gripper, Melts the ice [77][82].

This parameter is not considered only in micro context because with macro objects there is evidence of thermal grippers (rename ice grippers into something like liquid-solid transition grippers since they are not only based on ice) where the work piece can be heated up taking advantage of the melted surface to ensure the grasp, this happens for instance with a chocolate candy.

Eventually, in very particular context, the heat sensitivity could be seen from the gripper point of view; for instance a gripper that works in a hazardous environment.

HEAT SENSITIVITY		
Question		**Possible answer**
1	*Is the object sensible to heat?*	Yes
		No

Hygienic requirements

Some objects, especially the one belonging to the food category, have to meet high hygienic standards, this has to be evaluated in a separate parameter because it does not derive directly from other object characteristics and this is not even just a prerogative of food, because food industry is not the only contest with high hygienic requirements, hygienic process planning also play an essential part in the pharmaceutical industry.

A plethora of standards and regulations dictates practically all aspects in the hygienically safe production of food, pharmaceuticals and medical supplies. In this case, DIN EN 1672-2 plays a key role in food machines. According to the specifications outlined therein, producers must provide proof of the proper design of their systems and components and also carry out a documented risk analysis during the process. Special attention is given to the standard for designing systems, machines and their components: surfaces must be corrosion-resistant, non-toxic, and easy to clean. The materials or coatings used must not contaminate the food nor transfer any undesired odors, colors or tastes. Gaps, cracks, and other dead spaces where residues from food or cleaning products can accumulate are not permitted. Connecting elements such as screws or rivets should be avoided or must be easy to clean. If possible, bearings and shaft exits must be outside the areas for processing food and must be greased with lubricants that are safe for use with foods [84].

There are many kind of grippers that, when specifically designed, can meet hygienic requirements, such as:

- Bernoulli gripper [14][15] and contactless grippers in general;

- Magnetic gripper [16];

- Vacuum gripper[82];

- Friction and jaw grippers[80];

Hygienic grippers could be so required in food industry but even in other sectors like pharmacological.

Part features and physical properties

Part properties: conductivity

The conductivity of the work piece is important when dealing with electrostatic grippers where, due to the electrostatic induction, homogeneous fields are sufficient to generate an electrostatic gripping force in the case that conducting materials have to be handled. Whereas inhomogeneous fields are needed for handling insulating materials, those inhomogeneous fields offers the gripper self-centering capabilities [54]. Anyway, recent studies [21] demonstrated how the self-centering is also possible independently from the kind of material and its properties.

So, while the grasping works in both cases, even without different implications, problems arises in the releasing task; As shown in the work of Fantoni and Porta [33] the active releasing strategy, which follows the principle of electrostatic force control, points out some problems in releasing conductive components[21].

CONDUCTIVITY		
Question		**Possible answer**
1	*Is the object conductive?*	Yes
		No

Part properties: ferromagnetic

An object, in order to be attracted from a magnet, has to be ferromagnetic; ferromagnetism is the most significant kind of magnetism discussed in physic as it is the only type that creates enough forces to ensure a safe grasp using a magnetic gripper.

This represent the fundamental necessary condition to be eligible for magnetic gripper grasping, but not the only one since the objects has to be both ferromagnetic and not sensible to magnetic fields.

FERROMAGNETIC		
	Question	**Possible answer**
1	*Is the object ferromagnetic?*	Yes
		No

Part properties: hole for grasping

A part could be designed with an hole that could be used to achieve the grasp by frictional, with an internal grasp, or expansion grippers, which need a hole of a specific diameter in order to grasp the work piece.

The user, if he entered that the work piece has an hole for grasping, will be asked to define the specific diameter which is necessary to establish the specific expansion gripper.

PRESENCE OF HOLES		
	Question	Possible answer
1	*Does the object have any holes that are available for grasping?*	Yes
		No
2	*If yes, enter the diameter and height of the holes*	

Part properties: planar surface available for grasping

The presence of at least one planar surface available for grasping is a must have for gripper based on Bernoulli, Vacuum, and Van der Waals and in general for grippers that have their grasping force proportional to the contact area.

The presence of two opposite surfaces available for grasping is a necessary requirement for frictional gripper but, when the user defines that a work piece does not have at least two opposite surface available for grasping? Usually when the object is really fragile, or sensible to scratches, to dust, to stain etc... all of these characteristics have already been evaluated in separate parameters and adding this one could lead to mistakes.

PLANAR SURFACE AVAILABLE FOR GRASPING		
	Question	Possible answer
1	*Does the object have at least one planar surface available for grasping?*	Yes
		No

Part properties: regular curved surface available for grasping

A gripper that requires a flat surface could be even specifically designed to handle regular curved surfaces [60], therefore this is a parameter that have to be evaluated especially in macro context where it is possible to specifically design a gripper to match object shapes.

REGULAR CURVED SURFACE AVAILABLE FOR GRASPING		
	Question	**Possible answer**
1	*Does the object have at least one regular curved surface available for grasping?*	Yes
		No

Part properties: presence of holes

The presence of holes on object surface represents a major issues with grippers that need an available planar surface for grasping such as vacuum or Bernoulli which loses much grasping power and requires much more energy to hold the grasp, or Capillary, Electrostatics and Van der Waals which loses a significant part of contact area.

To establish the consequences of the presence of holes a Boolean parameter is not sufficient, it is needed to know the % of grasping surface that is represented by holes.

PRESENCE OF HOLES		
	Question	**Possible answer**
1	*Does the object have holes on the grasping surface? If yes, please select the level of this parameter from the list below.*	/ = no holes
		M = less than 20% of the surface
		H = between 20% and 40%
		VH = more than 40%

Part properties: wet

Grasping wet objects have implications both on the grasping phase, because some grasping principles, like Van der Waals, capillary or electrostatics, are not working properly, on the manipulation, because the object is slicker due to its wetness, and on the release.

Furthermore, an object which is both wet and has hygienic requirements, is more subject to contamination.

WET		
Question		**Possible answer**
1	*Is the object wet or dry?*	Wet
		Dry

Part positioning

In this category are located all the aspects related to releasing and positioning of the grasped object. A gripper could be able to grasp an object and execute a correct pick and place operation, but it may not have the necessary orientation capacity, or the necessary precision of positioning.

All the parameters linked with positioning (inserting, aligning, orienting) are strongly linked not only to a specific grasping principle, but with the specific gripper and even with the robot that manages the gripper, some examples are given in the description of the specific parameters.

If the operation is a basic pick and place, and has no specific precision requirements, a preliminary question is necessary to avoid pointless questions to the user.

PART POSITIONING		
	Question	Possible answer
1	*Is the object subject to operation that requires high precision, insertion or part orienting?*	Yes
		No

Symmetry

The importance of the symmetry of an object in part handling is a subject already highly discussed in DFA theories as it has implications in inserting and aligning and generally manipulating an object.

Boothroyd and D. showed the importance of alpha and beta symmetry in assembly, but it is also very significant in grasping.
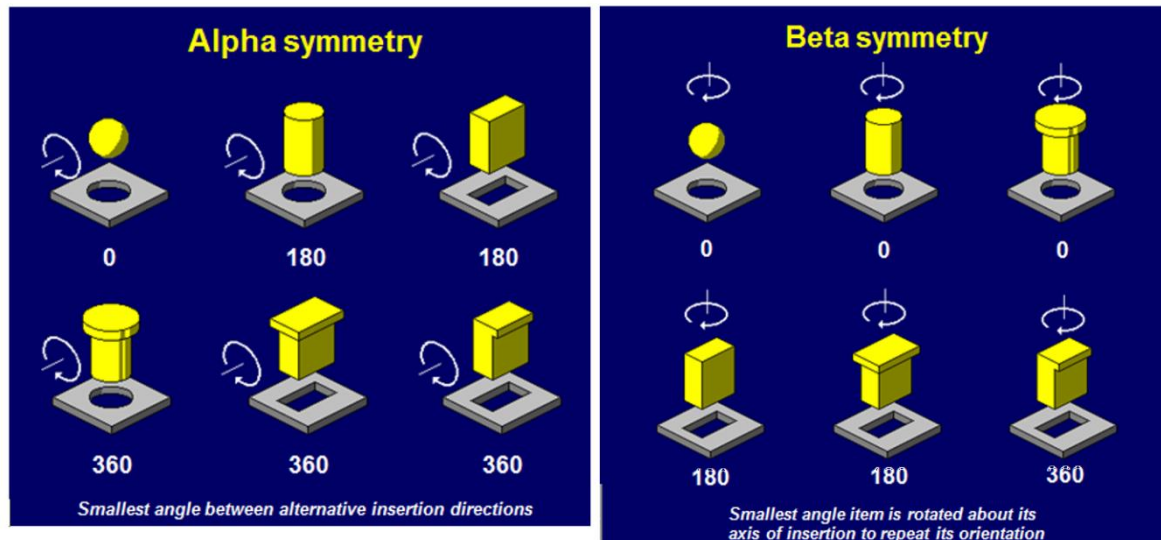
Figura 5 - Alpha and Beta symmetry

Alpha and Beta symmetry defines the level of symmetry of an object, the higher is this level the easier it will be to manipulate and place or insert it. This means that for an object with high symmetry it will probably be required a less dexterous gripper.

The user, with the help of the images above, will be asked to define the level of symmetry of the object.

Orienting

Orientation, following the Boothroyd and Dewhurst method, is classified with respect to rotational symmetry of a part about the axis perpendicular to the axis of insertion denoted by α-symmetry and about the axis of insertion denoted by β-symmetry.

In general, close part orientation tolerances in a gripping system can be accomplished into two ways [8]:

- The first method requires that the part is in its fully oriented state to the gripper, which means that during and after the grasp, there is no relative motion of the part in the gripper. This is the easiest method but any errors in initial

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orientation will remain, and still be present when the part reaches its destination.

- A second methodology consists in presenting the part to the gripper in a loosely oriented state, and using the grasping process to bring the part to its final state of orientation. This method is a sort of self-alignment, the part being grasped experiences relative motion during the grasping process, and the relative motion experienced moves the part in a manner such that the errors in part orientation are minimized to an acceptable level. This method requires the part to be grasped to contain at least one reference feature, by which the part will be oriented relative to the gripper. For example, in order to grasp the bolt in Figure , the side of the wrenching feature (reference feature) can be oriented against the side of a gripping jaw.

Furthermore this methodology narrows the range of available grippers only to those capable of orienting the part.
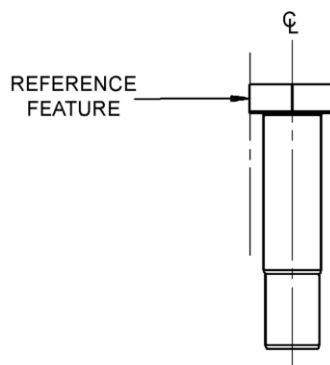
Figure 54 – Example of reference feature

Furthermore there are even solution, composed by a specifically designed gripper, and a dedicated vision system, that are able to orient even workpieces without reference features.

The level of symmetry of an object, together with other characteristics such as orienting, slippery, stickiness and shape, in relation to the specific grasping principle used, could be used to define the orienting difficulty index.

ORIENTING			
Question		**Possible answer**	**Corresponding value**
1	*Is the object already in its final orientation?*	Yes	
		No	
2	*(if 1. = no) the object has a reference feature?*		

Aligning

Parts should be designed to easily mate with the surface but, in case it is required that the gripper has to align an object with high precision, this could be a more or less complex operation depending mostly on the required precision.

In general, automated positioning at the macro scale is threated using conventional closed loop control and the needed sensors in relation to the kind of operation. In such context the main challenge concerns the picking of objects and the subsequent development of tools that are stiff enough to resist the effects of gravity and inertial forces. However, automated positioning at a micro scale becomes a difficult problem. When the size of the components decreases, handling becomes the bottleneck in the fabrication process and the most expensive task, owing to automation difficulties. This is especially true for very small components that require very restricted positioning tolerances.

Furthermore, since the gripper is the end effector of a robot, the gripper precision is strongly linked with the robot arm precision. In order to avoid such conflict a warning will be sent to the user who is required to check the level of accuracy of the robot.

In order to establish the required gripper positioning precision the user is required to answer to two questions:

ORIENTING		
Question		**Possible answer**
1	*The object has to be aligned with high precision?*	Yes
		No
2	*(if 1. = yes) please enter the required precision [mm]*	...

Inserting

A gripper, in order to insert a work piece, should be equipped with a force sensor, since monitoring the force acting on the work piece helps the insertion process and avoids damages, and should be designed with enough degrees of freedom.

Furthermore the insertion is a task which relies on many other factors, a gripper could be able to manage an insertion but, low light or shadows can alter the assembly scene preventing the automatic detection, through a vision system, of relevant features [99]. Another aspect that influences the insertion is the aligning, if the gripper or the robot are not capable to align with sufficient precision then the insertion will not be possible too.

Sensing

The state of the grasp in its initial phase, including even the recognition and selection of the object, and the effectiveness of the grasp during the manipulation can be monitored with the use of specific sensors.

The figure below summarizes into three different categories the principal sensing principles.
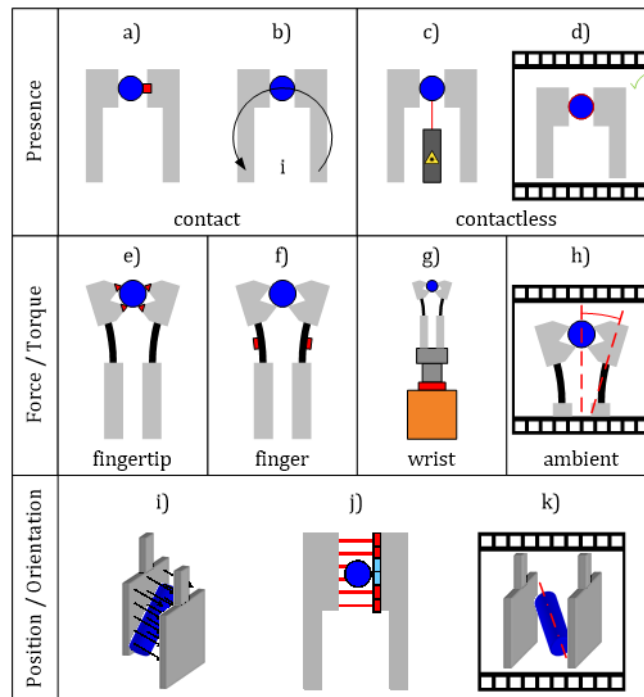
Figure 55 - Sensing principles: a) Mechanical switch; b) electrical sensor; c) photoelectric sensor; d) vision based; e) tactile sensor; f) strain gauges; g) force/torque sensor; h) vision based; i) capacitive or electrostatic; l) led-photodiode (often IR); m) vision based monitoring. [50]

Since those sensor are generally directly integrated in the device, obtaining accurate sensor information is more difficult at a micro-scale as sensors can be too large to be placed in a tiny environment. The main sensors used at a micro-scale are displacement, vision and force sensors because motion control, visual serving and force control strategies are often needed in micro domain. Furthermore these sensors have to be

extremely sensitive, compared to the ones used in macro manipulation, as the forces and displacements involved are much smaller.

The need of a sensor is not asked to the user at this moment, since there is not still a detailed gripper database to search through, but the system will sent an advice or a warning when a specific kind of sensing is or could be required.

