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Cognition, Understanding and Behavior

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RobotCub

Development of a cognitive humanoid cub

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Analysis and Pre-selection of the Sensor and Actuator Technologies

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1 Introduction

The aim of the present deliverable is the definition of adequate sensors and actuators in order to embody the iCub. In the Technical Annex the iCub is depicted as a robot shaped like a 2 and a half year old baby acting in a cognitive scenario, performing the tasks (as the neuroscientist and the psychologist suggested) useful to learn, interacting with the environment and humans.
The dimensions of the iCub according to the defined tasks are the main limitation in the choice of the actuators and sensors. Moreover, the iCub is quite an autonomous mobile robot; only the power supply and the high level control is not in the body: the wiring, the dimension of the electronic board for the acquisition or elaboration, the robustness, the safety are all critical in the design.

1.1 The path for the trade off

Starting from the tasks, we deduce the sensors and the actuators to embody the iCub. The neuroscientists and the control design partners elicited a list of sensors and the mechatronic designer partners proposed the kinematics, the actuation systems and the transmission systems. The past experience of each partner is the starting point for a survey in the technologies and the useful tool to discriminate between the options.

1.1.1 The tasks

We defined two main task from which we elicited the requirements to meet in the design: crawling and manipulation seem to be the more challenging tasks involving and stressing the main articulations and all the limbs these tasks show the complexity and the weakness of the mechanics (actuation, transmission and kinematics) and of the sensory system (in terms of range, sensitivity, wiring, load bearing etc.)

1.1.2 The preliminary specification

According to the main tasks and taking in account the cognitive nature of the iCub (embodied as much as possible in an anthropomorphic body) we defined a robot with:

- 2 underactuated hands (17DoFs/ 9DoMs)
- 2 arms (7 DoFs)
- 2 legs (6 DoFs)
- 1 head (6 DoFs)
- 1 spine/waist (3 DoFs)

with a kinematics close to human.

Due to the torques involved, we considered

- DC motors
- hydraulic actuators
- pneumatic actuators

We also considered the EAP actuators and the ultrasonic motors.

In the first prototype the iCub is expected to be endowed with:

- joint angle sensors
- torque/force/tension sensors
- tactile sensors
- switches on the possible contact points

- 3-axis gyroscope/accelerometer
- cameras for vision
- microphones for hearing

1.1.3 The selection methods

Obviously the design deals with the needs determined by the task and the limitations imposed by the dimensions, the costs, and of course by the technology. Before the selection, a survey on the state of the art is useful in order to identify the technology suitable for the iCub. The analysis of the characteristics and the features allow us to select the devices according to the specification.

2 The current sensors technologies in humanoid robots

Humanoid robots are autonomous systems that can grasp and manipulate and/or walk. According to the “cognitive nature” of the iCub, any existing system that exploits sensorimotor coordination is potentially interesting for this project.

A sensor is a device that when exposed to a physical phenomenon (temperature, displacement, force, etc.) produces a proportional output signal (electrical, mechanical, magnetic, etc.). The term transducer is often used synonymously with sensors. However, ideally, a sensor is a device that responds to a change in the physical phenomenon. On the other hand, a transducer is a device that converts one form of energy into another form of energy. Sensors are transducers when they sense one form of energy input and output in a different form of energy [1].
In the purposes of the iCub designers, the sensors have two basic functions:

- the sensors are required components in order to close the control loop and operate in *unstructured environment*
- the sensors are essential components in order to implement a sensorimotor coordination loop and a cognitive robot.

Sensors and actuators play an important role in robotics: they must operate precisely and function reliably as they directly influence the performance of the robot operation. A transducer, a sensor or actuator, like most devices, is described by a number of characteristics and distinctive features. In this section, we describe the different sensing methods for robotic applications and various significant designs that incorporate these methods. This section is divided into several subsections, namely, tactile sensors, force and torque sensors, joint angle and position sensors, vision, etc. (see also Deliverable 8.1).

2.1 Tactile sensors

In neuroscientiific literature, it is customary to refer to tactile sensation when dealing with cutaneous spatio-temporal discrimination of mechanical stimuli [2]. By definition, tactile sensing is the continuously variable sensing of forces and force gradients over an area. This task is often performed by an *mXn* array of industrial sensors called forcels. By considering the outputs from all of the individual forcels, it is possible to construct a tactile image of the explored object. This ability is a form of sensory feedback which is important in development of robots. These robots will incorporate tactile sensing pads in their end effectors. By using the tactile image of the grasped object, it is then possible to determine such factors as the presence, size, shape, texture, and thermal conductivity of the grasped object. The location and orientation of the object as well as reaction forces and torques can also be detected. Finally, the tactile image can be used to detect the onset of slipping. Much of the tactile sensor data processing is parallel with that of vision. Recognition of the contact with objects by extracting and classifying features in the tactile image has been a primary goal of many existing systems [3].

A review of past research (see [4] and [5] for details) has shown that a tactile sensor should have the following characteristics: most important, the sensor surface should be both compliant and durable, and the response of individual forcels should be stable, repeatable, and free from hysteresis. The response must be monotonic, though not necessarily linear. The Harmon's analysis has also generated extended tentative specification for tactile sensors:

- the sensor surface or its covering should combine compliance with robustness and durability
- the sensor should provide stable and repeatable output signals; loading and unloading hysteresis should be minimal
- since some degree of viscoelasticity is always present in plastic and elastomers, the mechanical loss should be independent of frequency in the range of use
- linearity is important although only monotonic response is absolutely necessary; some degree of non-linearity can be corrected through signal processing
- the sensitivity of each individual sensing unit should accordingly possess a faster response, related to their number, when multiplexing is performed.
- spatial resolution should be at least of 1-2 mm as a reasonable compromise between gross grasping and fine manipulation tasks; the area covered and the number of sensing units depend on the geometry and kinematics.

Why does the sense of touch seem to be so neglected? There are several reasons listed below.

Unlike sight and hearing, the sense of touch has no single sensory organ but operates throughout the skin as a distributed and diffuse process. The transduction of tactile signals is distributed over a much wider area than in a single localised sensory organ, such as eyes and ears. The simulation of this through the creation of an artificial tactile skin is a much more difficult task than the development of discrete sensing device.

Tactile sensing trough the skin is not a simple transduction of one physical property into an electrical signal. Touch takes many forms and includes the detection of shape, texture, friction, force, maybe pain or temperature or many other related physical properties. It is not very well understood how these different aspects of the tactile phenomena are related and how they are processed by the nervous system. Consequently, it is not easy to find suitable technological analogies in engineering.

Unlike sight and sounds which are well defined physical quantities we do not know what are the best measure to adopt for a tactile sensor. A whole range of physical properties can be measured and used as tactile signals, but it is unclear which is the most appropriate for a given application. It is worth mentioning an important distinction in tactile sensing between extrinsic and intrinsic sensing:

- Extrinsic sensors are devices that are mounted at or near the contact interface and deal with localised regions

- Intrinsic sensing refers to the derivation of contact data from force sensing within the mechanical structure of the system.

Tactile sensor designers have often referred to the human mechanoreceptors of the glabrous (hairless) skin to draw inspiration ([6],[7],[8],[9],[10],[11]). In most cases however, the development of tactile sensors have focused on the individual sensor components rather than on complete systems for tactile sensing.

State of the art in the area of tactile skins is extensive and it follows a brief overview as a premise in order to select the appropriate technology.

Dario and his colleagues presented numerous works ([12],[13],[14]). They suggested that the artificial skin should possess softness, elasticity, some mechanical resistance and the ability to identify different materials through thermal conductivity. However, much of the work in literature focuses into the sensing devices or better known as robotic tactile sensors ([15], [16], [17], [18]). Excellent reviews for this topic are found in Lee and Nicholls [19], Howe [20], Dario and De Rossi [21]. Capacitive, magnetic, optical, piezoresistive, piezoelectric, and other sensor principles have been proposed, developed and tested. Some examples are found in ([22], [23], [24], [25], [26], [27], [28], [29], [30]).

2.1.1 Piezoresistive and silicon based sensors

Beebe et al [31] describe a silicon based piezoresistive force sensor that addresses the problems of robust packaging, small size and overload tolerance. The sensor measures the force (rather than pressure) applied to a 3 mm raised dome on the device surface. The device exhibits a linear response, good repeatability and low hysteresis, and has a flexible and durable packaging. Arrays could be fabricated with an estimated spatial resolution of 1x3 mm. Trials are described using the device as a finger mounted sensor for measuring pinch force.
Woffenbuttel et al [32] have researched extensively into silicon fabricated sensors and see this approach as a way of avoiding some of the problems associated with elastic membranes such as hysteresis. Their work on piezoresistive and capacitive micromachined sensors has produced designs for arrays of force sensing elements using diaphragms or cantilevers as the sensing principle.
Beccai et al [33] proposed a three axial silicon-based sensors performing quantitative measurements with high reliability.

2.1.2 FSR

A notable commercial development is the FSR (Force Sensing Resistor). These are resistive polymer film elements manufactured by Interlink [34] and are widely used in pointing and position sensing devices such as joysticks. FSRs, being inexpensive and readily available, are found in many experimental tactile systems.
FSRs for normal force measurement are also commercially available on flexible but not conformal polymer substrates from companies such as Tekscan (Tekscan Inc., Ma, U.S.A.). Conductive rubber FSRs have also been developed ([35],[36]). Although examples of advanced robotic hands equipped with FSRs exist ([37],[38]) these sensors generally require serial or manual assembly and provide highly non-linear response. Most of the sensors that have been developed, mainly concern devices able to sense,

in a qualitative way, the contact force (more precisely the contact pressure). In addition, often devices are presented as tactile sensors even if they have only normal force sensing capabilities. Nevertheless, it is indicated by studies of tactile sensing in humans, that shear forces are critical for precision manipulation.