Force/torque

In some cases it may the need of an accurate gripping force monitoring during all the operation is very important. This could be useful for different purposes, for example for a correct increasing of the grasping force during operations with variable speeds, or to guarantee that a determinate threshold, in handling fragile objects such as food [9] or micro components, is not passed. The force sensors are also utilized when there is the necessity to control the grasping position or for force adaptive trajectory generation
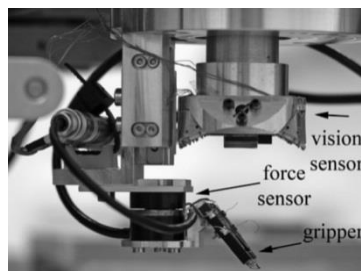
Figura 56 - Microgripper with a force sensor attached to the wrist [94]

A force sensor enhances the capabilities of a gripper, since it makes it more reliable during handling and works even as presence sensor.

Force sensors can be mainly divided by their physical measuring technique and by their mounting position at the handling device. Figure shows four different levels at which the sensor could be positioned.

Position/orientation

Monitoring the position and the orientation of the work piece not only increases the precision and reliability in positioning, but also allows the grasp of objects in non-oriented state; This is very important in micro assembly where the exact positioning and orienting of objects on a tray or within a feeder system is a very complex task [50].

Vision systems does not only rely on their hardware but, if object recognition both in shape and orienting is required, on a software of image recognition, proper illumination and proper gripper designs that allows to see-through both during grasping and handling.

In literature is possible to find a very accurate 3D vision sensor, developed together with a micro gripper, which enable a parallel robot to perform assembly tasks with relative positioning accuracies below 1 μm [97].

Anyway position/orientation monitoring can be achieved even with the use of a laser sensor and a micro mirror, as demonstrated by Reinhart and Zeilinger [98].

Presence

Presence sensors are divided into two categories: contact and contactless presence sensors.
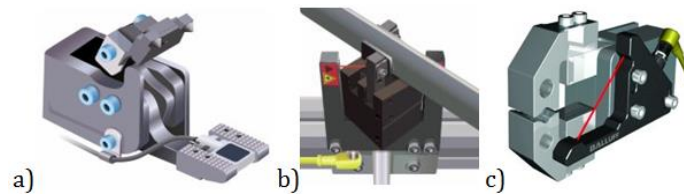
Figura 57 - Contactless presence sensors; a) flat-pack inductive proximity sensor; b) U-shaped photoelectric sensor; c) L-shaped photoelectric sensor[50][96]

Contact presence sensor

A contact presence sensor has the aim to establish when the gripper is effectively holding or just touching the work piece, it can be seen as a force sensor with less features since it does not need to establish how much force is involved in the grasp, but can act as a Boolean ON/OFF sensor: if force = 0 → OFF, if force > 0 → ON. The presence could also be detected with electrical sensor, which analyzes the electrical signal and with a proper threshold can distinguish if the work piece is present or not, this requires the material to be conductive.

Then it could be integrated in the gripper with less effort since it is cheaper and smaller than a force sensor.

Contactless presence sensor

The presence detection could also be achieved without contact and trough different kind of sensors.

The cheaper and easier way to detect the presence imply the use of Hall sensors, proximity switches or photoelectric sensors [50]. Even if is the cheaper way is still very

reliable, but has less feature compared to the previously discussed vision system which allows full presence, orientation and position detection both in grasping and in releasing.

The main advantage of this kind of presence sensor is that they can be positioned away from the contact region and then there are less constraints on their dimensions.

Environment

Some grasping principles are working only when the environment, where the operation takes place, meets certain demands, so the environment puts constraints on the selection of the grasping principle (e.g. electrostatic grippers works properly only in dust free environment). Micro components handling may for instance take place in clean (dust-free) environments, in dry environments, immersed in a fluid, or in a vacuum.

The implications of working in a particular environment, especially when dealing with micro components, can be very significant; for instance liquid environment influences many factors such as the needed gripping force, which will be obviously less, the absence of dust and the absence of electrostatic and surface tension effects[52].

Anyway, the system approach is overturned: the system will list the user eventual environmental constraints, such as the previously cited example of micro operation in a dust free environment, or hygienic environment when the operations involves products which needs to meet strict hygienic requirements, and so on.

In future developments could be evaluated even the effects of special environment, or rather an environment which deeply influences the grasping, releasing and handling process.

An example of special environment is the liquid environment which is briefly discussed below.

Liquid environment

Working underwater is a very particular condition, and a gripper has to be specifically designed to efficiently operate in such context.

Then, in order to ensure an efficient grasp in underwater environment two conditions need to be verified:

- The grasping principle should not be based on surface tension effects or electrostatic force since liquid environment reduces both [33];
- The gripper needs to be specifically designed;

Operation in such environment has important implication since it needs much less grasping force, compared with classic environment, thanks to the higher density of the fluid.
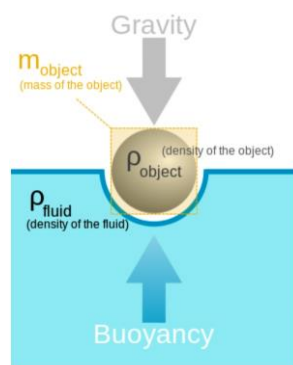
Figure 58 - The forces at work in buoyancy (http://en.wikipedia.org/wiki/Buoyancy)

Correlation between characteristics

Analyzing the correlation between characteristics has been made for the following reasons:

- Avoid contradictions: analyzing the relations helps to find and then to fix possible contradictions between characteristics;

- Avoid redundancy: if a characteristic has a strong relation with another a deeper analysis could reveal that one parameter is worthless and this, if not properly fixed, could be a relevant issue since it does not just increase the number of questions, but may also lead to mistakes in the gripper selection;

- Help to establish the correct order: since the value of a parameter could imply the value of another, the principal parameter should come first;

The following table summarizes the relations between the input parameters.

	Stacked objects	Tangled	Acceleration	Weight	Dimension	Density	Roughness	Hydrophobicity	Shape	Slippery	Stickiness	Porosity	Toughness	Stiffness	Object shape can change	Sensitivity to stain	Sensitivity to charge	Sensitivity to scratches and	Sensitivity to dust	Magnetic sensitivity	Heat sensitivity	Sensitivity to liquid	Sensitivity to water	Conductivity	Ferromagnetic	wet	holes on grasping surface	Hole for grasping	Planar surface available for	Regoular curved surface available	Hygienic requirements	Insertion	Simmetry	Aligning
Stacked objects																																		
Tangled																																		
Acceleration																																		
Weight																																		
Dimension		+		+																														
Density				++	++																													
Roughness		+																																
Hydrophobicity																																		
Shape					+																													
Slippery		-					--																											
Stickiness		+								--																								
Porosity						--	++		-																									
Toughness				+	+				+																									
Stiffness					+	+			+				+																					
Object shape can change		+			+				+				++	++																				
Sensitivity to stain																																		
Sensitivity to charge																																		
Sensitivity to scratches and bruises													+																					
Sensitivity to dust																																		
Magnetic sensitivity																																		
Heat sensitivity																																		
Sensitivity to liquid																+																		

Sensitivity to water							-					+					++	▓										
Conductivity													+					+	▓									
Ferromagnetic								+								+				▓								
wet			+				++										--				▓							
holes on grasping surface			-		-			++	-	-												▓						
Hole for grasping							++																▓					
Planar surface available for grasping							-										--							▓				
Regoular curved surface available for g.						++																			▓			
Hygienic requirements										++		++	++			+										▓		
Insertion					+				-																		▓	
Simmetry	++				+																				+			▓
Aligning																												▓

Every box that has strong positive (++) or negative (--) relation will be analyzed and, when necessary, a rule will be made.

- **Roughness and slippery**: high roughness excludes more than medium slippery, but this parameter cannot be excluded or unified with slippery since has implications in micro objects grasping and release.

  *If roughness ≥ H **then** slippery cannot be set lower than M*

- **Density and weight/dimension**: density is directly determined from weight and dimension, this is why it is highly correlated. No corrective actions are needed;

- **Density and porosity**: porosity and density are correlated negatively, this means that an object cannot have both high density and high porosity, since density is determined from two parameter that are asked for first;

  *If density = H **then** porosity cannot be set higher than M*

- **Porosity and roughness**: high porosity implies a minimum level of surface roughness.

  *If porosity ≥ H **then** roughness cannot be set lower than L*

- **Slippery and stickiness**: are two opposite parameters, an object cannot be sticky and slippery at the same time, but can have both the parameters set to low, this is why it is not possible to unify those into one parameter.

  *If slippery ≥ M **then** stickiness cannot be set higher than L*

  This happens when the part isn't ferromagnetic since, in particular contexts, it could be sticky and slippery at the same time.

  *If stickiness ≥ M **then** slippery cannot be set higher than L*

- **Hygienic requirements and sensitivity to stain**: if an object has to comply with hygienic requirements it will also be automatically sensitive to stain;

  *If hygienic requirements = T **then** set sensitivity to stain = T*

  Order: Hygienic requirements will be asked before than sensitivity to stain

- **Hygienic requirements and sensitivity to dust**: if an object has to comply with hygienic requirements it will also be automatically sensitive to dust;

  *If hygienic requirements = T **then** set sensitivity to dust = T*

  Order: Hygienic requirements will be asked before than sensitivity to stain

- **Sensitivity to liquid and sensitivity to water**: since water is a liquid, sensitivity to liquid imply sensitivity to water;

  *If sensitivity to liquid = T **then** set sensitivity to water= T*

  Order: Sensitivity to liquid will be asked before than sensitivity to water

- **Wet and slippery**: when a surface is wet its coefficient of friction cannot be high, this means that the object is somewhat slippery;

  *If wet = T **then** slippery cannot be set lower than M*

- **Wet and sensitivity to water**: a wet object cannot be sensible to water;

  *If wet = T **then** set sensitivity to water = F*

  Order: Wet will be asked before than sensitivity to water

- **Holes on grasping surfaces and porosity**: the decision to introduce the parameter "presence of holes on grasping surface" is because holes dramatically reduce the contact area, more than porosity. In order to avoid confusion to the user images should be provided;

- **Stiffness and object shape can change**: when an object is very stiff it cannot change its shape without being damaged.

If *Stiffness ≥ M* ***then*** *set object shape can change = F*

Order: Stiffness will be asked before than object shape can change;

- **Tangled objects and symmetry**: an object cannot be both 0° α and β symmetry and subject to tangle;

3.5 RULES

The expert system selects the appropriate grippers following a set of rules which works according to the input made of a set of parameters.

The rules can have different purposes but they are all activated upon the occurrence of a determined condition, which could be the exceeding of a threshold or the combination of one or more parameters. The rules can be divided into 3 different categories:

- **Exclusion rules**: most of the rules are exclusion rules. An exclusion rule excludes one or more grasping principles;
  *If shape=prism AND density=H **then** "Bernoulli AND "Acoustic SW AND Acoustic NF" are excluded*
- **Warnings**: some rules have been made to warn the user about something, such as avoiding high acceleration, or the need of soft pads with very fragile objects. Even the need of a monitoring system or a particular environment is given as a warning.
  *If Sensitivity to scratches and bruises=True AND insertion=True **then** write "warning: the use of a force sensor with an appropriate threshold is highly recommended in order to avoid scratches or bruises"*
- **Advice**: the system could give as an output even an advice, as it happens in DFA/DFMA systems, which can be a recommendation for redesign or the use of a particular grasping configuration.

*If Porosity ≥ M **then** write "Bernoulli or Vacuum grippers will waste much energy during the grasp, due to the significant level of porosity. Consider a redesign with lower porosity zones in order to ensure a more energy efficient grasp"*

The rules could be activated both for the selection of the grasping principle and for the definition of the specific gripper characteristics. On the specific grasping principle level there is a dedicate set of rules for every grasping principle. In this thesis work only the rules for frictional and vacuum gripper have been developed.

It has been chosen to develop a set of rules instead of an algorithm for many reasons:

- Developing and testing a set of rules represents the first step for building an algorithm;
- At this moment the system has as an input mostly qualitative characteristics and an algorithm works best with quantitative data;
- A set of rules could be easily updated without any particular skill;
- A set of rules could be kept even in future works for the choice of the appropriate grasping principle, and then a separated and dedicated algorithm will make the choice of the exact gripper;

3.6 THEORETICAL DATABASE STRUCTURE

One of the first purposes of this thesis work was building and structuring a gripper database, reporting every gripper characteristics and their reliability with determined parameters (such as different shapes, flexible objects etc...).

This has not been possible for a significant number of reasons. The most important is that at the moment there are not enough data sheets on grippers, and the ones currently available are usually not complete and/or with parameters measured in different working conditions, making grippers not comparable. When dealing with other grasping principles the situation is even worse since most of the data could be acquired only from papers; every paper has very different testing conditions and it is not uncommon to find papers with very incomplete data, both in terms of gripper and grasped object.

This comes from the lack of a standardized method to define gripper specific characteristics and from the fact that many of them are correlated with a lot of parameters. For example the maximum weight that a frictional gripper can sustain is influenced by: object weight, object surface (in terms of slippery, stickiness), contact surface, distance from the barycenter and acceleration.

However, especially for future works and better system logic understanding, a database structure, together with the relations between tables, has been defined, and it is reported in the following figure.
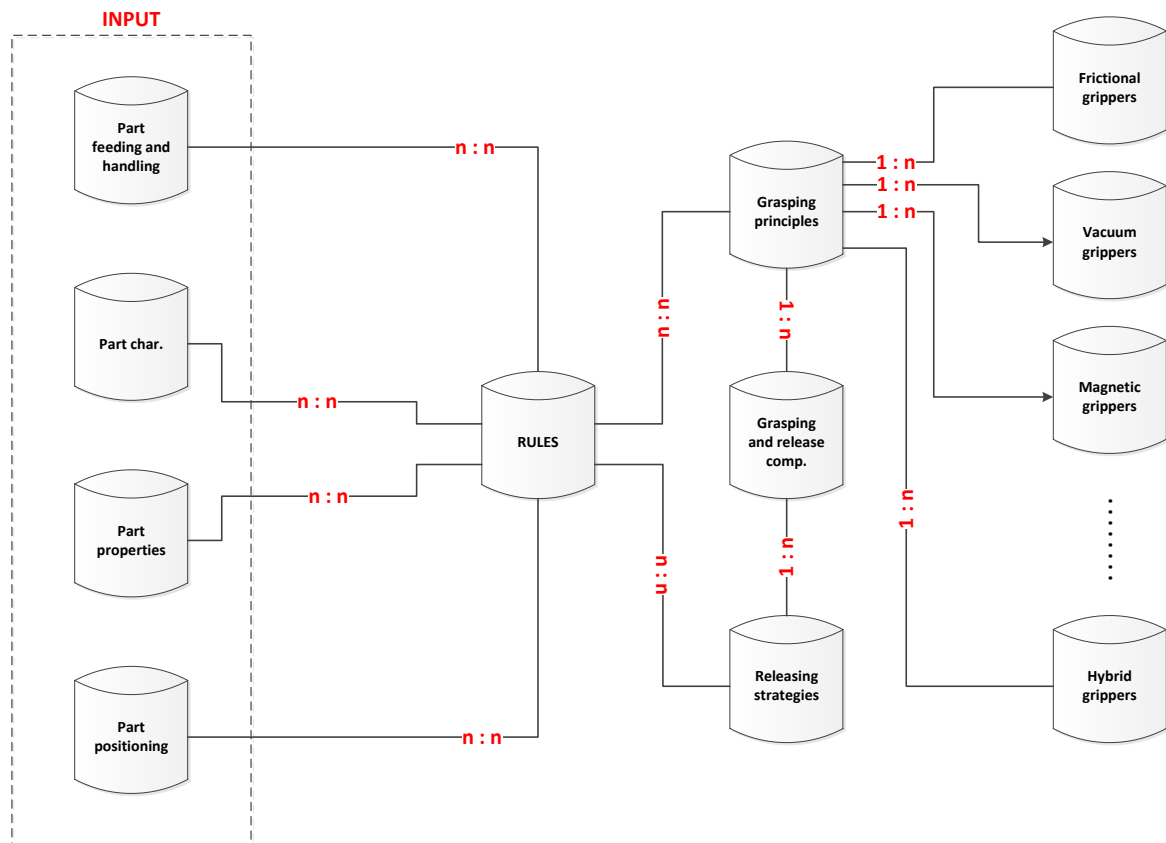
Figure 6 - Theoretical database structure

3.7 EVALUATING ALTERNATIVE DATA SOURCES

In this paragraph is discussed and evaluated the possibility to acquire data from different sources to, at least partially, automate the input phase.

Google images

Scope

The scope of this test is to establish if the new service, provided by Google, can be helpful in automatic definition of some object's characteristics (e.g. if the object is recognized as "cardboard box" subsequently, with another search in an appropriate database, it could be possible to extract its principal characteristics).

Test

The test has been done using five different objects, in different surrounding circumstances.

1. The first photo set was done in ideal conditions: a close-up of the object with white background;

2. The second photo set was done changing the background;

3. The last photo set included some other objects in the background as disturbing elements.

These are the objects used during the test:

Figure 59 - Test objects

Unfortunately the results were not encouraging as Google images has not been capable

to tag any of the objects in any condition discussed above although those were objects

of common use.

In the images below there are some examples:
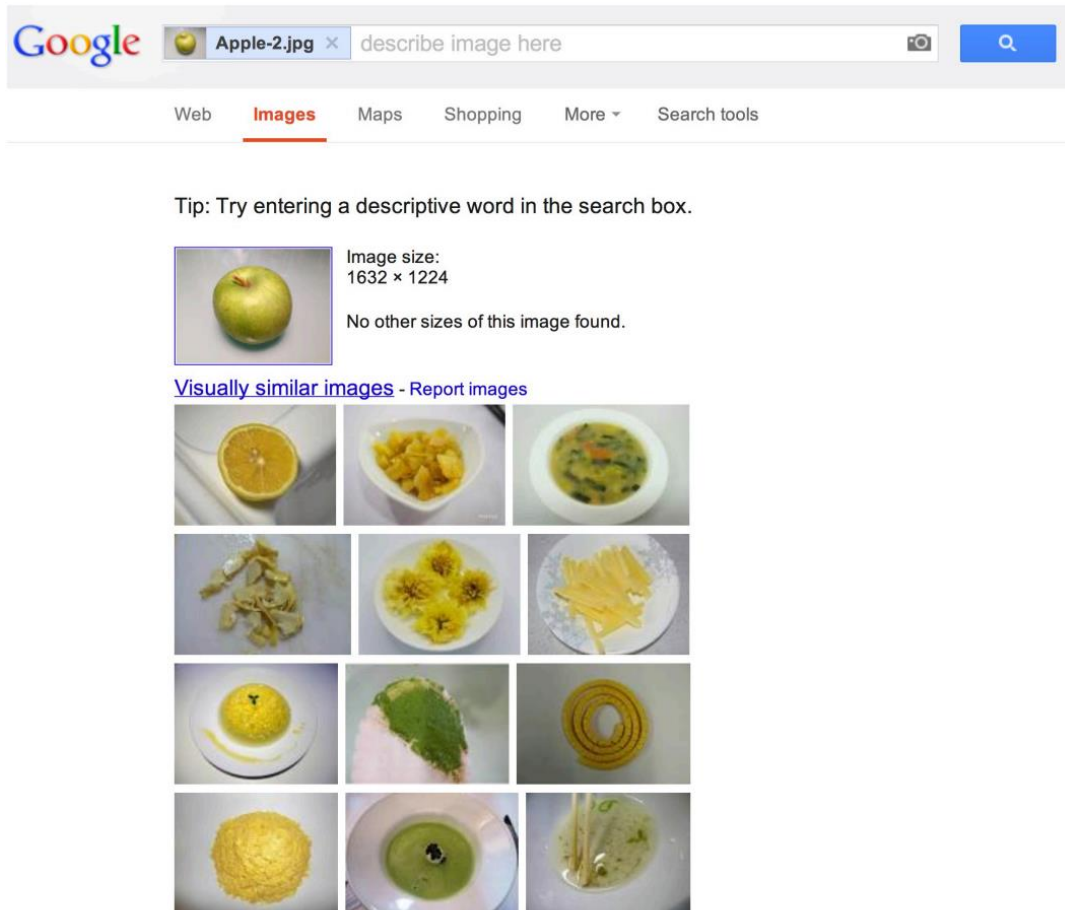
Figure 60 - Tag test - 1
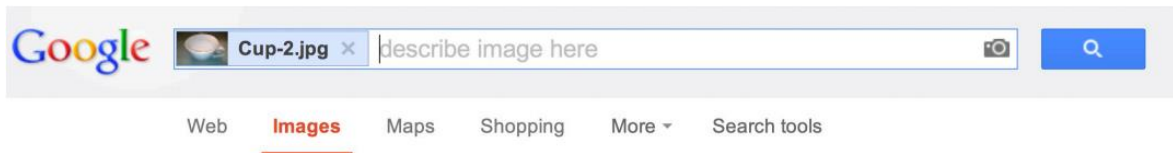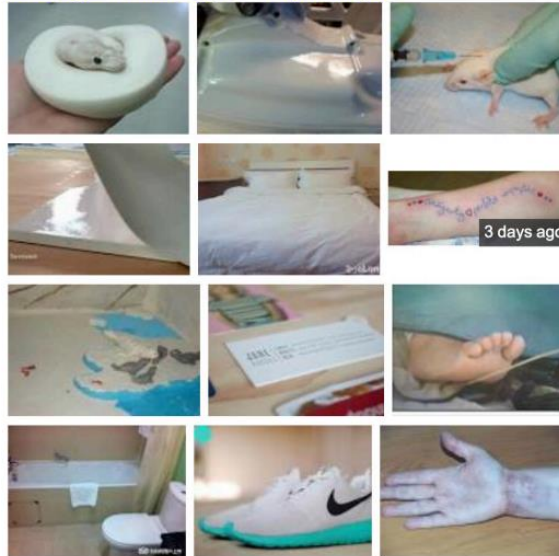
Figure 61 - Tag test - 2

As shown from the results above Google finds images that are visually similar, or rather, that have a similar color distribution, without trying in any way to recognize the kind of object.

The proof of the influence of the color distribution can be seen by analyzing the results obtained with the same object in the 3 different situation described above:
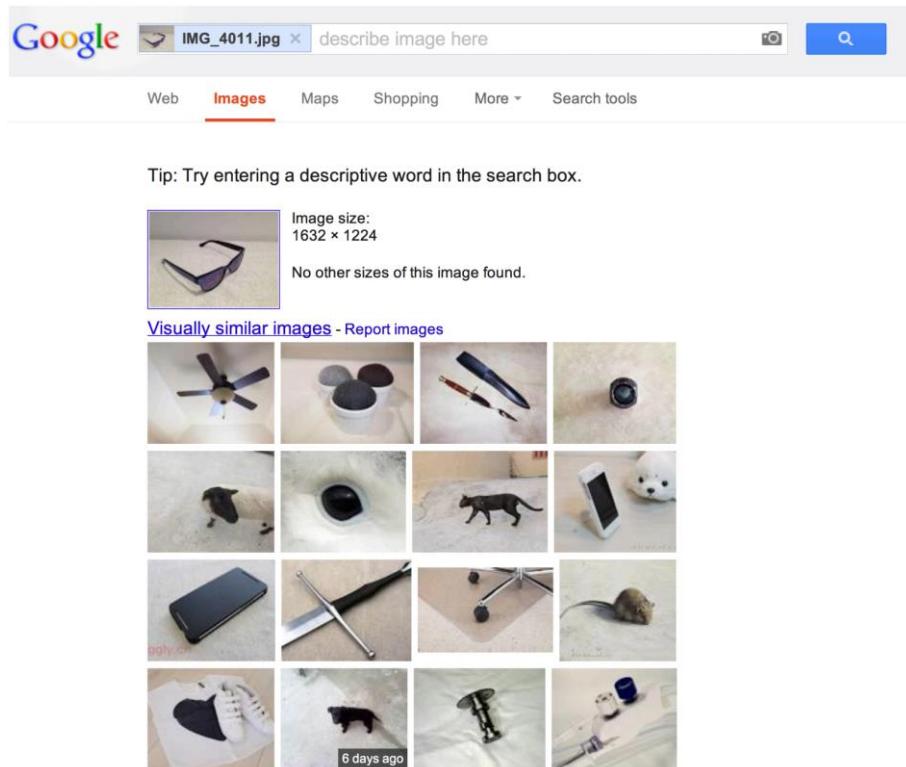
Figure 62 - Glasses close-up, white background
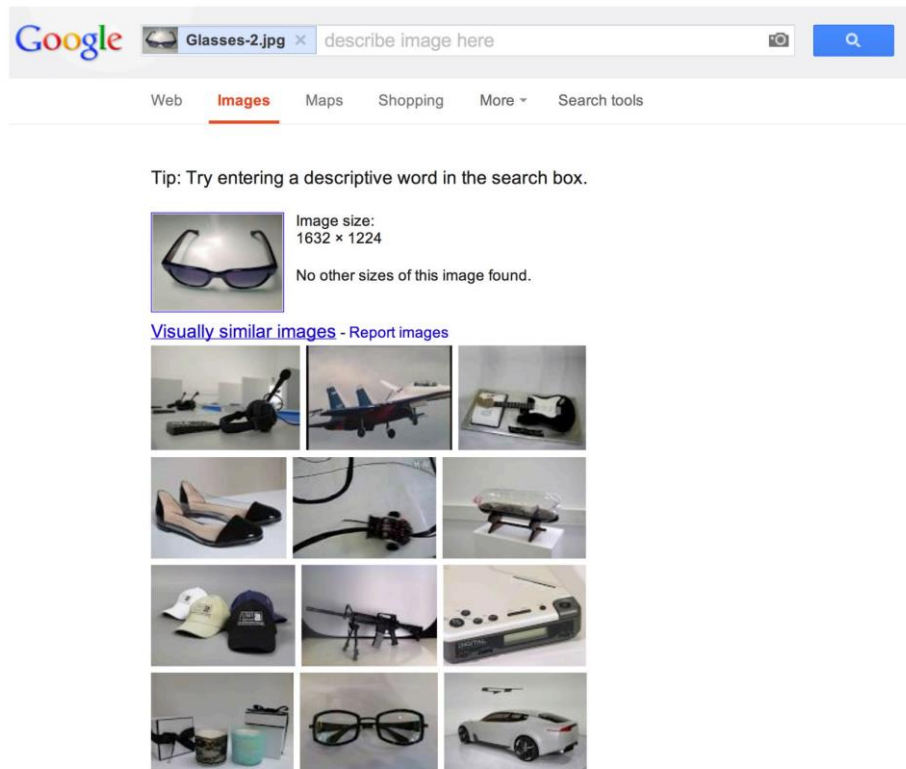
Figure 63 - Glasses close-up, glass background
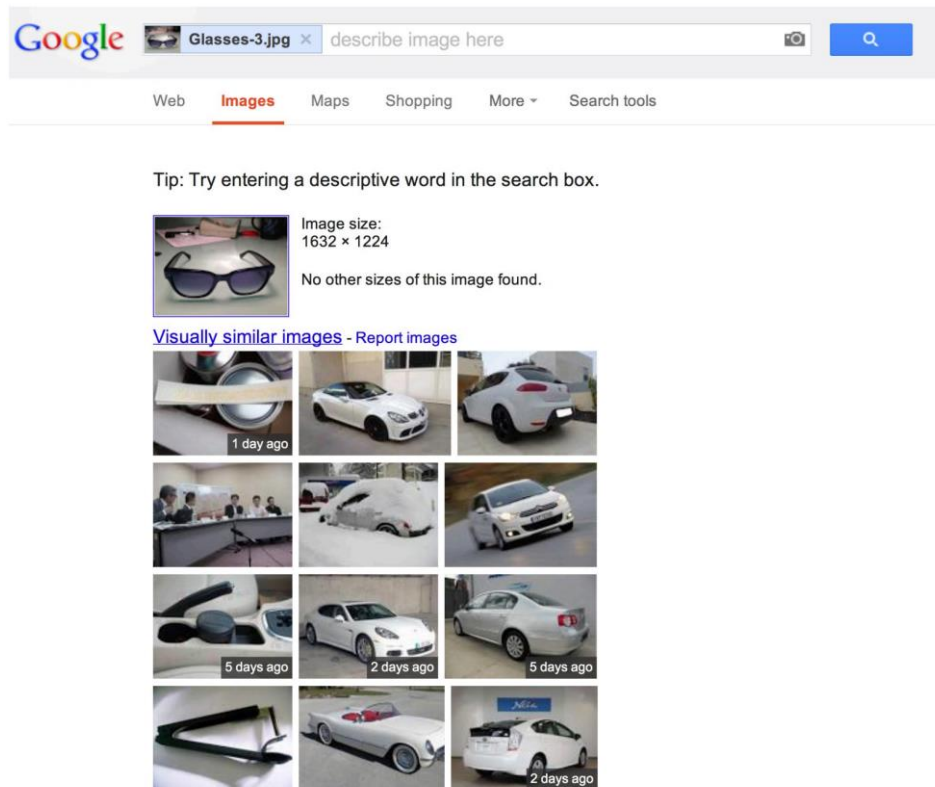
Figure 64 - Glasses close-up, disturbing elements in the background

Again is possible to see how there is not any kind of link, except the similar color distribution, between the images given as output (e.g. in *Figure 63 - Glasses close-up, glass background* we see cups, glasses, cars etc...).

Now, with these results, the question is: "what happens if the input image comes directly from a Google image research?".