2.1.3 Polymide based sensors

Another approach for the development of tactile skins is the research on sensing textiles by coating traditional fabrics with smart materials (piezoresistive, piezoelectric an piezocapacitive polymer) [39]. An enhancement to the latter approach is represented by the emerging of smart textiles. The latter are textiles with integrated electronics and/or microsystems and are mainly used to create wearable sensing solutions; nevertheless, such approach is not suitable to implement a hand skin-like system (i.e. textiles do not have skin biomechanical features).

Polyimide material has been successfully used in order to develop distributed and flexible tactile sensor arrays. Contact sensors have been implemented in a Kapton® (polyimide based) flexible matrix in order to replicate the fovea where the sensor density decreases starting from the most receptive area (fingertip) to the periphery, as other phalanges and palm ([40],[41]).

Moreover sensors have been developed by integrating other materials with polyimide, for example switch-type tactile sensor arrays able to detect multi-level thresholds of pressure have also been implemented by covering a polyimide based sensor array with rubber and a conductive cloth [42].

Advances in polyimide microfabrication technology are interestingly leading to the development of highly structured polyimide based tactile skins [43] and it has been demonstrated that polyimide based technology and material can be used to implement multimodal tactile sensors that can detect the hardness, thermal conductivity, temperature, and surface contour of a contact object [44]

Among the claimed main advantages are mechanical flexibility, robustness and low fabrication complexity. Nevertheless, in addition to such features reliable tactile feedback of forces and torques and dynamic slip sensing are required for dexterous, dynamic gripping and manipulation by artificial hands. Moreover, a sensitive skin should stretch, and desirably shrink and wrinkle, the way human skin does. Polyimide skins are flexible but not elastic, thus 3D objects cannot be covered freely.

A combined three axis force and slip sensor has been described by Yamada and Cutkosky [45]. A domed tactile head transmits force to three nibs that each rest on polyimide resistive sensor pads. The applied force is resolved into three axes and slip is detected by a piece of piezoelectric PVDF film moulded into the head. The signal rates reported were 014 Hz for force sensing and 0 kHz for the stress rate sensor.

2.1.4 QTC based sensors

Recently, Peratech Ltd, (http://www.peratech.co.uk), presented a new piezoresistive sensors based on quantum tunnel composite material. QTC's have the unique capability of transformation from a virtually perfect insulator to metal like conductor when deformed. That deformation can result from the compression, twisting or stretching of the material and QTC's response can be tuned appropriately to the spectrum of forces applied. The transition from insulator to conductor follows a smooth and repeatable curve, with the resistance dropping exponentially.

What is it that gives QTCs their unique properties? The clue is in the name. Standard composites are usually made from polymers filled with carbon. In these some carbon particles always contact one another creating a conduction path. As pressure is applied, more come into contact and therefore more conduction pathways build up. This conduction process is known as percolation.
In QTCs the conduction process is fundamentally different. In QTCs the metal particles never come into contact. They do however get very close. So close that Quantum Tunnelling is possible between the metal particles.
Quantum Tunnelling is a phenomenon that derives from Quantum Mechanics. In quantum mechanics an electron is not viewed as a solid particle but more like a wave. You can think of the wave as describing the probability that the electron would happen to be at that location. When the wave meets a barrier, for instance a non-conductive material, the wave doesn't instantly go to zero, but decays exponentially. If the wave hasn't reached zero by the time it has reached the other side of the barrier then it emerges on the other side. In other words there is a probability that the electron could be found on the other side of the barrier; the electron has effectively "tunnelled" through the non-conductive barrier.
Example of application can be found in the Shadow Hand [46].

2.1.5 Soft materials for tactile sensing

In the past, most devices have relied on fairly rigid, solid materials for their construction, including the all important contact surface. Perhaps this was the natural place to start as rigid systems have less complexity and there are less variables to control. Following studies of human tactile performance and the physical nature of the tissues and skin, it now seems that softer materials may have much to offer. Elastic overlays and compliant contact surfaces are often advocated for their frictional and other properties, although their low pass filtering behaviour can be a disadvantage. But now even less rigid materials, such as fluids and powders, are being examined.
Shimoga and Goldenberg [47] have examined a range of materials with different consistencies and found that soft surfaces have more desirable characteristics for contact surfaces than hard materials and that of the soft materials, gels are better than plastics, rubber, sponge, or paste, with powders being the second best. The factors considered included impact and strain energy dissipation\ conformability to surfaces and hysteresis effects.
Sawahata, Gong and Osada [48]have described an interesting piezoelectric effect in polymer gels. A weak polyelectrolyte gel was shown to change pH when mechanically compressed. The reverse effect also occurs (an applied potential causes the gel to swell visibly). Using polyacrylamide, the authors constructed a simple tactile cell which captured the electrical change and demonstrated a few millivolts being generated on loading. The fact that human tissue is also composed of electrolytic materials with very similar mechanical properties suggests intriguing possibilities for new designs of sensing fingers.
A different use of gels involves electrorheological effects, for example the application of a strong electric field across a suitable gel can change it from a fluid to a plastic solid. Voyles, Fedder and Khosla [49] have designed a tactile actuator on this principle together with a matching sensor. The actuator-sensor pair has male-female symmetry for the purpose of remote monitoring of touch sensing. The fingertip-shaped sensor detects contact events on its external surface using a gel layer as a dielectric in

capacitive sensing, while the similarly shaped actuator (or tactor) recreates the remotely sensed tactile events on its internal surface by changing the solidity of areas of the gel in contact with the human operator.

2.1.6 Other sensors

Gray and Fearing [50] report on an 8x8 capacitive fabricated array that is 1 mm^2 in area. This gives a spatial resolution at least 10 times better than the human limit of 1 mm and is intended for medical applications involving small manipulators and endoscopic surgery. It could be mass produced and therefore disposable (a fairly novel idea in tactile sensing). Severe hysteresis was the main drawback. For capacitive sensors also see the recent work at the Tokyo university [51].

Omata and Terunuma [52] point out that most sensors are incapable of sensing many of the range of physical properties that materials exhibit[Most sensors measure pressure or force and are unable to sense many effects that are experienced by humans, e.g., friction, stickiness, texture, hardness, and elasticity. With a view to palpation applications in medical examination they argue that hardness and softness detection require different approaches, especially for sensing variations in soft tissue, and describe a sensor that approximates to humans in this respect. The sensor has a piezoelectric resonator, driven at 61 kHz, and works on the principle that contact with an object will cause a change in resonating frequency. The device is packaged into an acrylic tube, 15 mm diameter by 65 mm long, and in simulated cancer tests it detected 3 mm diameter glass balls 20 mm below the surface of a silicone breast model. The main problems were the need to maintain a constant contact pressure (20 grams) and a slow time response.

Mixed function sensing is an interesting possibility. Li and Shida [53] describe a multifunction sensor consisting of two interleaved planar spiral coils 35 mm in diameter. The coils can be used in three ways: as a capacitive sensor where the dielectric constant of the object affects the capacitance between the coils; as an inductor where the frequency transfer function between the coils can distinguish a magnetic, non magnetic or nonconducting material; and as a thermal sensor where one coil acts as a heater and the other a temperature sensing resistor. Problems include the thermal time response of several seconds, the need to insulate metallic objects (cellophane tape was used), and an implicit assumption of constant applied contact pressure.

A different but promising looking technique is acoustic ultrasonic sensing. Microphones are known to be useful for detecting surface noise that occurs at the onset of motion and during slip. Ando and Shinoda describe a device that senses contact events from their ultrasonic emission at the contact point. A PVDF polymer is used in a 2x2 array of receivers to localise the contact point on a silicone rubber sensing dome. They reported that this sensor is very effective in detecting slip and surface roughness during movement. In a variation of the design, Shinoda and Ando [54], used ultrasonic transmitters and receivers to detect changes in wavefronts due to distortion and could detect displacements as small as ten micrometers.

2.2 Force and torque Sensors

Force sensors are required for a basic understanding of the response of a system. For example, cutting forces generated by a machining process can be monitored to detect a tool failure or to diagnose the causes of this failure in controlling the process parameters, and in evaluating the quality of the surface produced. Force sensors are

used to monitor impact forces in the automotive industry. Robotic handling and assembly tasks are controlled by detecting the forces generated at the end effector. Direct measurement of forces is useful in controlling many mechanical systems.
Due to the use of tendon transmission in robotics, in this section tension sensor will be considered. The tension is and indirect measure of the force or torque applied. Likewise in the hydraulic o pneumatic system pressure sensors are useful to determine the force or the torque applied.
The most of force sensors are based on measuring a deflection caused by the force. Relatively high deflections (typically, several micrometers) would be necessary for this technique to be feasible. The excellent elastic properties of helical springs make it possible to apply them successfully as force sensors that transform the load to be measured into a deflection. The relation between force and deflection in the elastic region is demonstrated by Hooke’s law.

2.2.1 Strain Gauge-Based Force Sensor

Force sensors that employ strain gage elements or piezoelectric (quartz) crystals with built-in microelectronics are common. Both impulsive forces and slowly varying forces can be monitored using these sensors. Of the available force measuring techniques, a general subgroup can be defined as that of load cells. Load cells are comprised generally of a rigid outer structure, some medium that is used for measuring. A lot of strain gage-sensor based are depicted in literature.
The DLR developed an ad hoc strain-gaged based six axes load cell used in the fingertip of the DLR hand. The diameter is about 20mm. The force and the torque measure range ar 10N for F_x and F_y, 40N for F_z, 150Nmm for the M_x, M_y and M_z respectively. Also a 200% mechanical overload protection is provoded in the structure. Themaechanical structure of the sensor is composed of two sensitive parts, one is a round plate (base element) with three symmetrical sensitive beams, another one is a cantilever beam. There are three elastic beams in the base element, wich are sensitive to the M_x, M_y and F_z. The cantilever beam is a rectangular pipe with a very thin wall. By using specialized torsion shear strain gages it can measure the F_x, F_y and M_z. [55].

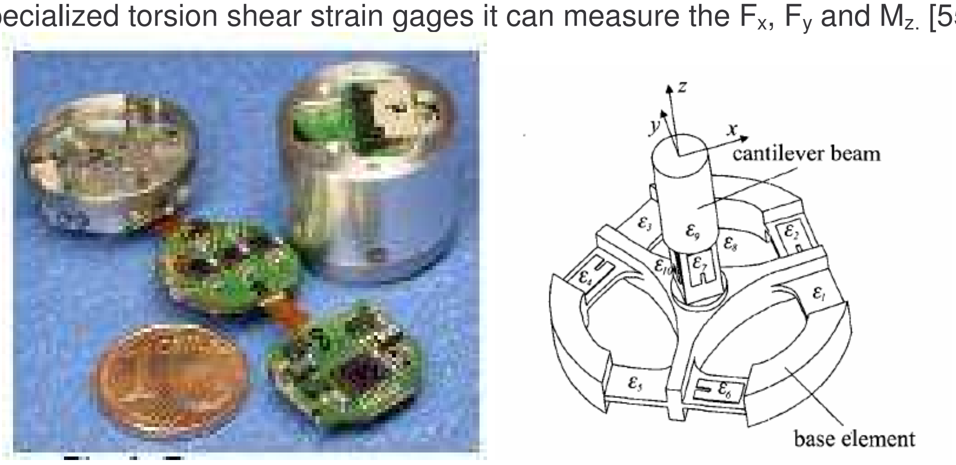


Fig 2.2.1.1

With the same aim the RCH1 hand is endowed with a smaller three axis sensors in the fingertips detecting about 5N on each components in a 12mm diameter [56].

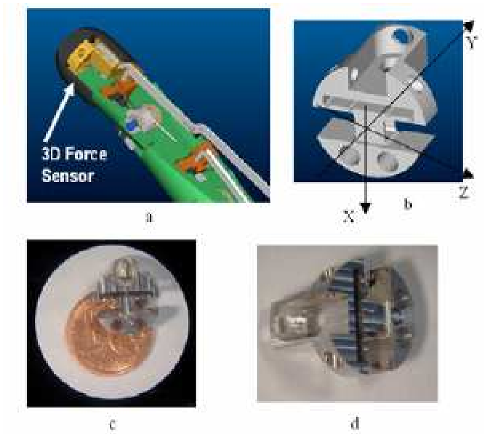


Fig 2.2.1.2

Six axes load cell is in the legs of ASIMO [57], in HRP-2 [58] and in Robonaut [59].

Commercial load cell are supplied by:
- http://www.precisiontransducers.com/
- http://www.i-s-i.com
- http://www.cooperinstruments.com/
- http://www.amtiweb.com
- http://www.ati-ia.com/
- http://www.mech.canterbury.ac.nz/research/hamlet/flc.html
- http://www.sandia.gov/isrc/Load_Cell/load_cell.html
- http://www.futek.com/
- http://www.sensotec.com/loadcellnew.htm
- http://www.burster.com/products.html
- http://www.entran.com/ltoc.htm

The dimension, the load and the overload, and the price are the parameter to take in account in the selection.

Obviously, load button cell are often used in the tension measuring. But the researchers also developed *ad hoc* strain gage-based tension sensor.
Utah hand has one of the first implementation involving strain gages in measuring the cable tension: an idler pulley is assembled on a cantilever beam. The cable/tendon running on the pulley generates a flexion in the beam. The cantilever beam deflection is detected by the means of strain gages eliciting the tension (through the moment generated) [60].

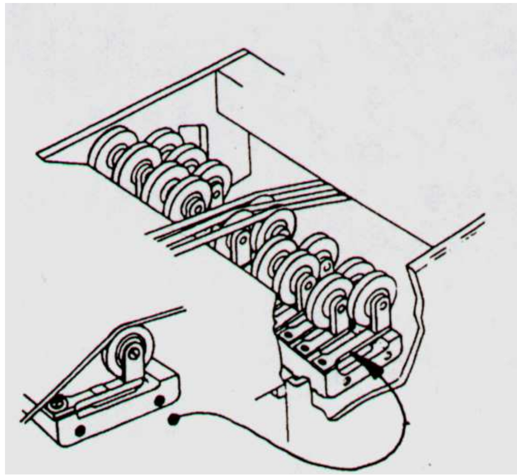


Fig 2.2.1.3

The same operating principle is applied in the tension sensor proposed by Caldwell et al [61]. In the application the cable tension is also measured using miniature cantilever beams, see figure below.

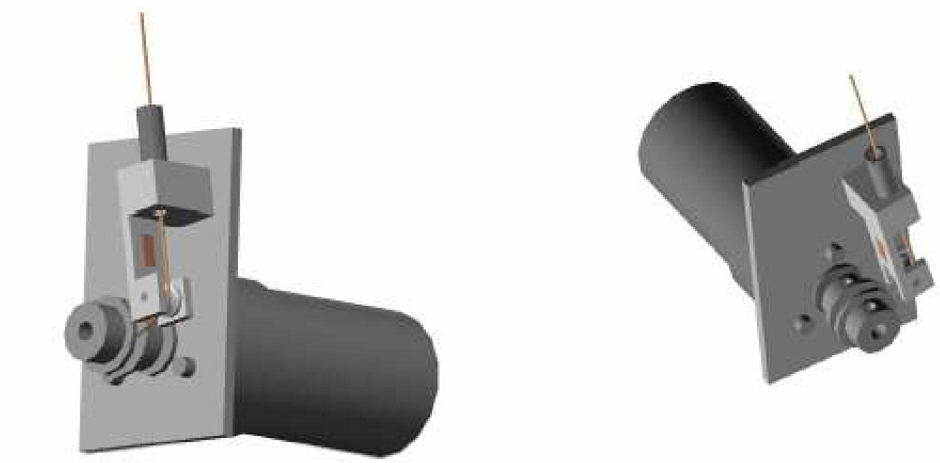
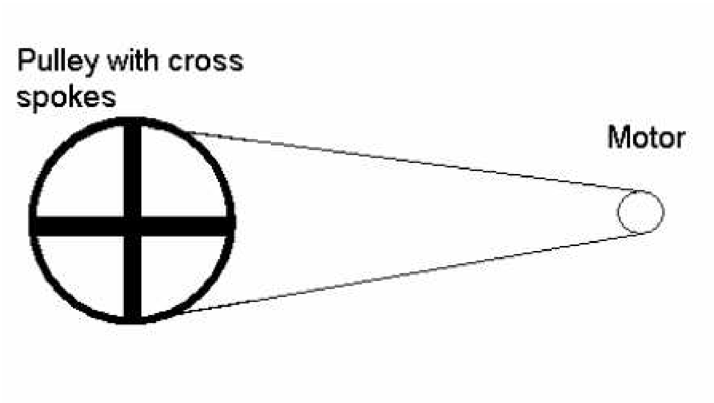


Fig. 2.2.1.4 Cable Tension Measurement using a strain gauge load element

As it can be seen two strain gauges are placed on both sides of the metal beam that is subjected to strain. The strain gauges are connected in a half bridge configuration. The metal element that bares the strain gauges is precisely machined with a smooth finish in order to ensure predictable and linear behaviour of the strain gauge. The thickness of the material is very important for the sensitivity and the overall behaviour of the sensor. Not too thin to avoid permanent deformation- Not too thick to avoid low sensitivity and high noise from higher amplification. The initial no-load cable tension may also affect the accuracy of the measurement.



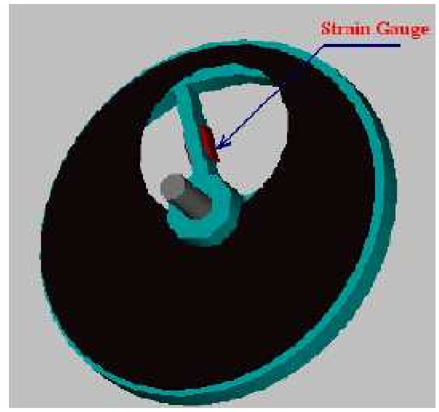


Fig. 2.2.1.5

For tension measuring, Caldwell and his collegues also proposed a different arrangement: the two strains gauges are mounted on a cross structure internally machined on the joint pulley. A pair of strain gauges are mounted at the opposite sites of one of the four cross spokes. Calibration of the torque sensor can be easily performed by applying external known torque loads using a load cell. This arrangement will be more suitable for joint torque sensing for in major joints (legs, spine and arm) while the firts is more suitable for measuring the cable tension in places where space is limited and the beam with the strain gauges needs to be placed remotely at the actuator site[62].

In the DIST hand the bending of a beam structure is generated as in figure by the anthagonistic tendons. In this way the strain gages provide the tension exerted on the cable [63].

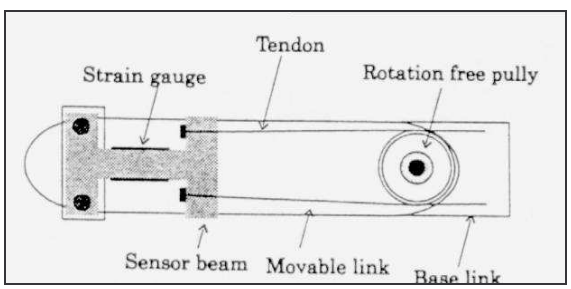


Fig 2.2.1.6

2.2.2 Other Force Sensors

In hydraulic or pneumatic devices, the pressure is a fundamental measure to define the applied torque or force. Most pressure sensor used today do not use the old fashioned *fluid barometer* principle, wherein the height of a column of liquid is measured as an indicator of pressure, but, instead, the they used sealed gas or vacuum-filled cavities: these are referred as *aneroid* pressure sensors. The basic operating principle of such an aneroid pressure sensor is to couple the pressure to be measured to one surface of a membrane and to measure its deflection with strain gage or capacitive sensors. Of course micromachined piezo resistive pressure sensors are in this frame [64].