In order to find out the answer, the steps are:

1. Search "glasses" on Google images;

2. Download the first image given as output;

3. Do a new search using as input the downloaded image.
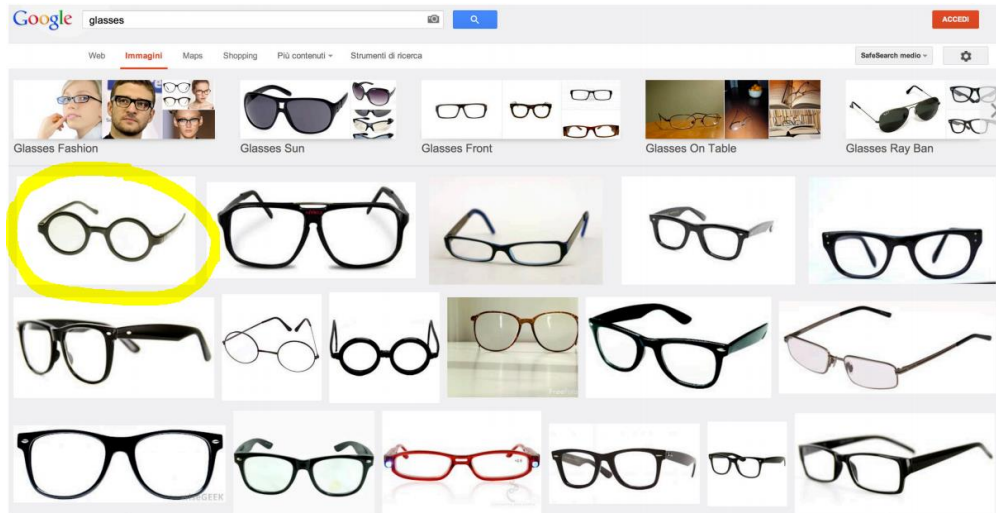
Figura 65 - Step 1
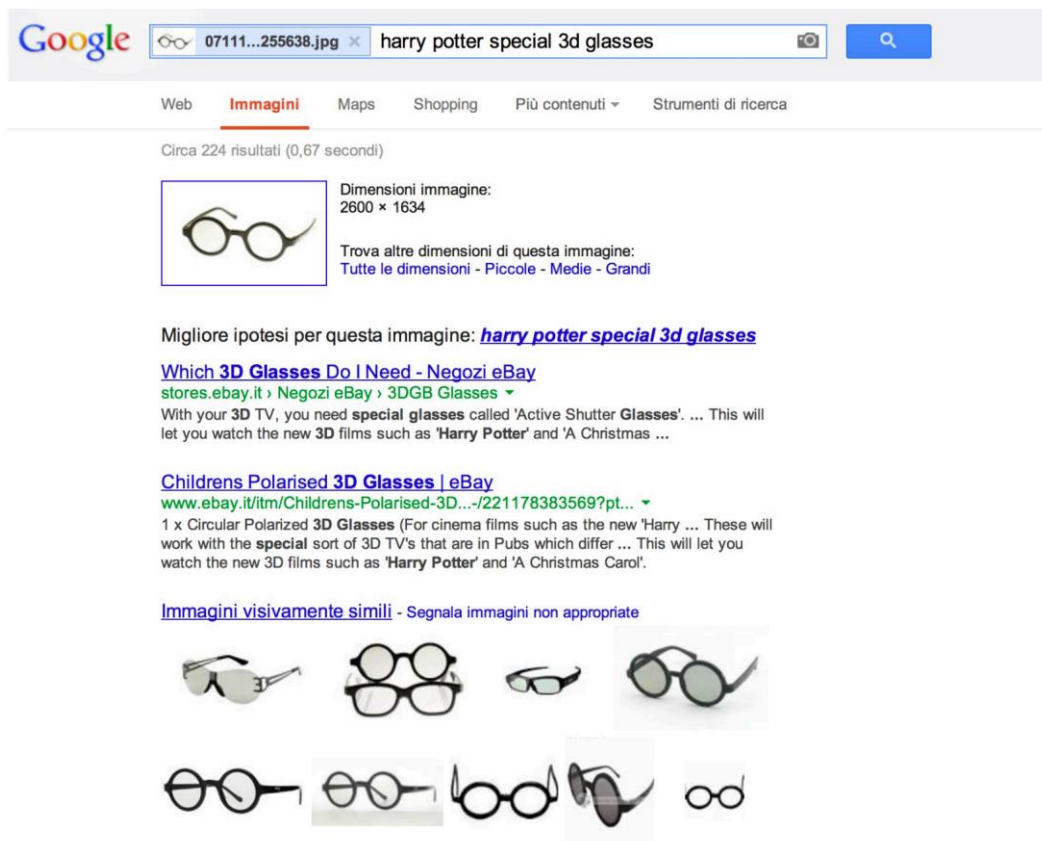
Figura 66 - Step 3

The results are interesting: Google is not capable to assign any tag with an image given

by the user but if the images comes from Google search the assigned tag is extremely

accurate (not only "glasses" but "Harry Potter special 3d glasses"). As output we have images visually similar and responding to the same tag.

This is strange, it seems that Google has in some way pre-tagged many of the image given as output from a textual search. Indeed, with a further research, we discovered that Google did an image tagging game[10] between 2006 and 2011 to improve the output given by their images researches.

So this service comes in handy when the image is supported by a description or a simple tag, in this way Google gives as output similar images responding to the same tag.

This instrument also requires very low image resolution to work properly, a test done on the same image shows how the output is almost identical until the image goes below the width of 300pixel.

---

[10] *The game was not designed simply for fun, it was also a way for Google to ensure that its keywords were matched to correct images. Each matched word was supposed to help Google to build an accurate database used when using the Google Image Search.*
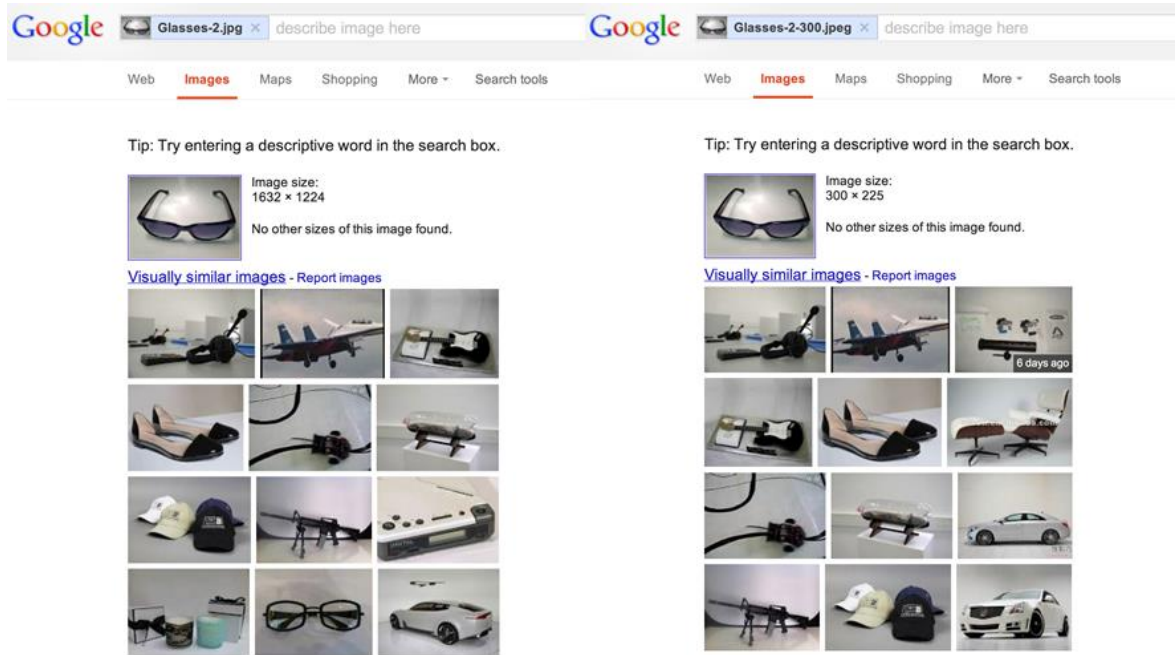
Figure 67 - 1632x1224 pixel image output (left) and 300x225 pixel image output (right)

This can be useful as a full size image, including many different objects, could be cropped into many smaller usable images.

MatWeb

Once the object is correctly tagged it comes in handy to automatically extrapolate some of its characteristics in order to use them as input; MatWeb is one site that provides this kind of service.

MatWeb's searchable database of material properties includes data sheets of thermoplastic and thermoset polymers such as ABS, nylon, polycarbonate, polyester, polyethylene and polypropylene; metals such as aluminum, cobalt, copper, lead, magnesium, nickel, steel, superalloys, titanium and zinc alloys; ceramics; plus semiconductors, fibers, and other engineering materials.

This is the output we get using as search input "glass" and by choosing the first result.

Borosilicate Glass				
Categories:	Ceramic; Glass; Oxide; Silicon Oxide			
Material Notes:	Properties will vary somewhat, depending on exact composition. Borosilicate glass is noted for its low thermal expansion and chemical resistance. Therefore it is used frequently in laboratory equipment and near heat sources such as lamps.			
Key Words:	SiO2			
Vendors:	No vendors are listed for this material. Please click here if you are a supplier and would like information on how to add your listing to this material.			

Printer friendly version Download as PDF Download to Excel (requires Excel and Windows)
Export data to your CAD/FEA program   Add to Folder: ☐ My Folder ∨ 0/0

Physical Properties	Metric	English		Comments
Density	2.40 g/cc	0.0867 lb/in³		

Mechanical Properties	Metric	English		Comments
Knoop Microhardness	4.1	4.1		GPa
Modulus of Elasticity	60.0 - 64.0 GPa	8700 - 9280 ksi		
Fracture Toughness	0.770 MPa-m½	0.701 ksi-in½		

Thermal Properties	Metric	English		Comments
CTE, linear	4.00 µm/m-°C @Temperature 0.000 - 300 °C	2.22 µin/in-°F @Temperature 32.0 - 572 °F		
Thermal Conductivity	1.10 W/m-K	7.63 BTU-in/hr-ft²-°F		
Melting Point	800 °C	1470 °F		Softening Point

Component Elements Properties	Metric	English		Comments
Al2O3	2.0 - 7.0 %	2.0 - 7.0 %		
B2O3	7.0 - 13 %	7.0 - 13 %		
Na2O or K2O	4.0 - 8.0 %	4.0 - 8.0 %		
SiO2	70 - 81 %	70 - 81 %		

Figure 68 – MatWeb

The information gained from the site are useful to define, with quantitative data, some important object characteristics such as:

- Weight: from density and size;

- Toughness: from mechanical properties;

- Material properties;

- Porosity: from density, a material with very low density have an higher chance to be porous;

- Stiffness: from mechanical properties;

So, the use of this method can help the user in the definition n of a subset of the object characteristics when the user only have to give in input the kind of material.

Importing data from a CAD file

In the last years almost all companies switched from 2D CAD drafting to the world of 3D CAD modeling. Designing using 3D CAD means being able to make models from which a wide range of information products can be generated, such as:

- Very detailed geometrical features;

- Material type;

- Weight;

- Compression and shock resistance;

Furthermore since complicated work piece geometry underlines the need for a deeper analysis in finding the right prehension points, and since it is hard to establish those making questions to the user, the use of a CAD file as input would greatly increase the system reliability.

Not only would the reliability be improved, but even the time effort from the user, since he will be asked to answer a significant lower number of questions.

Anyway a CAD file is not always available for some categories, for example the food category.

4   RESULTS AND DISCUSSIONS

4.1 FOCUS ON FOOD

Food products are usually identified as fragile and very sensitive to stain, scratches, bruises and contamination. This is why they require delicate and hygienic handling since their quality and is not only affected by how the food is produced and stored, but even how it is processed, packaged and in general handled by automatic systems.

The gripper should be then designed in order to grasp and handle the product maintaining its conditions unchanged.

Existing systems still rely on human labor which still has more flexibility and dexterity compared to an automatic system, but has even more chances to contaminate the product. This is why many food manufacturers are interested in robot handling not only for automation, speed and cost reasons[11], but also they also have interest in reducing the amount of manual labor where open foods are handled because, compared to humans that have a tendency to cough, shed e.g. hair, skin fragments and saliva, robots can potentially improve production hygiene.

The range of food products spaces from fish filets, meat, sliced tomatoes etc... All those products have much different characteristics, this underlines how the high hygienic requirements are not the only issue, most of them are even fragile and very flexible. Some objects, like meat, jelly or fish are easily manipulated in case of human handling

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[11] *As labour costs increase and legislation is making it more costly for the company if workers are injured (repetitive motion injuries) a robot alternative becomes more attractive (Brumson, 2008).*

and, in order to define an automatic grasping strategy, is necessary to design a gripper with sensory mechanism that reproduce the human's behavioral models other than focusing on a design compatible with non-rigid and fragile objects.

This is why the handling of food represents one of the worst scenarios in robotic grasping, this thesis work then focuses to test the reliability of the expert system on food products, in particular with four different cases, as showed in the following table.

	Wurstel	Tomato slice	Biscuit	Candy
Parameter	**Value**	**Value**	**Value**	**Value**
Size	VS	S	S	VS
Weight	L	VL	VL	VL
Density	L	M	L	M
Shape	Line - c	Flat-c	Flat-c	Bulk-p
Roughness	VL	L	VH	L
Slippery	M	L	VL	L
Stickiness	VL	L	VL	L
Toughness	L	VL	VL	L
Stiffness	L	L	VH	VH
Object shape can change	F	F	F	F
Porosity	VL	VH	VH	VL
Part p.: conductive	F	F	F	F
Part p.: ferromagnetic	F	F	F	F
Part p.: hole for grasping	F	F	F	F
Part p.: planar surface available for grasping	F	T	T	T
Part p.: regular curved surface available for grasping	T	F	F	F
Part p.: wet	T	T	F	F
Part p.: presence of holes on the grasping surface	/	H	M	/
Hygienic req.	T	T	T	T
Sensitivity to scratches and bruises	T	T	F	T
Sensitivity to liquid	F	F	T	T
Sensitivity to water	F	F	T	T

Sensitivity to charge	F	F	F	F
Sensitivity to stain	T	T	T	T
Sensitivity to dust	T	T	T	T
Magnetic sensitivity	F	F	F	F
Sensitivity to heat	T	T	T	T
Sensitivity to acceleration	F	F	F	F

All those object are very different, they range from very flexible to very stiff, from very high porosity to very low, from wet to dry etc… and they are all more or less fragile, which represents a more difficult grasp.

In the following paragraph are analyzed all the 4 objects taken as example and other 2 belonging one to general macro category and one to micro category, the results will be then discussed and eventual correction evaluated.

4.2 ANALYSIS OF SYSTEM OUTPUT

The following tables report the output of the expert system showing, step by step, how the exclusions have been made.

Then are reported the grasping principles capable to grasp the object with some notes, and at last, only for frictional gripper, a table resumes the minimal requirement to choose the gripper. Those requirements could be used, in future works, to search through a frictional gripper database and filter the ones that are compatible.

The results will be then analyzed with the objective to improve the output quality.