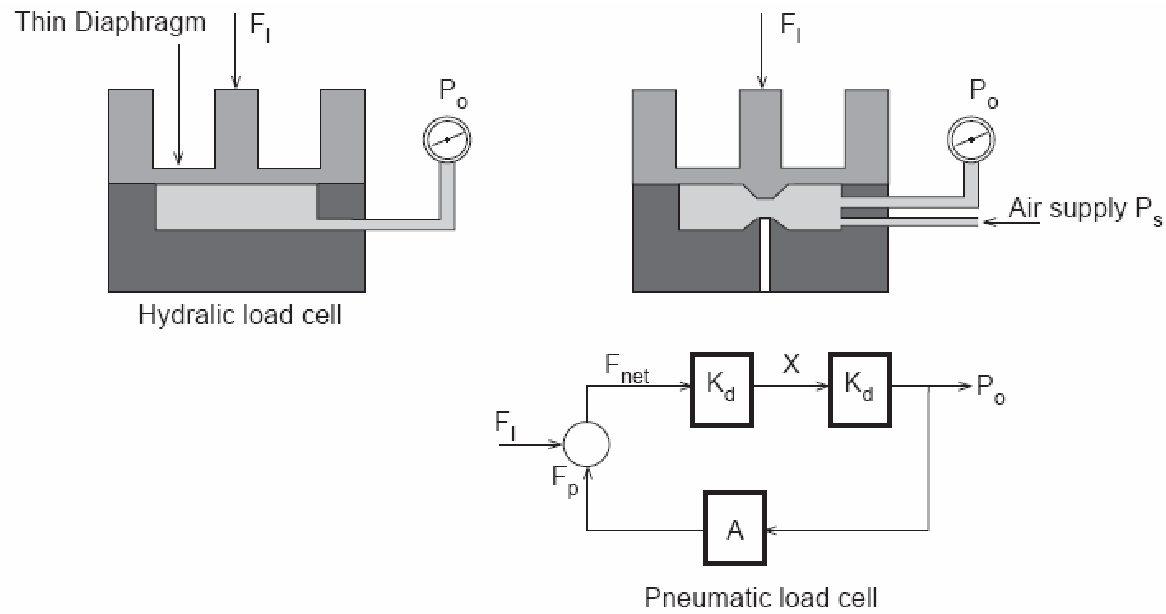


Fig 2.2.2.1

Magnetoelastic transducer devices operate based on the Joule effect; that is, a ferromagnetic material is dimensionally altered when subjected to a magnetic field. The principle of operation is as follows: initially, a current pulse is applied to the conductor within the waveguide. This sets up a magnetic field circumference-wise around the waveguide over its entire length. There is another magnetic field generated by the permanent magnet that exists only where the magnet is located. This field has a longitudinal component. These two fields join vectorially to form a helical field near the magnet which, in turn, causes the waveguide to experience a minute torsional strain or twist only at the location of the magnet. This twist effect is known as the *Wiedemann effect* [65]. Magnetoelastic force transducers have a high frequency response (on the order of 20 kHz). Some of the materials that exhibit magnetoelastic include Monel metal, Permalloy, Cekas, Alfer, and a number of nickel–iron alloys. Disadvantages of these transducers include: (1) the fact that excessive stress and aging may cause permanent changes, (2) zero drift and sensitivity changes due to temperature sensitivity, and (3) hysteresis errors.

Fiber optic strain sensors are miniature interferometers ([66],[67]). Many commercially available sensors are based on the Fabry–Perot interferometer. The Fabry–Perot interferometer measures the change in the size of a very small cavity.

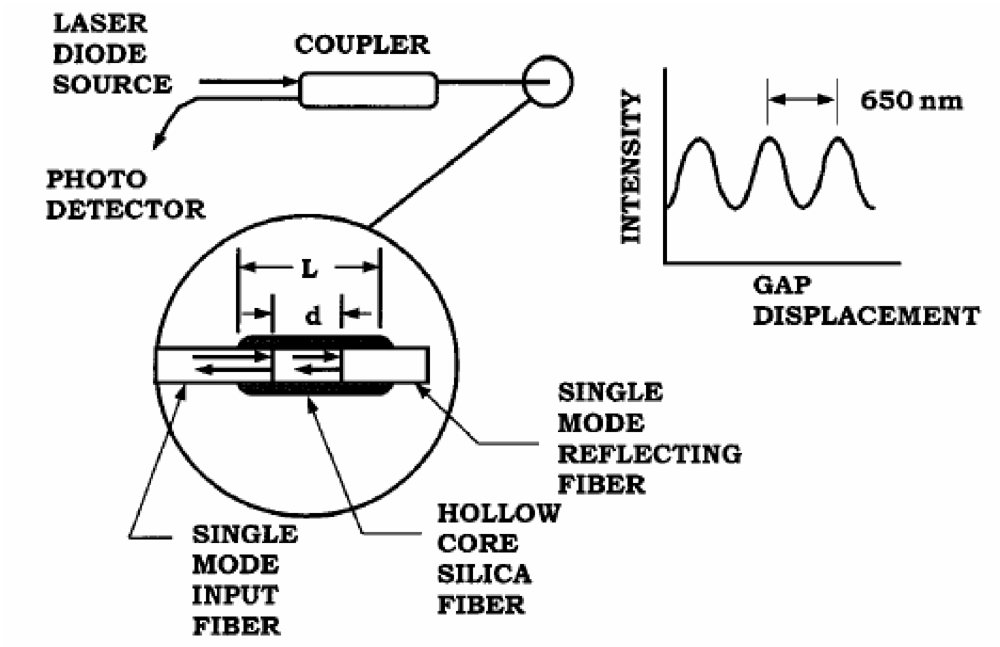


Fig 2.2.2.2

Fabry–Perot strain sensors (as in the figure above) comprise a laser light source, single-mode optical fibres, a coupler (the fibre optic equivalent of a beam splitter), a cavity that senses strain, and a photodetector. Light leaves the laser diode. It passes down the fibre, through the coupler, and to the cavity. The end of the fibre is the equivalent of a partially silvered mirror. Some of the light is reflected back up the fibre and some is transmitted. The transmitted light crosses the cavity and then is reflected from the opposite end back into the fibre where it recombines with the first reflected beam. The two beams have a phase difference related to twice the cavity length. The recombined beam passes through the coupler to the photodetector. If the two reflected beams are in phase, there will be constructive interference. If the two beams are out of phase, there will be destructive interference. The cavity is bonded to a specimen. When the specimen is strained, the cavity stretches. This results in a phase change of the cavity beam, causing a cycling between constructive and destructive interference. For a 1.3 mm light source, each peak in output corresponds to a 650 nm gap displacement. The gap displacement divided by the gap length gives the strain. The output is continuous between peaks so that a 3 mm gage can resolve 1 mstrain. [68]
A very simple device to have a rough idea of the torque exerted by a DC motor is a sensing resistor detecting the current consumption (as depicted in the figure with the H bridge. Example of application can be found in robotic arms such as the ARMAR [69] and the Waseda arm [70].

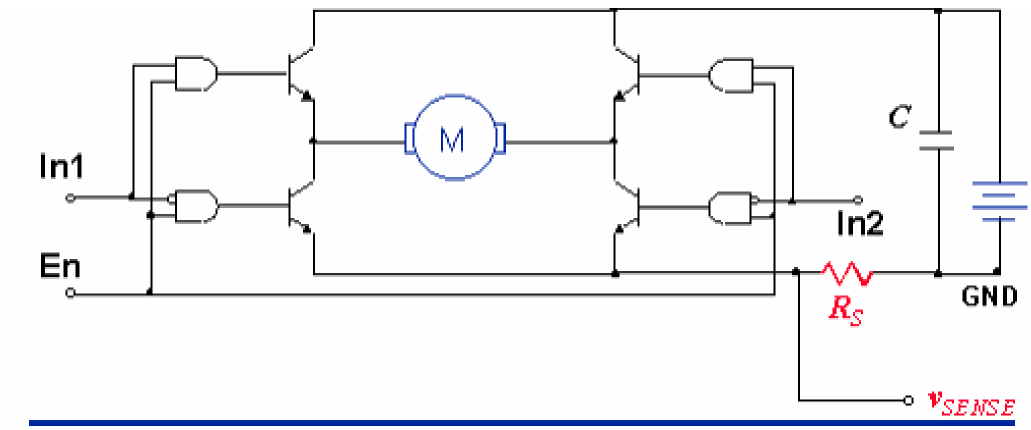


Fig 2.2.2.3

2.3 Joint angle and position sensors

By far the most common motions in mechanical systems are linear translation along a fixed axis and angular rotation about a fixed axis. More complex motions are usually accomplished by composing these simpler motions and often detected by composing simpler sensors.

2.3.1 Potentiometer

Broadly, a potentiometers resistive element can be classified as either *wirewound* , or *nonwirewound* . Wirewound elements contain tight coils of resistive wire that quantize measurement in step-like increments. In contrast, nonwirewound elements present a continuous sheet of resistive material capable of essentially unlimited measurement resolution.

Wirewound elements offer excellent temperature stability and high power dissipation abilities. The coils quantize measurement according to wire size and spacing. Providing the resolution limits are acceptable, wirewound elements can be a satisfactory choice for precision measurement; however, conductive plastic or hybrid elements will usually perform better and for considerably more cycles. These and other popular nonwirewound elements are described in more detail below. Conductive plastic elements feature a smooth film with unlimited resolution, low friction, low noise, and long operational life. They are sensitive to temperature and other environmental factors and their power dissipation abilities are low; however, they are an excellent choice for most precision measurement applications. Hybrid elements feature a wirewound core with a conductive plastic coating, combining wirewound and conductive plastic technologies to realize some of the more desirable attributes of both. The plastic limits power dissipation abilities in exchange for low noise, long life, and unlimited resolution. Like wirewounds, hybrids offer excellent temperature stability. They make an excellent choice for precision measurement. Cermet elements, made from a ceramic-metal alloy, offer unlimited resolution and reasonable noise levels. Their advantages include high power dissipation abilities and excellent stability in adverse conditions. Cermet elements are rarely applied to precision measurement because conductive plastic elements offer lower noise, lower friction, and longer life. Carbon composition elements, moulded under pressure from a carbon–plastic mixture, are inexpensive and very popular for

general use, but not for precision measurement. They offer unlimited resolution and low noise, but are sensitive to environmental stresses (e.g., temperature, humidity) and are subject to wear.
In the following table the main advantages and drawback dealing with potentiometers.

Advantages	Disadvantages
Easy to use	Limited bandwidth
Low cost	Frictional loading
Nonelectronic	Inertial loading
High-amplitude output signal	Wear
Proven technology	

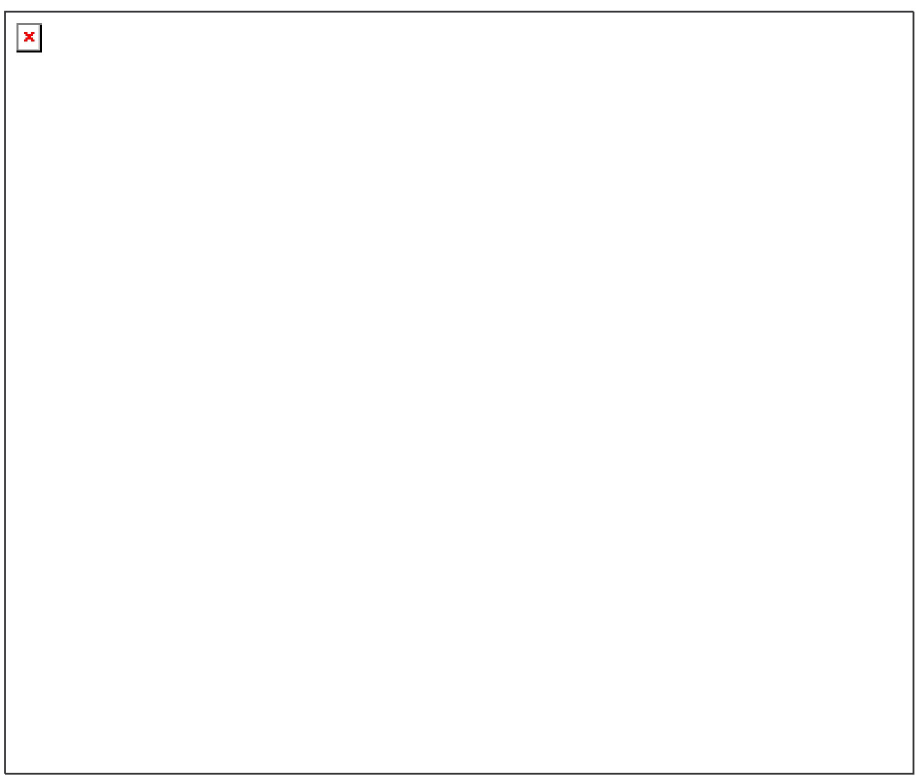
Table 2.3.1.1

Potentiometer are successfully used in the DLR arm [71] but, where is possible, contactless sensors are preferable, because of the limited lifetime or the potentiometer.

2.3.2 Encoders

Optical encoders are used to measure either angular or linear positions. Those used for angular detection are commonly called rotary or shaft encoders, since they usually detect the rotation of a shaft. Optical encoders encompass a variety of devices, all of which use light as the means to transform movement into electrical signals. All devices have two basic building blocks: a main grating and a detection system. It is the position of one with respect to the other that is detected. The main grating represents the measurement standard. For linear measurements, the main grating, commonly called the scale, is one or more sets of parallel lines of constant or specially coded pitch supported by a substrate. Similarly, a rotary encoder has a grating with radial lines on a disk. Both linear and rotary encoders can, in principle, be absolute or incremental, although in practice, linear absolute encoders employing optical principles are quite uncommon and have drastically limited performance characteristics (accuracy, resolution, and/or maximum operating speed).
The *incremental encoder* detects movement relative to a reference point. As a result, some form of reference signal is usually supplied by the encoder at a fixed position in order to define a reference position. The current position is then incremented (or decremented) as appropriate. Multiple reference marks can also be used, where the distance between successive marks is unique so that as soon as two successive marks have been detected, it becomes possible to establish absolute position from then on.
The reference point can also be mechanical. Should power be lost or a signal transmission error occur, then the absolute position is lost and the encoder must return to one or more reference points in order to reset its counters. Unfortunately, a loss of count may not be detected until a reference point is re-accessed. Furthermore, reading errors may accumulate.
On the other hand, *absolute encoders* produce a set of binary signals from which the absolute position can be deduced without the knowledge of the previous motion history. The current position is known right from powering-on. In the case of absolute rotary encoders, single and multiturn devices are available. Multiturn devices use an internal mechanical transmission system to drive a second grating that serves as turn counter. Most incremental encoders use quadrature signals as output to carry the motion

information. Some encoders use one square-wave signal, which is used for position in one direction only. Also, this single square wave can be fed into either a PLC (programmable logic controller) or another electronic interface that converts this signal to a rate or RPM (revolution per minute) for speed indication. However, whenever bidirectional operation is required, quadrature signals are necessary. Quadrature signals come in analogue or digital form. The analogue form consists simply of a sine and a cosine signal. The number of sinusoidal cycles per unit change of the measured variable (a revolution or 360° for a rotary encoder) determines the basic resolution of the encoder prior to interpolation. The digital form consists of two square-wave trains, 90° (often called electrical degree) out of phase. The 90° phase lag is indispensable in order to detect the motion direction and hence increment or decrement the position counter accordingly. The main optical techniques to generate the quadrature signals are geometric masking, Moiré fringes, and diffraction based. For linear encoders, the basic resolution is related to the distance travelled by the grating in order for the encoder to produce one full quadrature cycle. For rotary encoders, the basic resolution is usually described as the number of quadrature cycles per turn. The resolution of an encoder system can be increased by electronic means. With analogue quadrature signals, it is possible to interpolate within each quadrature cycle. The limit of the interpolation factor depends on the quality (mark space, quadrature separation, and jitter) of the basic signals. With square-wave signals, multiplication by a factor of two or four is easily achieved. Increasing the resolution in this manner does not, however, improve the trueness, often called accuracy (or linearity) of the measurement. Absolute encoders are classified according to the type of code used. The main four codes are Gray, binary (usually read by vee-scan detection), optical resolving, and pseudorandom. All absolute encoders use geometric masking to generate the code [72].



Tab 2.3.2.1

Manufacturer	Model Number	Steps per turn	No. of turn	Price[a]
BEI	M25	65,536	1	$2130
BEI	MT40	512	16	$1240
BEI	MT40	65,530	512	$5000
Gurley	25/04S	131,072	1	$1900
Heidenhain	ROC 424	4096	4096	
Lucas Ledex	AG60E	360 or 512	1	$486
Lucas Ledex	AG661	4096	4096	$1260
TR Electronic	CE65[b]	8192	4096	$1408

[a] Based on orders of one unit. Must not be used to compare products since many other characteristics, not listed in this table, determine the price.
[b] Programmable output.

Tab 2.3.2.2

TABLE 6.21 Commercial Optical Linear Incremental Encoders

Manufacturer	Model No.	Output type	Pitch[a]	Resolution[b]	Length (mm)	Price[c](length)
Canon	ML-16+	Sine wave	1.6 µm	0.4 µm	To 300	$1525 (50 mm)
Canon	ML-08+	Sine wave	0.8 µm	0.2 µm	To 150	$3100
Gurley	LE18	Square wave	20 µm	0.1 µm	To 1500	$750 (1000 mm)
Gurley	LE25	Square wave	20 µm	0.1 µm	To 3000	$800 (1000 mm)
Heidenhain	LS603	Sine wave	20 µm	5 µm	To 3040	$932 (1020 mm)
Heidenhain	LIP401	Sine wave	2 µm	0.005 µm	To 420	$4000 (100 mm)
Renishaw	RG2	RS422A	20 µm	0.5 µm	To 60,000	$640 + $360/1000 mm
Sony	BS75A-30NS	Square wave	0.14 µm	0.05 µm	30	$2628

[a] Period of the quadrature cycle without electronic divide-by-four or interpolation.
[b] With electronic interpolation supplied by the manufacturer.
[c] Based on orders of one unit. Must not be used to compare products since many other characteristics, not listed in this table, determine the price.

Tab 2.3.2.3

BEI Sensors and Motion Systems Company	Renco Encoders Inc.
Encoder Systems Division	26 Coromar Drive
13100 Telfair Avenue	Goleta, CA 93117
Sylmar, CA	Tel: (805) 968-1525
Tel: (848) 341-6161	Renishaw plc,
Canon USA Inc.	Transducer Systems Division
Components Division	Old Town, Wotton-under-Edge
New York Headquarters :	Gloucestershiire GL12 7DH
One Canon Plaza	United Kingdom
Lake Success, NY 11042	Tel: +44 1453 844302
Tel: (516) 488-6700	TR Electronic GmbH
DR. JOHANNES HEIDDENHAIN GmbH	Eglishalde 6
DR.-Johannes-Heidenhain-Strasse 5	Postfach 1552
D83301 Traunreut, Deutschland	D-7218 Trossingen
Tel: (08669)31-0	Germany
Gurley Precision Instruments Inc.	Tel: 0 74 25/228-0
514 Fulton Street	Sony Magnescale Inc.
Troy, NY 12181-0088	Toyo Building, 9-17
Tel: (518) 272-6300	Nishigotanda 3-chome
Ledex Products	Shinagawa-ku, Tokyo
Lucas Control Systems Products	141 Japan
801 Scholz Drive	Tel: (03)-3490-9481
P.O. Box 427	
Vandalia, OH 45377-0427	
Tel: (513) 454-2345	

Tab 2.3.2.4

The absolute encoders seem to be too big for the Cub. The optical incremental encoder can be found in the Armar [67], on each motor shaft of the Robonaut humanoid [59], in the DLR arm and hand [69].