Wurstel		Grasping principle excluded															
		Friction			Magnetic		Vacuum	Bernoulli	Capillary	Electrostatic	Van der Waals	Needle	Expansion	Acoustic		Solid-liquid s.	
Parameter	**Value**	2F	3F	J	P	E								SW	NF		**Notes**
Size	VS													■	■		
Weight	L								■								
Density	L																
Shape	Line - c							■									
Roughness	VL																
Slippery	M																
Stickiness	VL																
Toughness	L																
Stiffness	L																Avoid high acceleration
Shape can change	F																
Porosity	VL																
Part p.: conductive	F																
Part p.: ferromagnetic	F				■	■											
Part p.: hole for grasping	F												■				
Part p.: planar surface available for grasping	F										■						
Part p.: regular curved surface available for grasping	T																
Part p.: wet	T									■							
Part p.: presence of holes on the grasping surface	F																
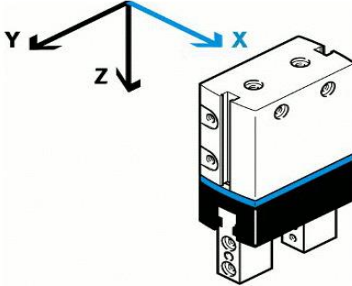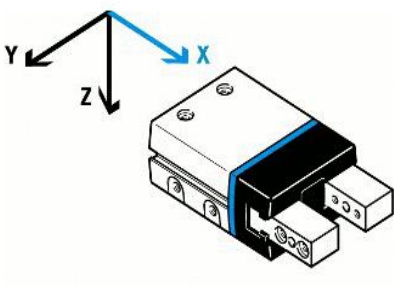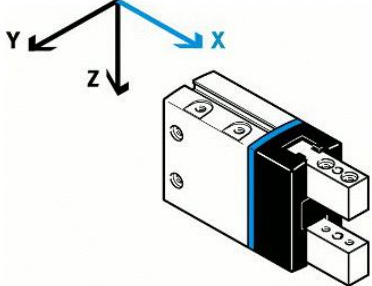
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Property																Notes
Hygienic req.	**T**															Warning: gripper should be specifically designed in order to meet hygienic standards. Warning: hygienic environment required
Sensitivity to scratches and bruises	**T**									🟥						
Sensitivity to liquid	**F**															
Sensitivity to water	**F**															
Sensitivity to charge	**F**															
Sensitivity to stain	**T**															
Sensitivity to dust	**T**															
Magnetic sensitivity	**F**															
Sensitivity to heat	**T**															
Sensitivity to acceleration	**F**															

Wurstel results

grasping principle	Notes	Environment
Friction 2f/3f	*The use of a force sensor is highly recommended, avoid strong contact pressure on small contact area.* *Multiple attachment points and/or large contact area are highly recommended in order to prevent any damage to the grasped object.* *Fingers have to be specifically designed to handle fragile objects* *Avoid high acceleration* Warning: gripper should be specifically designed in order to meet hygienic standards	*Hygienic*
Friction jaw	*Warning: jaw gripper fingers must be specifically designed to match the object shape* *The use of a force sensor is highly recommended, avoid strong contact pressure on small contact area.*	*Hygienic*

	Multiple attachment points and/or large contact area are highly recommended in order to prevent any damage to the grasped object. Fingers have to be specifically designed to handle fragile objects. Avoid high acceleration Warning: gripper should be specifically designed in order to meet hygienic standards	
Solid-liquid s.	The gripper should be specifically designed to match the object shape Avoid high acceleration Warning: gripper should be specifically designed in order to meet hygienic standards	
Vacuum	The grasp of objects with regular curved is feasible only with specific multi cups gripper for curved surfaces (octopus) or with compliant multi cups. Avoid high acceleration Warning: gripper should be specifically designed in order to meet hygienic standards	

Friction									

Safety factor	min - static grasping force [N]	L - acc	M - acc	H – acc						
		min - dynamic grasping force [N]	min - dynamic grasping force [N]	min - dynamic grasping force [N]	min - stroke per finger [mm]	min - suggested finger length [mm]	min - stroke per finger [mm]	min - suggested finger length [mm]	min - stroke per finger [mm]	min - suggested finger length [mm]
2	1,76580000	2,6487	5,2974	10,5948	93,50	8,33	13,75	56,67	13,75	56,67

Tomato slice		Grasping principle excluded															Notes
		Friction			Magnetic		Vacuum	Bernoulli	Capillary	Electrostatic	Van der Waals	Needle	Expansion	Acoustic		Solid-liquid s.	
Parameter	Value	2F	3F	J	P	E								SW	NF		Notes
Size	S								■					■			
Weight	VL																
Density	M																
Shape	Flat-c																
Roughness	L																
Slippery	L																
Stickiness	L																
Toughness	VL											■					
Stiffness	L																Avoid high acceleration
Object shape can change	F		■														
Porosity	VH						■	■									
Part p.: conductive	F																
Part p.: ferromagnetic	F				■	■											
Part p.: hole for grasping	F												■				
Part p.: planar surface available for grasping	T																
Part p.: regular curved surface available for grasping	F																

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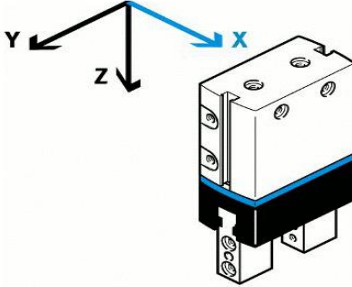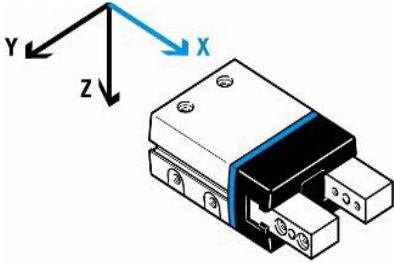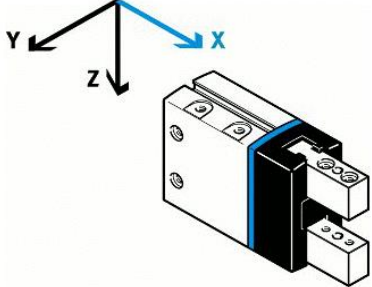
Part p.: wet	**T**									🟥	🟥						
Part p.: presence of holes on the grasping surface	**H**													🟥			
Hygienic req.	**T**																Warning: gripper should be specifically designed in order to meet hygienic standards Warning: hygienic environment required
Sensitivity to scratches and bruises	**T**																
Sensitivity to liquid	**F**																
Sensitivity to water	**F**																
Sensitivity to charge	**F**																
Sensitivity to stain	**T**																
Sensitivity to dust	**T**																
Magnetic sensitivity	**F**																
Sensitivity to heat	**T**																
Sensitivity to acceleration	**F**																

Tomato slice Results

grasping principle	Notes	Environment
Friction 2f	*select the grasping direction with the lower value of finger stroke* *better with multiple frictional gripper or multiple attachment points, jaw grippers better with larger contact area* *The use of a force sensor is highly recommended, avoid strong contact pressure on small contact area* *Multiple attachment points and/or large contact area are higly recommended in order to prevent any damage to the grasped object* *Fingers must use soft pads and preferably with larger contact area*	*Hygienic*

	Avoid high acceleration Warning: gripper should be specifically designed in order to meet hygienic standards	
Friction jaw	*fingers must be specifically designed to match the object shape* *the grasping direction with the lower value of finger stroke is not available* *The use of a force sensor is highly recommended, avoid strong contact pressure on small contact area* *Multiple attachment points and/or large contact area are higly recommended in order to prevent any damage to the grasped object* *Avoid high acceleration* Warning: gripper should be specifically designed in order to meet hygienic standards	*Hygienic*
Solid-liquid s.	*Avoid high acceleration* Warning: gripper should be specifically designed in order to meet hygienic standards Warning: the object could be damaged or its quality compromised if the transition between solid and liquid state is too fast.	*Hygienic*

Friction										

Safety factor	min - static grasping force [N]	L - acc min - dynamic grasping force [N]	M - acc min - dynamic grasping force [N]	H - acc min - dynamic grasping force [N]	min - stroke per finger [mm]	min - suggested finger length [mm]	min - stroke per finger [mm]	min - suggested finger length [mm]	min - stroke per finger [mm]	min - suggested finger length [mm]
2	0,39240000	0,5886	1,1772	2,3544	27,50	3,33	27,50	16,67	5,50	16,67

Biscuit		Grasping principle excluded															
		Friction			Magnetic		Vacuum	Bernoulli	Capillary	Electrostatic	Van der Waals	Needle	Expansion	Acoustic		Solid liquid t.	
Parameter	**Value**	2F	3F	J	P	E								SW	NF		**Notes**
Size	**S**								🟥					🟥			
Weight	**VL**																
Density	**L**																
Shape	**Flat-c**																
Roughness	**VH**										🟥						
Slippery	**VL**																
Stickiness	**VL**																
Toughness	**VL**											🟥					
Stiffness	**VH**																
Shape can change	**F**																
Object shape can change	**F**																
Porosity	**VH**						🟥	🟥									Warning: Consider a redesign with some parts of the area with lower porosity if more grasping principles are needed
Part p.: conductive	**F**																
Part p.: ferromagnetic	**F**				🟥	🟥											
Part p.: hole for grasping	**F**												🟥				
Part p.: planar surface available for grasping	**T**																
Part p.: regular curved surface available for grasping	**F**																
Part p.: wet	**F**																
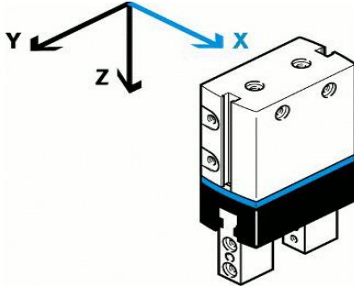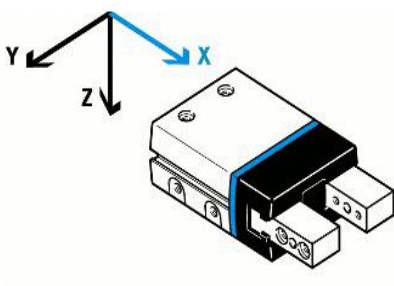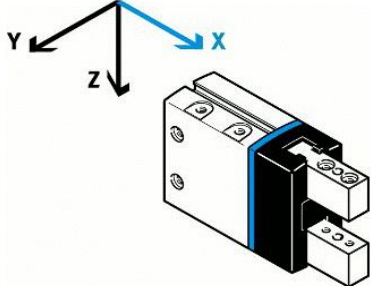
Part p.: presence of holes on the grasping surface	**M**																			
Hygienic req.	**T**																		Warning: hygienic environment required Warning: gripper should be specifically designed in order to meet hygienic standards	
Sensitivity to scratches and bruises	**F**																			
Sensitivity to liquid	**T**																	🟥		
Sensitivity to water	**T**																			
Sensitivity to charge	**F**																			
Sensitivity to stain	**T**																			
Sensitivity to dust	**T**																			
Magnetic sensitivity	**F**																			

Biscuit results

grasping principle	Notes	Environment
Friction 2f	*select the grasping direction with the lower value of finger stroke* *The use of a force sensor is highly recommended, avoid strong contact pressure on small contact area* *Multiple attachment points and/or compliant fingers are highly recommended in order to prevent any damage to the grasped object* *Fingers have to be specifically designed to handle fragile objects. The use of softpads is recommended*	*Hygienic*
Friction jaw	*fingers must be specifically designed to match the object shape* *the grasping direction with the lower value of finger stroke is not available* *The use of a force sensor is highly recommended, avoid strong contact pressure on small contact area* *Multiple attachment points and/or compliant fingers are highly recommended in order to prevent any damage to the grasped object*	*Hygienic*

		Fingers have to be specifically designed to handle fragile objects. The use of softpads is recommended	
Electrostatic			*Hygienic*
Acoustic - NF			*Hygienic*

					Friction						
Safety factor	min - static grasping force [N]	L - acc	M - acc	H - acc							
		min - dynamic grasping force [N]	min - dynamic grasping force [N]	min - dynamic grasping force [N]	min - stroke per finger [mm]	min - suggested finger length [mm]	min - stroke per finger [mm]	min - suggested finger length [mm]	min - stroke per finger [mm]	min - suggested finger length [mm]
2	0,294300	0,44145	0,8829	1,7658	35,75	2,67	35,75	21,67	4,4	21,67
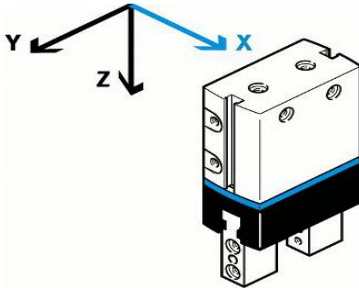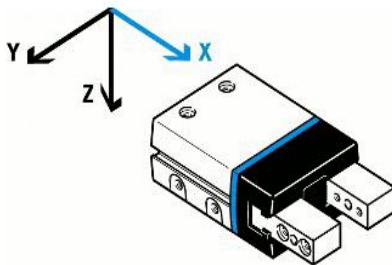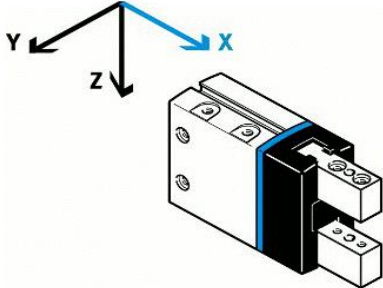
Chocolate candy		Grasping principle excluded															
		Friction			Magnetic		Vacuum	Bernoulli	Capillary	Electrostatic	Van der Waals	Needle	Expansion	Acoustic		Solid liquid t.	
Parameter	**Value**	2F	3F	J	P	E								SW	NF		**Notes**
Size	VS											■		■	■		
Weight	VL																
Density	M								■	■							
Shape	Bulk-p		■														
Roughness	L																
Slippery	L																
Stickiness	L																
Toughness	L																
Stiffness	VH																
Object shape can change	F																
Porosity	VL																
Part p.: conductive	F																
Part p.: ferromagnetic	F				■	■											
Part p.: hole for grasping	F												■				
Part p.: planar surface available for grasping	T																
Part p.: regular curved surface available for grasping	F																
Part p.: wet	F																
Part p.: presence of holes on the grasping surface	/																
Hygienic req.	T																

Sensitivity to scratches and bruises	**T**																
Sensitivity to liquid	**T**														🟥		
Sensitivity to water	**T**																
Sensitivity to charge	**F**																
Sensitivity to stain	**T**																
Sensitivity to dust	**T**																
Magnetic sensitivity	**F**																
Sensitivity to heat	**T**																
Sensitivity to acceleration	**T**																

Chocolate candy results

grasping principle	Notes	Environmental r.
Friction 2f	*select the grasping direction with the lower value of finger stroke* *The use of a force sensor is highly recommended, avoid strong contact pressure on small contact area* *Multiple attachment points and/or compliant fingers are highly recommended in order to prevent any damage to the grasped object* *Fingers have to be specifically designed to handle fragile objects. The use of softpads is recommended*	*Hygienic environment*
Friction jaw	*fingers must be specifically designed to match the object shape* *The use of a force sensor is highly recommended, avoid strong contact pressure on small contact area* *Multiple attachment points and/or compliant fingers are highly recommended in order to prevent any damage to the grasped object* *Fingers have to be specifically designed to handle fragile objects. The use of softpads is recommended*	*Hygienic environment*
Vacuum	*Multiple attachment points and/or large contact area with compliant cup are highly suggested in order to prevent any damage to the grasped object*	*Hygienic environment*

		Friction								
Safety factor	min - static grasping force [N]	L - acc	M - acc	H - acc						
		min - dynamic grasping force [N]	min - dynamic grasping force [N]	min - dynamic grasping force [N]	min - stroke per finger [mm]	min - suggested finger length [mm]	min - stroke per finger [mm]	min - suggested finger length [mm]	min - stroke per finger [mm]	min - suggested finger length [mm]
2	0,294	0,442	0,882	1,766	16,5	5	11	10	8,25	10

4.2.1 Discussion of the first results

Analyzing the first results it is possible to notice how these are convincing, since the grasping principles identified as reliable are all plausible, this also applies to the warnings and advices. Anyway it also clear that there are some evident drawbacks that should be fixed or at least underlined for future researches.