2.3.3 Hall Effect sensor

The Hall Effect is a property exhibited in a conductor affected by a magnetic field. A voltage potential V_H, called the Hall voltage, appears across the conductor when a magnetic field is applied at right angles to the current flow. Its direction is perpendicular to both the magnetic field and current. The magnitude of the Hall voltage is proportional to both the magnetic flux density and the current. The magnetic field causes a gradient of carrier concentration across the conductor. The larger number of carriers on one side of the conductor, compared to the other side, causes the voltage potential V_H [73]
Interesting packaging are from Honeywell Inc. (http://www.honeywell.com): the ss490 series shows good specification and dimension.

SPECIFICATIONS (V_s = 5.0 v, t_a = -40 to +125°C, unless otherwise noted)

Catalog Listing Type		SS495A	SS495A1	SS495A2	SS495B	SS496A	SS496A1	SS496B
Supply Voltage (VDC)		4.5 to 10.5						
Supply Current @ 25°C (mA)	Typ.	7.0						
	Max.	8.7						
Output Type (Sink or Source)		Ratiometric						
Output Current (mA)								
Typ. Sink or Source	Vs > 4.5 V	1.5						
Min. Source	Vs > 4.5 V	1.0						
Min. Sink	Vs > 4.5 V	0.6						
Min. Sink	Vs > 5.0 V	1.0						
Operating Temperature		-40 to +150°C (-40 to +302°F)						
Magnetic Range, Gauss	Typ.	± 670	± 670	± 670	± 670	± 840	± 840	± 840
	Min.	± 600	± 600	± 600	± 600	± 750	± 750	± 750
Output Voltage Span	Typ.	0.2 to (Vs-0.2)						
	Min.	0.4 to (Vs-0.4)						
Null (Output @ 0 Gauss, V)		2.50 ±0.075	2.50 ±0.075	2.50 ±0.100	2.50 ±0.150	2.50 ±0.075	2.50 ±0.075	2.50 ±0.150
Sensitivity (mV/G)		3.125 ±0.125	3.125 ±0.094	3.125 ±0.156	3.125 ±0.250	2.50 ±0.100	2.50 ±0.075	2.50 ±0.200
Linearity,	Typ.	-1.0						
% of Span)	Max.	-1.5						
Temperature Error								
Null Drift	(%/°C)	± 0.06	± 0.04	± 0.07	± 0.08	± 0.048	± 0.03	± 0.06
Sensitivity Drift	(%/°C)							
≥ 25°C Max.		-0.01, +0.05	-0.02, +0.06	-0.02, +0.06	-0.01, +0.05	- 0.01, +0.05	-0.01, +0.05	- 0.02, +0.06
< 25°C Max.		0.0, +0.06	0.0, +0.06	- 0.01, +0.07	- 0.02, +0.06	0.0, +0.06	0.0, +0.06	- 0.02, +0.06

Tab. 2.3.3.1

This sensors have been used in the Dist [61]as in the figure, in DLR Hand, in the Utah hand [60] and in the UB hand [74] and in RTR2 hand [75].

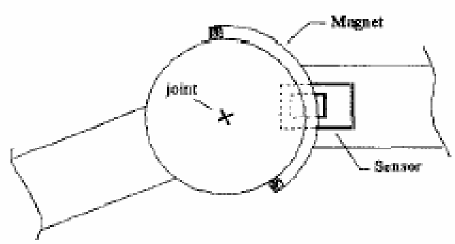


Fig. 2.3.3.1

2.3.4 Switches

This subsection deals with the contactless switches. These switches are used as zero sensors, especially with no absolute sensors.
Allegro Microsys Inc. (http://www.allegromicro.com) provide the family 1100 (http://www.allegromicro.com/sf/1101/) with identical dimension and packaging of the Honeywell ss490.
Optical switches are provided by Omron Corp. (http://www.omron.com/); the smaller ones are from the EE-SXxxxx family in 1x3 packaging.

2.3.5 Other position sensor

Other physical effects are exploited in the position measurement: inductive sensors, capacitive, sensors, magnetoresistive sensor, ultrasonic sensors, optical sensors (and laser sensors).

We just want mention the megnetoresistor sensor from Honeywell HMC1512 (http://www.ssec.honeywell.com/magnetic/datasheets/hmc1501-1512.pdf): this device in a 4x5 mm packaging is field direction sensitive and so suitable for angular detection. Please also see the 'Optical flex sensor [76]. This sensor consists of a flexible tube having two ends, a reflective interior wall within the flexible tube and a light source placed within one end of the flexible tube and a photosensitive detector placed within the other end of the flexible tube to detect a combination of direct light rays and reflected rays when the flexible tube is bent.

2.4 Other sensors

2.4.1 Digital Camera (Dragonfly)

The head is equipped with two digital cameras from PTGrey-Research. During the test phase the Firefly2 model was used. It contains a remote head that is embedded in the eyeballs while the electronics are separated. The next version will be equipped with DragonFly cameras from the same supplier, since it provides more flexible control over the camera parameters and higher quality, see specifications below.

Experiments were conducted with these cameras to test the lens quality. The main conclusion is that depth of field is good enough to provide reasonable quality images both at short and longer distances.

Imaging Device
1/3'' Sony CCD 640x480 Option: ICX084, B&W or Color 1024x768 Option: ICX204, B&W or Color HAD image sensor with square pixels Progressive scan
Supported frame rates:
640x480 Option: 30, 15, 7.5, 3.75 FPS 1024x768 Option: 15, 7.5, 3.75, 1.875 FPS
Signal to noise ratio: > 60dB
Supported formats
B&W models: 8-bit or 16-bit Mono Color models: 8-bit or 16-bit Bayer tiled image (color space conversion done on the host computer)
Synchronization: < 120µs
Dimensions: 64 X 51mm


2.4.2 Inertial sensors

The other main sensor in the head is an inertial sensor providing angular and linear accelerations as well as absolute head orientation. The MTx is a small and accurate 3DOF Orientation Tracker. It provides drift-free 3D orientation as well as kinematic data: 3D acceleration, 3D rate of turn (rate gyro) and 3D earth-magnetic field. The sensor is available with an open source library for development.

Output Orientation performance 3D orientation (Quaternions/Matrix/Euler angles) Dynamic Range: all angles in 3D 3D acceleration Angular Resolution[1]: 0.05 deg 3D rate-of-turn Static Accuracy (Roll/Pitch): <0.5 deg 3D earth-magnetic field (normalized) Static Accuracy[2] (Heading): <1 deg Temperature Dynamic Accuracy[3]: 2 deg RMS **Sensor performance** rate of turn acceleration magnetic field temperature Dimensions 3 axes 3 axes 3 axes - Full Scale (standard) ± 1200 deg/s ± 17 m/s^2 ± 750 mGauss -55…+125 ℃ Linearity 0.1% of FS 0.2% of FS 0.2% of FS <1% of FS Bias stability[4] (1ó) 5 deg/s 0.02 m/s^2 0.5 mGauss 0.5 ℃ accuracy Scale Factor stability[4] (1ó) - 0.05% 0.5% - Noise density 0.1 deg/s/vHz 0.001 m/s^2/vHz 0.5 mGauss (1ó) - Alignment error 0.1 deg 0.1 deg 0.1 deg - Bandwidth (standard) 40 Hz 30 Hz 10 Hz - **Options** Full Scale ± 150 deg/s ± 100 m/s^2 ± 300 deg/s ± 900 deg/s Other options on request	**Interfacing** Max update rate: 512 Hz (calibrated sensor data) 100 Hz (orientation data) Digital interface: RS-232, RS-422 and USB (external converter) Operating voltage: 4.5 - 15V Power consumption: 360 mW (orientation output) **Housing** Dimensions: 38x53x21 mm (WxLxH) Weight: 30 g Ambient temperature operating range: 0 - 55 deg Celsius 

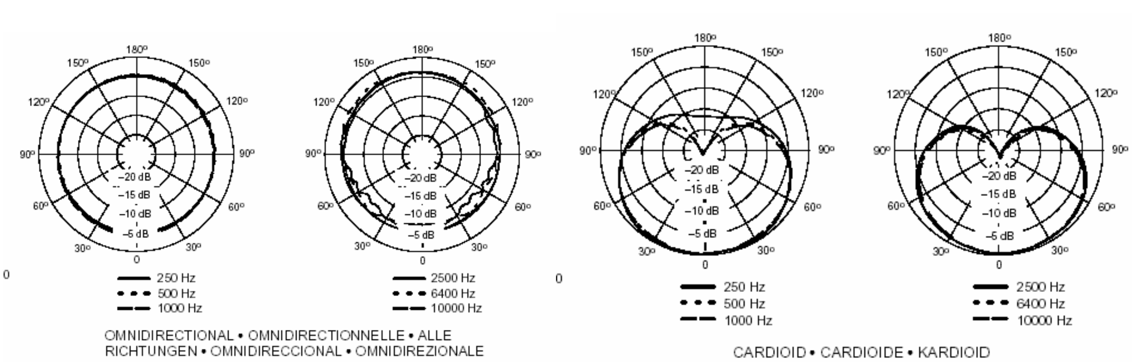
2.4.3 Microphones

The head will be equipped with at least two microphones allowing for sound source localization and audio-based attention mechanisms. Tests are being carried with the two following models:

Model	Shure – Model MX183	RS – Model 242-8911
Type	Condenser (electret bias)	Condenser (electret bias)
Frequency Response	50 to 17,000 Hz	de 50Hz a 16kHz
Polar Pattern	Omnidirectional	Omnidirectional
Open Circuit Sensitivity (at 1 kHz, ref. 1V/Pascal*)	–27.5 dB (42.2 mV)	-65dB □3dB
Max SPL (1kHz at 1%THD, 1 kΩ load	116.7 dB	not specified
Equivalent Output Noise (A-weighted)	20.5 dB	not specified
Signal to Noise Ratio (referenced at 94 dB SPL)	73.5 dB	not specified
Power Requirements:	11 to 52 Vdc phantom, 2.0 mA	1,5 Vdc
Output Impedance	180Ω	1.000Ω
Dimension	12 x 22 mm	8×18mm
		

The sensor pattern should be chosen among omnidirectional and cardioid. Also the localization and the number of sensors in head/body is being evaluated.