The first exclusions are based only on one parameter: object size. This is linked to the unavoidable decision to divide the work pieces in different dimensional categories, an exclusion based just on the object size could lead to improper grasping principles exclusions, since every gripper could be specifically build to manage a very wide range of sizes and since there are still particular cases that can show adhesion effects overcome gravity even on objects that, following the actual system logic, are tagged as macro (e.g. a very thin paper sheet belongs to macro category, but its weight, compared to its dimension, makes it graspable even from gripper with very low grasping force and it will not be released just by gravity). Since there is no way to establish thresholds that does not lead to improper grasping exclusion, a possible solution to this problem is to redesign the rules that excludes the objects basing only on its size linking them to other parameters, such as weight and/or density.

Another important aspect, noticed during the first tests, is that the system reliability is strongly based on the quality of the input. This means that if the user misunderstands how to evaluate a parameter the output could be compromised. An interesting way to evaluate and possibly fix this problem could be conducing some studies involving a group of selected users and analyze if there are significant differences in the input values.

Furthermore, as regards the test n.4 chocolate candy, in literature are present some thermal grippers that are based on melting object surface and use that substrate to grasp the object, the release is still achieved by heating up again the surface and overcome the grasping forces. This is in contrast with the exclusion of solid-liquid transition gripper. A possible fix is to add a new parameter or modify the existing one "heat sensitivity", however its implementation is delayed until the expert system will be implemented into a software in order to be able to better evaluate the effects of such changes on the quality of the other outputs.

Even in the tomato slice there is an improper exclusion: Bernoulli gripper has been excluded since the object has high porosity. In literature there is evidence of an experimental Bernoulli gripper grasping sliced tomatoes [14].

The system is still not able to establish a ranking. A score system that allows the user to select the more appropriate grasping principle and then gripper is surely useful but not so simple. Firstly because "appropriate" could have different meanings, it depends on user requirements, in some operations a slightly less reliable but cheaper gripper could be preferred, and in other cases the pick&place time could be a very important parameter. Secondly because the ranking could be made directly on the grippers and there is not still a detailed database of grippers, mainly for lack of data, which allows to do such evaluation. Furthermore, in order to make the ranking reliable, some tests should be done on the reliability of some exponents of the grasping principle category with a predefined set of objects;

Hybrid grippers are not yet implemented. Implementing hybrid grippers is not the system's primary goal, the focus is still on improving its reliability and only then hybrid grippers support will be implemented.

5   Conclusions and future developments

5.1 Conclusions

In this work we have proposed an expert system that is capable of excluding correctly unfeasible grasping principles and that is also currently capable of defining basic gripper requirements for grippers belonging to the frictional category. Its reliability has been tested with several different objects with a full case study on the food category (in 4.2 together with the evaluation of possible improvements).

However the effectiveness and reliability of the system needs to be investigated more deeply.

5.2 Limitations of the system and suggestions for future researches

During the development of the system, we discovered how the selection of the proper gripper is very hard to achieve compared to what happens in DFA techniques, since the grasping process is strictly linked with the phases before (feeding) and the phases after (positioning, releasing or inserting); changes in one of those phases could imply modifications of the whole process and then of gripper requirements. Finding a way to evaluate every possibility, including the variability of the objects, requires a lot of study and work that could be done iteratively. Since the system is based on a set of rules that is easily updatable, acquiring data through the feedback obtained with different objects and grippers will be a key for improving both effectiveness and efficiency.

Furthermore, the system actually chooses the grasping principles that are, by their nature, able to manage the selected object without being specifically designed. However, since every gripper can be specifically designed to manage very different kind of objects in very different contexts, it would be much more useful and interesting if the search can be done on a wide gripper database. Thus in case of enough technical and economic data about every gripper, the proposed ranking can have even more sense. At the present, the system shows how the lack of detailed and standardized gripper data is the main drawback. A standardized methodology for describing gripper's characteristics and collecting enough data to build a solid gripper database will be the main goal of future developments. However, establishing a general ranking would be hardly feasible at the moment, mainly because the parameters are too many (reliability, cycle time, cost, environment, etc...) and all correlated (e.g. reliability influences cycle times and also costs and vice versa); anyhow it would be interesting even a ranking based on just one parameter at a time, since it would improve system reliability.

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APPENDIX

Rules

Parameter	Value	parameter 2	value	parameter 3	value	Parameter 4	value	Notes	Frictional 2F	3F	J	Magnetic P	E	Vacuum	Bernoulli	Capillary	Electrostatic	Van der Waals	Needle	Expansion	Acoustic SW	NF	Solid liquid t.
Weight	UL																					X	
	VL																				X		
	L															X					X		
	M														X	X					X		X
	H														X	X	X	X			X	X	X
	VH														X	X	X	X	X	X	X	X	X
Dimension	micro											X								X	X	X		
	VS	shape	NOT line																	X		X		
	VS	shape	line																			X		
	S																							
	M	shape	flat	density	H											X	X				X		
	M	shape	NOT flat	density	≥M											X	X				X		
	M																						X
	L															X	X	X	X			X		
	XL															X	X	X	X			X		
	ALL	shape						if the biggest dimensional parameter is greater than the sum of the remaining 2 multiplied for 3, automatically set object shape as LINE.															
Density	H							CORR: porosity cannot be set lower than M								X					X	X	
	VH														X	X	X		X		X	X	X
	H	Shape	Amorphous					Warning: avoid unbalanced grasps, multiple grasping points are raccomended															
			Line					Warning: avoid unbalanced grasps, multiple grasping points are higly raccomended															
	L or VL	Toughness	VL	Stickiness	≤M				X	X													
	H	holes on grasping surface	≥M											X				X					

Parameter	Value	parameter 2	value	parameter 3	value	Parameter 4	value	Notes	2F	3F	J	P	E	Vacuum	Bernoulli	Capillary	Electrostatic	Van der Waals	Needle	Expansion	SW	NF	Solid liquid t.
Shape	line	*stiffness*	L or VL					Warning: multiple grasping points are higly raccomended							■							■	
	spherical							Warning: Van der Waals have to be specifically designed to match the curved surface of the object															
	Prism									■													
	Prism	**Density**	≥M												■	■	■				■	■	
	Cylinder	**Density**	≥M												■	■					■	■	
	flat - circular	*stiffness*	≤L	*shape can change*	F					■													
	flat - square									■													
	line							Warning: ice, needle and VdW grippers should be specifically designed to match the object shape															
	line - c														■	■					■	■	
	line - p									■					■						■	■	
Roughness	≥H																		■				
	≥H	*slippery*						CORR: slippery cannot be set lower than M															
Slippery	VH								■	■													
	≥M	**Part properties: ferromagnetic**	F	stickiness				stickiness cannot be set higher than L															
		Inserting	true					Warning: inserting could be harder due to high object slippery.															
	H or VH	*orienting*	true					Warning: if orienting is achieved with ribbons between the gripper fingers, orienting will be harder or impossible															
Stickiness	≥H							Warning: gravity may not be sufficient as releasing strategy with contact gripppers															
	≥M	**Part properties: ferromagnetic**	F	slippery				slippery cannot be set higher than L															
	≥H	*orienting*	true					Warning: if orienting is achieved with ribbons between the gripper fingers, orienting will be harder or impossible														■	

Grasping principle excluded

Parameter	Value	parameter 2	value	parameter 3	value	Parameter 4	value	Notes	Frictional 2F	3F	J	Magnetic P	E	Vacuum	Bernoulli	Capillary	Electrostatic	Van der Waals	Needle	Expansion	SW	Acoustic NF	Solid liquid t.
Thoughness	VL							Warning: gripper has to be specifically designed to handle fragile objects											X				
	L							Warning: gripper should be specifically designed to handle fragile objects															
	L or VL	*stiffness*	L or VL					Warning: avoid high acceleration in order to avoid object damages or rips															
Stiffness	L or VL							Warning: avoid high acceleration															
		inserting	true					Warning: inserting could be done only with low forces, a force sensor to monitor the inserting is higly suggested. If higher forces are needed consider a redesign with higher stiffness.															
		acceleration	M					handling may be possible only with multiple grasping points															
		acceleration	≥M	*Toughness*	<M			Grasping may not possible, consider reducing the acceleration.															
	≥M	*Object sthape can change*						CORR: set object shape can change to False															
Part properties: ferromagnetic	False											X											
Part properties: ferromagnetic	T	*Toughness*	≤M					Warning: Permanent magnetic gripper should use a releasing strategy with low contact forces				X											
Part properties: hole for grasping	False																			X			
Part properties: reflective	False																						
Part properties: planar surface ava	False	*Shape*	NOT sphere	*p.p. regular curved surface*	F									X	X			X				X	
Part properties: regular curved surface available for grasping"	F	*Part p: planar surface available for grasp.*	F											X	X		X	X				X	
	T							Warning: Van der Waals have to be specifically designed to match the curved surface of the object															
Part properties: ferromagnetic	true	*stacked objects*	true	*Shape*	flat			Consider a redesign of the feeding system if magnetic grasping is needed.						X	X							X	

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Parameter	Value	parameter 2	value	parameter 3	value	Parameter 4	value	Notes	2F	3F	J	P	E	Vacuum	Bernoulli	Capillary	Electrostatic	Van der Waals	Needle	Expansion	SW	NF	Solid liquid t.
Part properties: ferromagnetic	true	stacked objects	true	Shape	flat			Magswitch may solve this problem				■	■										
Part properties: wet	T																		■				
								Warning: " solid-liquid transition gripper" the object could be damaged or its quality compromised if the transition between solid and liquid state is too fast.																
Part properties: holes on grasping	≥H														■						■	■	
	VH													■	■			■			■	■	■
	≥H	Porosity	≥M											■	■						■	■	
Porosity	≥H							Advice: Consider a redesign with some parts of the area with lower porosity if more grasping principles (vacuum or Bernoulli) are needed															
		Roughness						CORR: roughness cannot be set lower than L															
	≥M	Shape	flat											■									
	VL	Toughness	≥M	density	≥M														■				
	<M	Density	≥H	Toughness	≥H	Stiffness	≥H												■				
	≥M							Advice: Bernoulli and Vacuum will waste much energy during the grasp, due to the significant level of porosity. Consider a redesign with some parts of the surface with lower porosity in order to ensure a more efficient grasp											■				
Hyigienic requirements	True							every gripper with hygienic capabilities set to FALSE will be excluded.															
								Warning: hygienic environment required															
								Warning: gripper should be specifically designed in order to meet hygienic standards															
		sensitivity to stain	Set: T	sensitivity to dust	Set: T			both parameters will be set to true															

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Parameter	Value	parameter 2	value	parameter 3	value	Parameter 4	value	Notes	Frictional 2F	3F	J	Magnetic P	E	Vacuum	Bernoulli	Capillary	Electrostatic	Van der Waals	Needle	Expansion	SW	NF	Solid liquid t.
Sensitivity to scratches and bruises	*true*							Warning: bernoulli should be in a dust free environment															
								Warning: Magnetic (P) gripper must use a releasing strategy which doesn't scratch or bruise the work piece															
								Grasping principles that can easily bruise the object are excluded											■				
		insertion	*true*					Warning: the use of a force sensor with an appropriate threshold is highly recommended in order to avoid scratches or bruises															
Magnetic sensitivity	T											■	■										
Senitivity to liquid	T	*Sensitivity to water*	*Set: T*					Set sensitivity to water T															
Sensitivity to water	True							Grasping principles that uses water are excluded								■							■
Sensitivity to charge	True							Grasping principle based on electrostatic effects are excluded									■						
Sensitivity to stain	True															■							
Sensitivity to dust	True							Warning: Dust free or hygienic environment required															
Sensing	True							Every gripper with specified sensing capabilities set to FALSE will be excluded															
Inserting	True											■		■	■	■	■	■	■		■	■	■
Aligning	true							If the gripper doesn't match the required precision, the insertion will also be impossible															
Stacked objects	True	*Shape*	*flat*											■					■				
				porosity	*L or above*			vacuum is excluded							■	■	■						
Shape	Amorphous	*orienting*	*true*					Increased orienting difficulty index							■	■							
Acceleration	≥M														■	■						■	

Parameter	Value	parameter 2	value	parameter 3	value	Parameter 4	value	Notes	Grasping principle excluded (Frictional: 2F 3F J / Magnetic: P E / Vacuum / Bernoulli / Capillary / Electrostatic / Van der Waals / Needle / Expansion / Acoustic: SW NF / Solid liquid t.)
The following rules are only for micro objects									
Shape	Spherical							Warning: Van der Waals have to be specifically designed to match the curved surface of the object	
		Toughness	M ≤						
	Prism								
	flat - square								
	Prism	**Density**	H						
	Cylinder	**Density**	H						
	line							Warning: ice, needle and VdW grippers should be specifically designed to match the object shape	
	line - c								
	line - p								
Part properties: flat surface for grasping	F								
	F	**Thoughness**	≤M						
Environment	dust free							Dust free environment is required for Bernoulli, Vacuum and Electrostatic gripppers	
Environment	Vacuum							Not yet implemented	
Orienting	T								
Density	L	**Toughness**	M						
Roughness	H or VH								
Slippery	VH								
	H or VH	**Inserting**	true					Not yet implemented: Increase difficulty index	
Toughness	VL							Every gripper based on contact grasping is excluded	
	L								
Stiffness	L or VL							Warning: do not handle with high acceleration in order to avoid object damages	
Porosity	H or VH								
	>M	**shape**	flat						
Part properties: ferromagnetic	F								
Part properties: planar surface ava	False	**Shape**	NOT sphere	**p.p. regular cur**	F				

Parameter	Value	parameter 2	value	parameter 3	value	Parameter 4	value	Notes	2F	3F	J	P	E	Vacuum	Bernoulli	Capillary	Electrostatic	Van der Waals	Needle	Expansion	SW	NF	Solid liquid t.
Part properties: regular curved sur	F	*Part properties: planar surface available for grasping*	F									X			X			X	X	X		X	
	T																						
Part properties: planar surface ava	F	*Part properties: regular curverd surface available for grasping*	T									X			X			X	X	X		X	
Part properties: regular curved sur	F											X			X			X	X	X		X	
Part properties: ferromagnetic	T	*stacked objects*	true	*Shape*	flat								X					X		X			
Part properties: wet	T														X			X	X			X	
Part properties: holes on grasping	≥H														X			X		X	X	X	
	VH													X	X				X		X	X	
	≥H	*Porosity*	≥M											X	X				X				
Sensitivity to scratches and bruises	T								X	X	X	X											
Magnetic sensitivity	T											X	X										
Sensitivity to charge	T											X					X						
Sensitivity to liquid	T											X				X							X
Sensitivity to water	T											X											
Sensitivity to stain	T							Warning: contact grippers should operate in a clean and dust free environment				X											
Inserting	T											X			X			X	X		X	X	
Hydrophobic	T											X				X							
Stacked objects	T	*stacked objects*	Flat									X			X		X	X	X	X	X		

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Parameter	Value	parameter 2	value	parameter 3	value	Parameter 4	value	Notes	Grasping principle excluded													
									Frictional			Magnetic		Vacuum	Bernoulli	Capillary	Electrostatic	Van der Waals	Needle	Expansion	Acoustic		Solid liquid t.
									2F	3F	J	P	E								SW	NF	
The following rules are only for friction gripper																							
								Only jaw grippers: Warning: jaw gripper fingers must be specifically designed to match the object shape															
Stiffness	≤M	*shape*	*flat*					**2f and 3f** - select the grasping direction with the lower value of finger stroke															
		shape	*flat*					**Jaw** - the grasping direction with the lower value of finger stroke isn't available															
	≤L	*shape can change*	*False*					Warning: multiple attachment points are necessary to ensure a safe grasp															
	≤L							better with multiple frictional gripper or multiple attachment points, jaw grippers better with larger contact area															
Toughness		*shape*	*flat*					select the grasping direction with the lower value of finger stroke															
	≤L							The use of a force sensor is highly recommended, avoid strong contact pressure on small contact area															
								Multiple attachment points and/or compliant fingers are higly recommended in order to prevent any damage to the grasped object															
								Fingers have to be specifically designed to handle fragile objects. The use of softpads is recommended															
Sensitivity to scratches and bruises	T							Fingers must use soft pads and preferably with larger contact area															
								The use of a force sensor is highly recommended, avoid strong contact pressure on small contact area															

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Parameter	Value	parameter 2	value	parameter 3	value	Parameter 4	value	Notes	Frictional			Magnetic		Vacuum	Bernoulli	Capillary	Electrostatic	Van der Waals	Needle	Expansion	Acoustic		Solid liquid t.
									2F	3F	J	P	E								SW	NF	
The following rules are only for vacuum gripper																							
Presence of holes	≥M							due to the presence of holes on the grasping surface is highly recommended the of use smaller cups instead of one big suction cup															
Roughness	≥H							Warning: Vacuum gripper's cups have to be specifically designed to grasp surfaces with high roughness															
Shape	spherical	*Dimension*	≥VS					The grasp of spherical objects is feasible only with specific multi cups gripper for curverd surfaces (see Octopus)															
Shape	Line	*Density*	H					Multiple attachment points are required in order to ensure a safe grasp															
part properties: regular curved sur	T	*Dimension*	≥VS					The grasp of objects with regular curved is feasible only with specific multi cups gripper for curved surfaces (octopus) or with compliant multi cups.															
Toughness	≤L							Multiple attachment points and/or large contact area with compliant cup are highly suggested in order to prevent any damage to the grasped object															
Stiffness	≤L							Multiple cups are higly suggested in order to ensure a safer grasp															
	≤L	*shape can change*	False					Warning: multiple attachment points are necessary to ensure a safe grasp															
Sensitivity to scratches and bruises	T							Better in a dust free environment															
Electrostatic gripper								Warning: requires dust free environment															
Magnetic P gripper								Warning: requires a dedicated releasing system															

| | | | | | Passive releasing strategies | | | | | | | | | Active Releasing strategies | | | | | | | | | |
| | | | | | Gripper | | | | | | | Env. | | Forces | | | | | | | Contact area r. | | | |
Parameter	Value	parameter 2	value	conseguences	Cond. mat/coat - grounded gr.	Low difference of EV potential	Hydrophobic coating	Low Hamaker constant coating	Hard materials	Rough surface	Spherical fingers	Dry atmosphere	Ionized air	Air pressure (direct/indirect)	Acceleration or vibration	Micro heater	Electrostatic force control	Different adhesion force	Engagement by substrate/tool	Gluing on the substrate	3D handling of the gripper	Additional tool	Roughness change	Electrowetting
Weight	<0,1g														X						X			
Weight	<0,2g	shape	flat												X						X			
Aligning with high precision	T													X	X									
Material or coating: conductive	F																	X						
Material or coating: conductive	T																X							
Material or coating: hydrophobic	F																							
Shape	Flat														X									
Toughness	L or VL																		X			X		
Toughness	VL																		X			X		
														X	X									
Stickiness	H or VH			Roughness change, Rough surface, low hamaker constant coating are available only when the release is achieved while the workpiece is already in contact with the deposal place				(gray)		(gray)													(gray)	
Sensitivity to stain	T													X										
Sensitivity to water	T													X										
Sensitivity to liquid	T																			X				
Sensitivity to charge	T													X										
Sensitivity to scratches and bruises	T																		X			X		
Sensitivity to heat	T															X								
Inserting	T	toughness	<M												X					X				

Case studies

DVD		Grasping principle excluded															
		Frictional			Magnetic		Vacuum	Bernoulli	Capillary	Electrostatic	Van der Waals	Needle	Expansion	Acoustic		Solid liquid t.	
Parameter	Value	2F	3F	J	P	E								SW	NF		Notes
Size	M								X					X		X	
Weight	VL																
Density	L																
Shape	Flat - c																
Roughness	VL																
Slippery	L																
Stickiness	L																
Toughness	M																
Stiffness	H																
Shape can change	F																
Porosity	VL																
Part p.: conductive	F																
Part p.: ferromagnetic	F				X	X											
Part p.: hole for grasping	F												X				
Part p.: planar surface available for grasping	T																
Part p.: regular curved surface available for grasping	F																
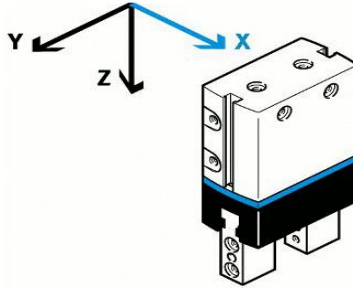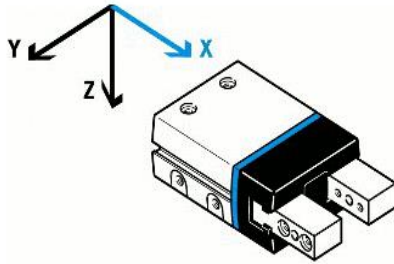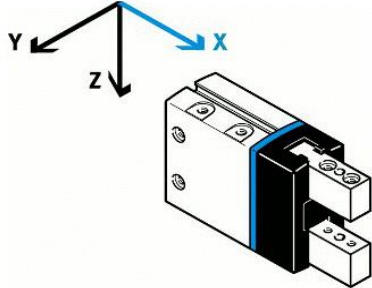
			Notes
Part p.: wet	**F**		
Part p.: presence of holes on the grasping surface	**M**		
Hygienic req.	**F**		
Sensitivity to scratches and bruises	**T**	🟥	
Sensitivity to liquid	**T**		
Sensitivity to water	**T**		
Sensitivity to charge	**F**		
Sensitivity to stain	**T**		
Sensitivity to dust	**T**		Warning: Dust free or hygienic environment required
Magnetic sensitivity	**F**		
Sensitivity to acceleration	**F**		
Heat sensitivity	**F**		

Results

grasping principle	Notes	Environment
Frictional 2f	*Fingers must use soft pads and preferably with larger contact area* *Select grasping direction with lower value of finger stroke*	*Dust free*
Frictional 3f	*Fingers must use soft pads and preferably with larger contact area* *Select grasping direction with lower value of finger stroke*	*Dust free*
Frictional Jaw	*Fingers must use soft pads and preferably with larger contact area* *Jaws must be specifically designed to match object shape* *the grasping direction with the lower value of finger stroke isn't available*	*Dust free*
Vacuum	*Due to the presence of holes on the grasping surface is highly recommended the use of smaller cups instead of just one big suction cup*	
Van der Waals		*Dust free*

Bernoulli		Dust free
Acoustic NF		Dust free
Electrostatic		Dust free

Frictional									
Safety factor	min - static grasping force [N][12]	L - acc	M - acc	H - acc					
		min – dynamic grasping force [N]	min – dynamic grasping force [N]	min – dynamic grasping force [N]	min - stroke per finger [mm]	min - suggested finger length [mm]	min - stroke per finger [mm]	min - suggested finger length [mm]	min - stroke per finger [mm]	min - suggested finger length [mm]
2	0,31392000	0,47088	0,94176	1,88352	64,90	1,00	64,90	39,33	3,00	39,33

[12] Warning: those values are valid in case of a well-balanced grasp, in case of unbalanced grasp consider an higher safety factor and avoid very long fingers.

15" notebook neoprene sleeve

Parameter	Value	\<Frictional\> 2F	3F	J	\<Magnetic\> P	E	Vacuum	Bernoulli	Capillary	Electrostatic	Van der Waals	Needle	Expansion	\<Acoustic\> SW	NF	Ice	Notes
Size	M								X					X		X	
Weight	L																
Density	L																
Shape	Flat-s		X														
Roughness	VH										X						
Slippery	VL																
Stickiness	VL																
Toughness	M																
Stiffness	VL																Warning: avoid high acceleration
Shape can change	T																
Porosity	M																Bernoulli and Vacuum will waste much energy during the grasp, due to the significant level of porosity. Consider a redesign with some parts of the surface with lower porosity in order to ensure a more efficient grasp
Part p.: conductive	F																
Part p.: ferromagnetic	F				X	X											
Part p.: hole for grasping	F												X				
Part p.: planar surface available for grasping	T																

Grasping principle excluded

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Part p.: regular curved surface available for grasping	**F**																			
Part p.: wet	**F**																			
Part p.: presence of holes on the grasping surface	**F**																			
Hygienic req.	**F**																			
Sensitivity to scratches and bruises	**F**																			
Sensitivity to liquid	**F**																			
Sensitivity to water	**F**																			
Sensitivity to charge	**F**																			
Sensitivity to stain	**F**																			
Sensitivity to dust	**F**																			
Magnetic sensitivity	**F**																			
Sensitivity to acceleration	**F**																			
Heat sensitivity	**F**																			

Results

grasping principle	Notes	Environment
Frictional 2f	*Select the grasping direction with the lower value of finger stroke* *Better with multiple frictional gripper or multiple attachment points*	
Frictional Jaw	*Jaws better if with larger contact area* *The grasping direction with the lower value of finger stroke isn't available* *Jaws must be specifically designed to match the object shape*	
Needle		
Electrostatic		Dust free

Bernoulli	Bernoulli and Vacuum will waste much energy during the grasp, due to the significant level of porosity. Consider a redesign with some parts of the surface with lower porosity in order to ensure a more efficient grasp	
Vacuum	Bernoulli and Vacuum will waste much energy during the grasp, due to the significant level of porosity. Consider a redesign with some parts of the surface with lower porosity in order to ensure a more efficient grasp	

Frictional										
Safety factor	min - static grasping force [N]	L - acc	M - acc	H - acc						
		min – dynamic grasping force [N]	min – dynamic grasping force [N]	min – dynamic grasping force [N]	min - stroke per finger [mm]	min - suggested finger length [mm]	min - stroke per finger [mm]	min - suggested finger length [mm]	min - stroke per finger [mm]	min - suggested finger length [mm]
2	4,12020000	6,1803	12,3606	24,7212	203,50	5,00	145,75	123,33	8,25	123,33

Egg		Grasping principle excluded															
		Frictional			Magnetic		Vacuum	Bernoulli	Capillary	Electrostatic	Van der Waals	Needle	Expansion	Acoustic		Solid liquid t. gripper	
Parameter	**Value**	2F	3F	J	P	E								SW	NF		**Notes**
Size	S								🟥					🟥			
Weight	L																
Density	M																
Shape	Bulk - s							🟥							🟥		Warning: Van der Waals gripper have to be specifically designed to match the curved surface of the object
Roughness	VL																
Slippery	VL																
Stickiness	VL																
Toughness	VL											🟥					
Stiffness	VH																
Shape can change	F																
Porosity	VL																
Part p.: conductive	F																
Part p.: ferromagnetic	F				🟥	🟥											
Part p.: hole for grasping	F												🟥				
Part p.: planar surface available for grasping	F									🟥							
Part p.: regular curved surface available for grasping	T																Warning: Van der Waals gripper have to be specifically designed to match the curved surface of the object
Part p.: wet	F																

Part p.: presence of holes on the grasping surface	**F**																		
Hygienic req.	**F**																		
Sensitivity to scratches and bruises	**T**																		
Sensitivity to liquid	**F**																		
Sensitivity to water	**F**																		
Sensitivity to charge	**F**																		
Sensitivity to stain	**F**																		
Sensitivity to dust	**F**																		
Magnetic sensitivity	**F**																		
Heat sensitivity	**F**																		
Acceleration sensitivity	**F**																		
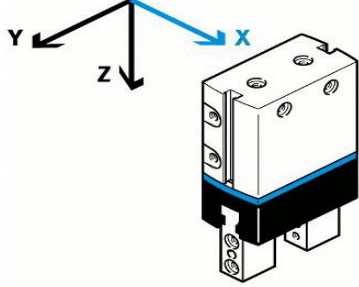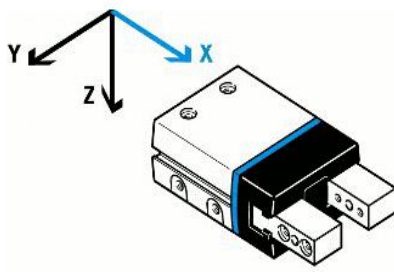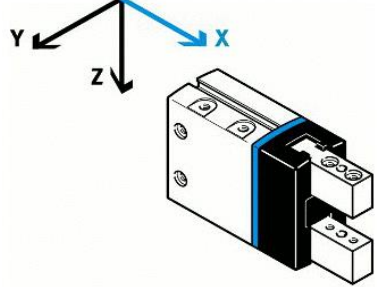
Results

grasping principle	Notes	Environment
Friction 2f	*The use of a force sensor is highly recommended; avoid strong pressure on small contact area.* *Multiple attachment points and/or a large contact area are highly recommended in order to prevent any damage to the grasped object* *Fingers have to be specifically designed to handle fragile objects*	
Friction 3f	*The use of a force sensor is highly recommended* *Multiple attachment points and/or a large contact area are highly recommended in order to prevent any damage to the grasped object* *Fingers have to be specifically designed to handle fragile objects*	
Van der Waals	*Van der Waals gripper have to be specifically designed to match the curved surface of the object*	
Vacuum	*The grasp of spherical objects is feasible only with specific multi cups gripper for curved surfaces* *The grasp of objects with regular curved is feasible only with specific multi cups gripper for curved surfaces*	
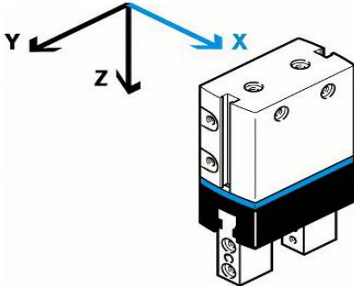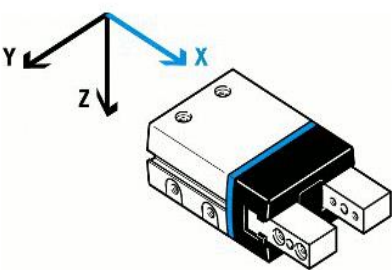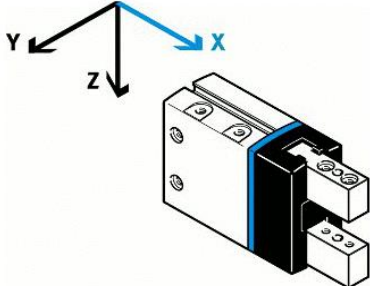
					Frictional					
Safety factor	min - static grasping force [N]	L - acc	M - acc	H - acc						
		min - dynamic grasping force [N]	min - dynamic grasping force [N]	min - dynamic grasping force [N]	min - stroke per finger [mm]	min - suggested finger length [mm]	min - stroke per finger [mm]	min - suggested finger length [mm]	min - stroke per finger [mm]	min - suggested finger length [mm]
2	1,37340000	2,0601	4,1202	8,2404	24,75	19,00	24,75	15,00	31,35	15,00

Multiple attachment points and/or a large contact area are highly recommended in order to prevent any damage to the grasped object

Steel block with holes		Grasping principle excluded																	
		Frictional					Magnetic	Vacuum	Bernoulli	Capillary	Electrostatic	Van der Waals	Needle	Expansion	Acoustic		Solid liquid t. gripper		
Parameter	**Value**	2F	3F	J	P	E									SW	NF		**Notes**
Size	S									🟥					🟥			
Weight	L																	
Density	H																	
Shape	Bulk–p		🟥						🟥	🟥						🟥		
Roughness	VL																	
Slippery	L																	
Stickiness	VL																	
Toughness	VH																	
Stiffness	VH																	
Shape can change	F																	
Porosity	VL												🟥					
Part p.: conductive	T																	
Part p.: ferromagnetic	T																	
Part p.: hole for grasping	N													🟥				
Part p.: planar surface available for grasping	T																	
Part p.: regular curved surface available for grasping	F																	
Part p.: wet	F																	

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Part p.: presence of holes on the grasping surface	VH						🟥				🟥							
Hygienic req.	F																	
Sensitivity to scratches and bruises	F																	
Sensitivity to liquid	F																	
Sensitivity to water	F																	
Sensitivity to charge	F																	
Sensitivity to stain	F																	
Sensitivity to dust	F																	
Magnetic sensitivity	F																	

grasping principle	Notes	Environment
Frictional 2f		
Frictional JAW	*fingers must be specifically designed to match the object shape*	
Magnetic P/E	*Permanent magnetic gripper requires a dedicated releasing system*	
Solid liquid t.		