The microphone Shure MX183 will probably be the final choice due to its superior specifications and in spite of its higher cost.



3 The current actuators technologies in humanoid robots

There are several kind of actuators used in Robotics, anyway not all of them are suitable for Humanoid Robots. The right choice is always due to the requirements and the tasks the platform has to perform. The iCub has to be able both to manipulate objects and move with a crawling strategy. In order to develop these *explorative* capabilities, a high power to weight ratio is needed as the platform as to be sized and shaped as a 2 years old child. On the other hand, mobility requires a certain independence of movement from the power source and maybe a certain degree of autonomy.
As cognitive tool, biomimicry is very important if we want to obtain a kind of correspondence between the iCub and the human model; nevertheless we don't have to burden the control too much as the number of DoFs is high.

Thus the actuator selection is not simple as we have to deal with lots of parameters and some of them are not properly compatible. In the following figures and tables a first comparison has been made ([77],[78])

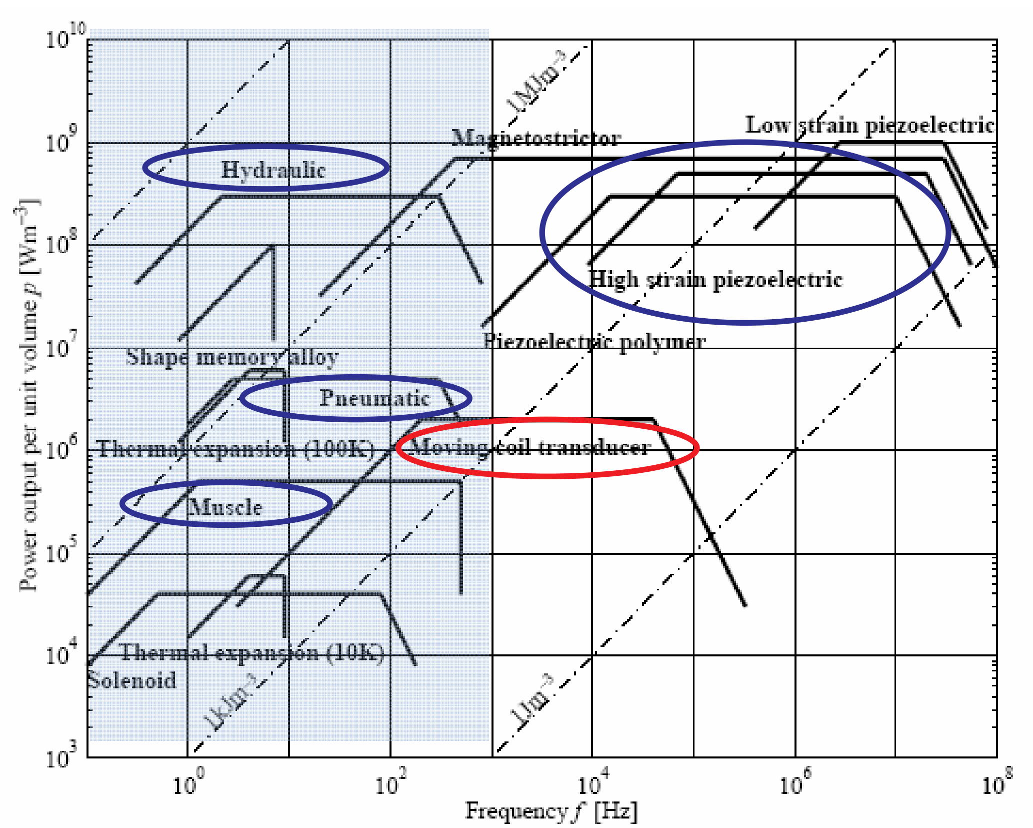


Fig 3.1

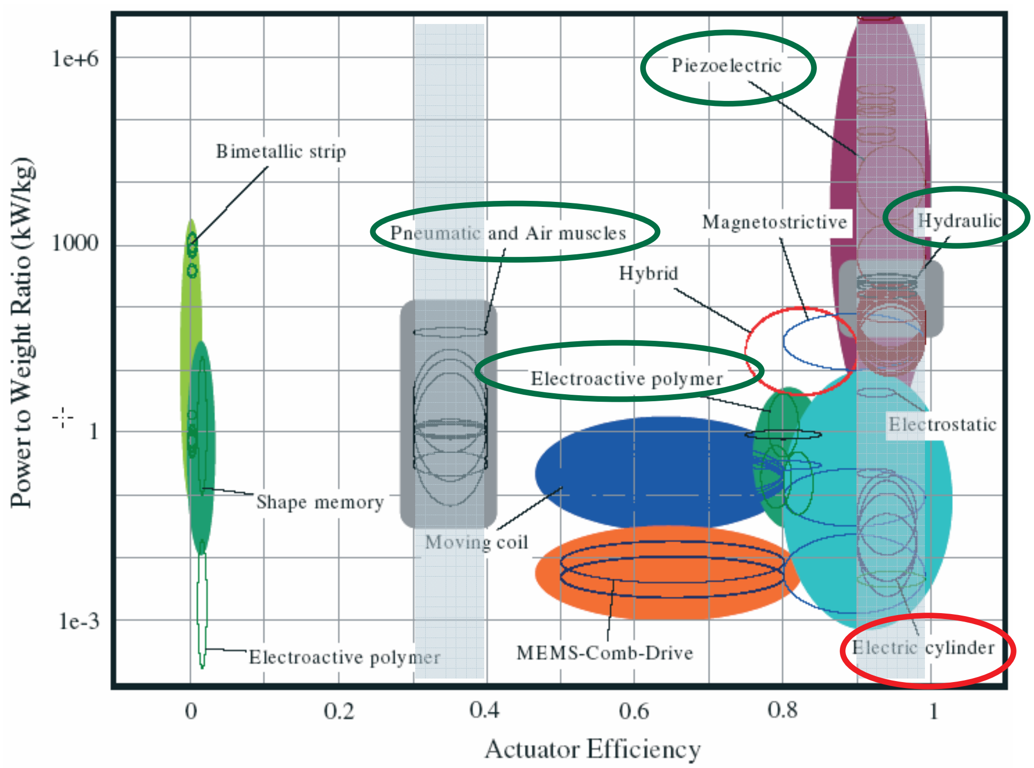

Piezoelectric
Bimetallic strip
Pneumatic and Air muscles
Magnetostrictive
Hydraulic
Hybrid
Electroactive polymer
Electrostatic
Shape memory
Moving coil
Electroactive polymer
MEMS-Comb-Drive
Electric cylinder
1e+6
1000
1
1e-3
0
0.2
0.4
0.6
0.8
1
Power to Weight Ratio (kW/kg)
Actuator Efficiency

Fig 3.2

Actuator			Features
			Electrical
Diodes, thyristor, bipolar transistor, triacs, diacs, power MOSFET, solid state relay, etc.			Electronic type Very high frequency response Low power consumption
			Electromechanical
DC motor	Wound field	Separately excited	Speed can be controlled either by the voltage across the armature winding or by varying the field current
		Shunt	Constant-speed application
		Series	High starting torque, high acceleration torque, high speed with light load
		Compound	Low starting torque, good speed regulation Instability at heavy loads
	Permanent magnet	Conventional PM motor	High efficiency, high peak power, and fast response
		Moving-coil PM motor	Higher efficiency and lower inductance than conventional DC motor
		Torque motor	Designed to run for a long periods in a stalled or a low rpm condition
	Electronic commutation (brushless motor)		Fast response High efficiency, often exceeding 75% Long life, high reliability, no maintenance needed Low radio frequency interference and noise production
AC motor	AC induction motor		The most commonly used motor in industry Simple, rugged, and inexpensive
	AC synchronous motor		Rotor rotates at synchronous speed Very high efficiency over a wide range of speeds and loads Need an additional system to start
	Universal motor		Can operate in DC or AC Very high horsepower per pound ratio Relatively short operating life
Stepper motor	Hybrid		Change electrical pulses into mechanical movement Provide accurate positioning without feedback
	Variable reluctance		Low maintenance
			Electromagnetic
Solenoid type devices			Large force, short duration
Electromagnets, relay			On/off control
			Hydraulic and Pneumatic
Cylinder			Suitable for liner movement
Hydraulic motor	Gear type		Wide speed range
	Vane type		High horsepower output
	Piston type		High degree of reliability
Air motor	Rotary type		No electric shock hazard
	Reciprocating		Low maintenance
Valves	Directional control valves Pressure control valves Process control valves		
			Smart Material actuators
Piezoelectric & Electrostrictive			High frequency with small motion High voltage with low current excitation High resolution

(continued)

Actuator	Features
Magnetostrictive	High frequency with small motion Low voltage with high current excitation
Shape Memory Alloy	Low voltage with high current excitation Low frequency with large motion
Electrorheological fluids	Very high voltage excitation Good resistance to mechanical shock and vibration Low frequency with large force
Micro- and Nanoactuators	
Micromotors	Suitable for micromechanical system
Microvalves	Can use available silicon processing technology, such as electrostatic motor
Micropumps	Can use any smart material