Frictional										
Safety factor	min - static grasping force [N]	L - acc	M - acc	H - acc						
		min - dynamic grasping force [N]	min - dynamic grasping force [N]	min - dynamic grasping force [N]	min - stroke per finger [mm]	min - suggested finger length [mm]	min - stroke per finger [mm]	min - suggested finger length [mm]	min - stroke per finger [mm]	min - suggested finger length [mm]
2	6,47460000	9,7119	19,4238	38,8476	28,05	17	28,05	17	28,05	17

micro glass sphere		Grasping principle excluded													Notes
		Frictional			Magnetic		Vacuum	Bernoulli	Capillary	Electrostatic	Van der Waals	Solid liquid t. gripepr	Acoustic		
Parameter	Value	2F	3F	J	P	E							SW	NF	Notes
Size	Micro														
Weight	UL														
Density	H														
Shape	Bulk-s						█	█			█			█	
Roughness	VL														
Slippery	L														
Stickiness	VL														
Toughness	L	█	█	█											
Stiffness	VH														
Shape can change	F														
Porosity	VL														
Hydrophobic	F														
Part p.: conductive	F														
Part p.: ferromagnetic	F				█	█									
Part p.: hole for grasping	F														
Part p.: planar surface available for grasping	F														

Part p.: regular curved surface available for grasping	**T**																		
Part p.: wet	**F**																		
Part p.: presence of holes on the grasping surface	**/**																		
Hygienic req.	**F**																		
Sensitivity to scratches and bruises	**T**																		
Sensitivity to liquid	**F**																		
Sensitivity to water	**F**																		
Sensitivity to charge	**F**																		
Sensitivity to stain	**F**																		
Sensitivity to dust	**F**																		
Sensitivity to heat	**F**																		
Magnetic sensitivity	**F**																		
Sensitivity to acceleration	**F**																		

| | | Passive releasing strategies | | | | | | | | | Active Releasing strategies | | | | | | | | | | |
| | | Gripper | | | | | | | Env. | | Forces | | | | | | | Contact area r. | | | |
Parameter	Value	Cond. mat/coat - grounded gr.	Low difference of EV potential	Hydrophobic coating	Low Hamaker constant coating	Hard materials	Rough surface	Spherical fingers	Dry atmosphere	Ionized air	Air pressure (direct/indirect)	Acceleration or vibration	Micro heater	Electrostatic force control	Different adhesion force	Engagement by substrate/tool	Gluing on the substrate	3D handling of the gripper	Additional tool	Roughness change	Electrowetting
Size	Micro																				
Weight	UL											🟥									
Density	H																				
Shape	Bulk-s																				
Roughness	VL																				
Slippery	L																				
Stickiness	VL																				
Toughness	L															🟥			🟥		
Stiffness	VH																				
Shape can change	F																				
Porosity	VL																				
Hydrophobic	F																				
Part p.: conductive	F																				
Part p.: ferromagnetic	F																				

Part p.: hole for grasping	F																								
Part p.: planar surface available for grasping	F																								
Part p.: regular curved surface available for grasping	T																								
Part p.: wet	F																								
Part p.: presence of holes on the grasping surface	/																								
Hygienic req.	F																								
Sensitivity to scratches and bruises	T																								
Sensitivity to liquid	F																								
Sensitivity to water	F																								
Sensitivity to charge	F																								
Sensitivity to stain	F																								
Sensitivity to dust	F																								
Sensitivity to heat	F																								
Magnetic sensitivity	F																								

Grasping Principle	Passive releasing strategies									Active Releasing strategies										
	Gripper							Env.		Forces							Contact area r.			
	Cond. mat/coat - grounded gr.	Low difference of EV potential	Hydrophobic coating	Low Hamaker constant coating	Hard materials	Rough surface	Spherical fingers	Dry atmosphere	Ionized air	Air pressure (direct/indirect)	Acceleration or vibration	Micro heater	Electrostatic force control	Different adhesion force	Engagement by substrate/tool	Gluing on the substrate	3D handling of the gripper	Additional tool	Roughness change	Electrowetting
Friction	🟩	🟩			🟩	🟩	🟩	🟩											🟩	
Solid-liquid state gripper												X								
Van der Waals	🟩			🟩		🟩											🟩			
Electrostatic	X								X		🟩		X	X	🟩		X	🟩		
Capillary			X							X	🟩			X	🟩	X	X	🟩		X
Suction										🟩		🟩			🟩	🟩				

grasping principle	Notes	Environment
Electrostatic		*Dust free*
Acoustic SW		
Solid liquid s.		

					Frictional					
Safety factor	min - static grasping force [N]	L - acc	M - acc	H - acc						
		min - dynamic grasping force [N]	min - dynamic grasping force [N]	min - dynamic grasping force [N]	min - stroke per finger [mm]	min - suggested finger length [mm]	min - stroke per finger [mm]	min - suggested finger length [mm]	min - stroke per finger [mm]	min - suggested finger length [mm]
2	0,00019620	0,000294	0,000589	0,001177	1,10	0,67	1,10	0,67	1,10	0,67

Micro copper sphere		Frictional			Magnetic		Vacuum	Bernoulli	Capillary	Electrostatic	Van der Waals	Solid liquid t.	Acoustic		Notes
Parameter	**Value**	2F	3F	J	P	E							SW	NF	
Size	Micro														
Weight	UL														
Density	H														
Shape	Bulk – s							🟥			🟥		🟥		
Roughness	VL														
Slippery	VL														
Stickiness	VL														
Toughness	VH														
Stiffness	VH														
Shape can change	F														
Porosity	VL														
Hydrophobic	F														
Part p.: conductive	T														
Part p.: ferromagnetic	T														
Part p.: hole for grasping	F														
Part p.: planar surface available for grasping	F						🟥								
Part p.: regular curved surface available for grasping	T														
Part p.: wet	F														

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Part p.: presence of holes on the grasping surface	**/**															
Hygienic req.	**F**															
Sensitivity to scratches and bruises	**F**															
Sensitivity to liquid	**F**															
Sensitivity to water	**F**															
Sensitivity to charge	**F**															
Sensitivity to stain	**F**															
Sensitivity to dust	**F**															
Sensitivity to heat	**F**															
Magnetic sensitivity	**F**															
Sensitivity to acceleration	**F**															

| Parameter | Value | | Passive releasing strategies | | | | | | | | | Active Releasing strategies | | | | | | | | | | |
| | | | Gripper | | | | | | | Env. | | Forces | | | | | | | Contact area r. | | | |
			Cond. mat/coat - grounded gr.	Low difference of EV potential	Hydrophobic coating	Low Hamaker constant coating	Hard materials	Rough surface	Spherical fingers	Dry atmosphere	Ionized air	Air pressure (direct/indirect)	Acceleration or vibration	Micro heater	Electrostatic force control	Different adhesion force	Engagement by substrate/tool	Gluing on the substrate	3D handling of the gripper	Additional tool	Roughness change	Electrowetting
Size	Micro																					
Weight	UL																					
Density	H																					
Shape	Bulk – s																					
Roughness	VL																					
Slippery	VL																					
Stickiness	VL																					
Toughness	VH																					
Stiffness	VH																					
Porosity	VL																					
Hydrophobic	F																					
Part p.: conductive	T														■							
Part p.: ferromagnetic	T																					
Part p.: hole for grasping	F																					
Part p.: planar surface available for grasping	F																					

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Part p.: regular curved surface available for grasping	**T**																							
Part p.: wet	**F**																							
Part p.: presence of holes on the grasping surface	**F**																							
Hygienic req.	**F**																							
Sensitivity to scratches and bruises	**F**																							
Sensitivity to liquid	**F**																							
Sensitivity to water	**F**																							
Sensitivity to charge	**F**																							
Sensitivity to stain	**F**																							
Sensitivity to dust	**F**																							
Sensitivity to heat	**F**																							
Magnetic sensitivity	**F**																							

Grasping Principle	Passive releasing strategies									Active Releasing strategies										
	Gripper							Env.		Forces							Contact area r.			
	Cond. mat/coat - grounded gr.	Low difference of EV potential	Hydrophobic coating	Low Hamaker constant coating	Hard materials	Rough surface	Spherical fingers	Dry atmosphere	Ionized air	Air pressure (direct/indirect)	Acceleration or vibration	Micro heater	Electrostatic force control	Different adhesion force	Engagement by substrate/tool	Gluing on the substrate	3D handling of the gripper	Additional tool	Roughness change	Electrowetting
Friction	x	x			x	x	x	x											x	
Ice												X								
Van der Waals	█			█		█											█			
Electrostatic	x								x		x			x	x		x	x		
Capillary			X							x	x				x	x	x	x		█
Suction										█		█			█	█				

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grasping principle	Notes	Environment
Electrostatic		*Dust free*
Acoustic SW		
Solid-liquid t.		
Magnetic		
Frictional 2f – 3f		
Frictional jaw		

			Frictional								
Safety factor	min - static grasping force [N]	L - acc	M - acc	H - acc							
		min - dynamic grasping force [N]	min - dynamic grasping force [N]	min - dynamic grasping force [N]	min - stroke per finger [mm]	min - suggested finger length [mm]	min - stroke per finger [mm]	min - suggested finger length [mm]	min - stroke per finger [mm]	min - suggested finger length [mm]
2	0,00245250	0,003679	0,007358	0,014715	1,65	1,00	1,65	1,00	1,65	1,00

Micro resistor		Grasping principle excluded												Notes
		Frictional			Magnetic		Vacuum	Bernoulli	Capillary	Electrostatic	Van der Waals	Solid liquid t.	Acoustic		
Parameter	Value	2F	3F	J	P	E							SW	NF	Notes
Size	Micro														
Weight	UL														
Density	H														
Shape	Bulk - c							🟥					🟥	🟥	
Roughness	VL														
Slippery	VL														
Stickiness	VL														
Toughness	H														
Stiffness	VH														
Shape can change	F														
Porosity	VL														
Hydrophobic	F														
Part p.: conductive	T														
Part p.: ferromagnetic	T														
Part p.: hole for grasping	F														
Part p.: planar surface available for grasping	T														
Part p.: regular curved surface available for grasping	T														
Part p.: wet	F														
Part p.: presence of holes on the grasping surface	F														

Hygienic req.	**F**														
Sensitivity to scratches and bruises	**F**														
Sensitivity to liquid	**F**														
Sensitivity to water	**T**								🟥		🟥				
Sensitivity to charge	**F**														
Sensitivity to stain	**F**														
Sensitivity to dust	**F**														
Sensitivity to heat	**T**														
Magnetic sensitivity	**T**				🟥	🟥									
Sensitivity to acceleration	**T**														

Parameter	Value	Cond. mat/coat - grounded gr.	Low difference of EV potential	Hydrophobic coating	Low Hamaker constant coating	Hard materials	Rough surface	Spherical fingers	Dry atmosphere	Ionized air	Air pressure (direct/indirect)	Acceleration or vibration	Micro heater	Electrostatic force control	Different adhesion force	Engagement by substrate/tool	Gluing on the substrate	3D handling of the gripper	Additional tool	Roughness change	Electrowetting
		Passive releasing strategies									**Active Releasing strategies**										
		Gripper							Env.		Forces							Contact area r.			
Size	Micro																				
Weight	UL																				
Density	H																				
Shape	Bulk - c																				
Roughness	VL																				
Slippery	VL																				
Stickiness	VL																				
Toughness	H																				
Stiffness	VH																				
Porosity	VL																				
Hydrophobic	F																				
Part p.: conductive	T													■							
Part p.: ferromagnetic	T																				
Part p.: hole for grasping	F																				
Part p.: planar surface available for grasping	T																				

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Part p.: regular curved surface available for grasping	**T**																						
Part p.: wet	**F**																						
Part p.: presence of holes on the grasping surface	**F**																						
Hygienic req.	**F**																						
Sensitivity to scratches and bruises	**F**																						
Sensitivity to liquid	**F**																						
Sensitivity to water	**T**						 																
Sensitivity to charge	**F**																						
Sensitivity to stain	**F**																						
Sensitivity to dust	**F**																						
Sensitivity to heat	**T**										 												
Magnetic sensitivity	**T**																						

| Grasping Principle | Passive releasing strategies | | | | | | | | | Active Releasing strategies | | | | | | | | | | |
| | Gripper | | | | | | | Env. | | Forces | | | | | | | Contact area r. | | | |
	Cond. mat/coat - grounded gr.	Low difference of EV potential	Hydrophobic coating	Low Hamaker constant coating	Hard materials	Rough surface	Spherical fingers	Dry atmosphere	Ionized air	Air pressure (direct/indirect)	Acceleration or vibration	Micro heater	Electrostatic force control	Different adhesion force	Engagement by substrate/tool	Gluing on the substrate	3D handling of the gripper	Additional tool	Roughness change	Electrowetting
Friction	x	x			x	x	x	■											x	
Solid liquid t.												■								
Van der Waals	x			x		x											x			
Electrostatic	x								x		x		■	x	x		x	x		
Capillary			■							■	■			■	■	■	■			■
Suction										■		■			■	■				

grasping principle	Notes		Environment
Electrostatic			*Dust free*
Van der Waals			
Frictional 2f – 3f			
Frictional jaw			

		Frictional								

Safety factor	min - static grasping force [N]	L - acc	M - acc	H - acc	min - stroke per finger [mm]	min - suggested finger length [mm]	min - stroke per finger [mm]	min - suggested finger length [mm]	min - stroke per finger [mm]	min - suggested finger length [mm]
		min - dynamic grasping force [N]	min - dynamic grasping force [N]	min - dynamic grasping force [N]						
2	0,00013734	0,000206	0,000412	0,000824	1,21	0,37	0,61	0,73	0,61	0,73