Tab 3.1

Driving principle	Actuator	Driving type	Driving range	Yield	Response speed	Driving voltage
Static electricity	Electrostatic rotary motor	Rotary	Large	Small (several gf)	Medium to high	High (5 to 500 V)
	Electrostatic linear	Direct driven	Small	Medium	High	High (5 to 500 V)
Piezo-electricity	Laminated vertical effect	Direct driven	Small (ε<0.1%)	Large (4 kgf/mm^2)	High (to 100 kHz)	High (10 to 200 V)
	Bimorph	Direct driven	Small (10 gf)	Medium (10 gf)	Medium (to 1 kHz)	High (10 to 200 V)
	Ultrasonic motor	Rotary	Large	Large	Small to medium	Medium/High (5 to 50 V)
Heat	Shape Memory Alloy	Direct driven	Large (ε<6%)	Large (4 kgf/ mm^2)	Medium	Low (to 5 V)
	Thermal expansion	Direct driven	Small (ε<0.5%)	Large	Medium	Low (to 5 V)
	Bimetal	Direct driven (bending)	Medium	Small	Medium	Low (to 5 V)
Electro-magnetic induction	Ordinary motor	Direct driven rotary	Large	Small to medium	Medium to high	Low
	Superconductive	Direct driven rotary	Large	Small	Medium to high	Low

Tab 3.2

In the next paragraphs the main actuation system used in Humanoid and Cognitive Robotics are discussed.

3.1 Ultrasonic motors

An ultrasonic motor (USM) is a new actuator that uses mechanical vibrations in the ultrasonic range as its drive source. USMs have important features such as high stall and specific torque, high torque at low speed, compactness in size, quiet operation and no electromagnetic interference. The torque of an USM is 10 to 100 times larger than conventional electromagnetic motors of the same size or weight. Due to these features USMs are presently being used for industrial, medical, robotic, space and automotive applications.
Besides these advantages, USMs have some disadvantages that must be solved for practical applications. It is also difficult to derive a complete mathematical model of USMs.
As the ultrasonic motor uses a different driving principle, it has a variety of characteristics that the electromagnetic motors do not have [79].

- *Low speed, high torque:* as it allows high torque at low speed (several r/min to several hundred r/min) direct drive is possible. Moreover, a small gear-ratio will suffice when reducing speed.

- *Self-retention characteristic*: as it is retentive even after the power is turned off, an electromagnetic brake is not necessary.

- *High response and controllability*: small rotor inertia and braking performance due to motor friction realize incomparable responsiveness and controllability.

- *Nonmagnetic nature*: since the ultrasonic motor does not use magnetic power as its driving force, it does not generate magnetism.

- *Compact, lightweight and quiet*: as it has a simple structure, it is compact and light. Moreover, since its rotational speed is low to begin with, it is quiet even when gears are used.

Making use these characteristics, the ultrasonic motor is used for the following purposes:

1) Adjusting the position of headrests ***(Compactness, Lightweight and quiet)***
2) Opening and closing of roll screens ***(Quietness, Low speed, Retentiveness)***
3) MRI injector ***(Non-magnetic nature)***
4) Camera and video camera auto-focus ***(High response, Quietness)***
5) Sorting of beet seedling ***(High response)***
6) Adjusting of car BS antennas ***(High response, Compactness, Non-magnetic nature)***
7) Remote control of auto-volume ***(Quietness, High response, Compactness)***
8) Robot hands and X,Y tables ***(Compactness, High response, Retentiveness)***

Ultrasonic motors run relatively strong and slow, are applicable for continuous operation only under certain condition, but can be operated in certain application without a gear. Without current supply they feature a high holding torque, and in case of overload they adopt the function of a slipping clutch. The motors operate quietly and without jerk. Since the power transmission is implemented by frictional engagement, the positioning must be carried out within a closed control loop. Known applications include focus setting in reflex and video cameras. The automotive, computer and toys industries as well as optics are further fields of application among others. In a certain design of this motor type, the operating frequency of 85 kHz provokes the rotor to move forward, a frequency of 95 kHz provokes it to perform a backward motion. The voltage amplitude is 6.. 8 V, the current consumption is 50…250 mA (depending on the velocity). With velocities between 0 and 300 m/s, thrusts of 0.5... 1 N are achieved. The displacement increment is 10…20 µm and the length of the motor is 25 mm. Table 3.1.1 lists advantages and disadvantages of piezoelectric transducers for use in actuator applications [80].

Advantages	Disadvantages
- large forces achievable, high stiffness	characteristic values of the ceramic are dependent on temperature and age
high electromechanical efficiency	piezo effect can be lost by the influence of high temperature, large electrical field strengths or mechanical shock
very short response time (range of µs)	strong self heating of the ceramic in dynamic operation
negligibly low power consumption in static operation	high-voltage power supply necessary for the capacitive load (up to several microfarad)
- various couplings between the field and the strain axes possible	
large selection and availability of different materials	

Tab 3.1.1

Moreover, custom USMs for robotics applications are being developed by JET PROPULSORY LAB by Xiaoqi Bao and Yoseph Bar-Cohen.
To establish a baseline for the performance of a USM that was made by JPL/QMI, a Shinsei (leader company in USMs) motor with a diameter of 1.2-inch was used (Shinsei Model USR30). See Figure 3.1.1

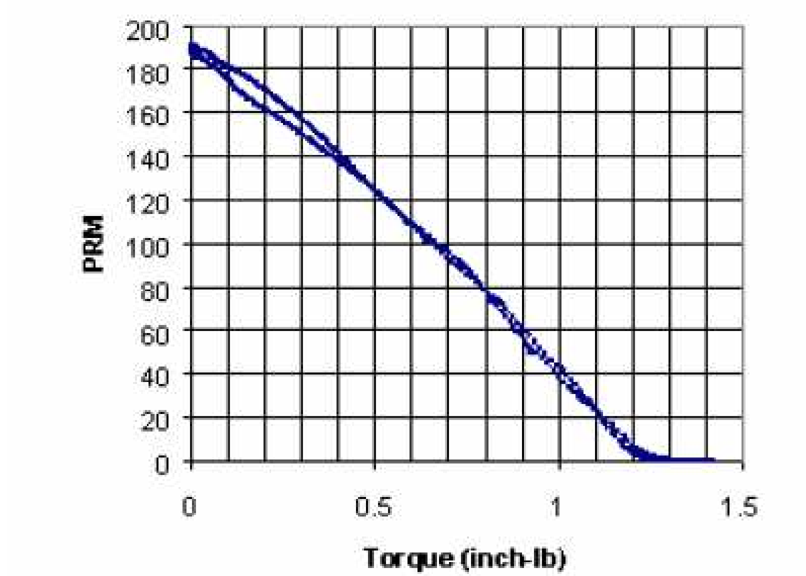


Fig. 3.1.1

PZT Diameter (mm)	Output power		
	Torque (kg-cm)	Speed (rpm)	Power (W)
JPL lab unit - USM D30	0.81	400	3.3
Shinsei USM D30	0.58	200	1.2

Tab 3.1.2

We have to say that if these motors are used for all the three joints (shoulder, elbow and wrist), we need to drive them. There might be limitations inherent in creating a compact package for all three controllers/power supplies. does there needtobe any heavy transformers and such. Each motor requires a 2-phase driver at frequency~30-50 kHz. Because of the high operation frequency, the sizes of transformers are small. The driver of D30 USM of Shinsei is 70x45x22 mm^3. The speed is electrically controllable.
The lifetime of this motor is 2000 hours; nevertheless the motor may build up heat while running continuously. Mounting the base of the motor to a heat conducting structure may be required in heavy usage ([81]).

In Table 3.1.3 the nameplate specifics of the main Shinsei USMs can be found:

Motor	Unit	USR60	USR45	USR30
Operating frequency	kHz	40	43	42
Operating voltage	Vrms	100	100	100
Rated torque	Nm	0.38	0.15	0.04
Rated output	W	4	2.3	1.0
Rated rotational speed	rpm	100	150	250
Mechanical time constant	ms	1	1	1
Weight	g	175	69	33
Rotation irregularity	%	2	2	2
Lifetime	h	1000	1000	1000
Operating temp. range	°C	−10 + 50	−10 + 50	−10 + 50

Table 3.1.3

These are the specifics of the Shinsei USR60 USM used at JPL

Driving frequency	40-44 kHz
Driving voltage	130 Vrms
Drive current	53mA
Rated torque	0.5 Nm (5 Kgf-cm)
Rated output	5.0 W
Rated rotational speed	100 rpm
Maximum torque	10 Nm and above (1.0 Kgf-cm)
Holding torque	1.0 Nm and above (1.0 Kgf-cm)
Responsibility	1msec or below (no inertia load or driver sweep)
Rotational direction	CW, CCW
Longevity	1,000 Hrs
Service temperature range	-10 ℃ to +55 ℃
Service temperature rise	70 ℃ at stator surface / 55 ℃ at case surface
Rotor inertia	7.2 x 10^–6 kg/m^2
Weight	0.23 kg

Table 3.1.4

3.2 EAPs

EAPs are rich in variety in terms of the basic actuator mechanism, the strength and extent of the displacement, the environmental needs and the complexity of synthesis or construction. We identify three basic groups involving electronic interactions, ionic interactions and phase transitions with associated conformational changes.

Active polymer gels by themselves fall typically in the low stress (low force)-high strain group, together with muscle. Their elastic modulus in the swollen state is low, typically of the order of 1000 Pa and, consequently, the forces that they can generate in unconstrained conditions are low. Measured values of force generation are about 1N/g of swollen gel. Isotropic volumetric free swelling can be very large indeed, with swelling ratios of 10-12 but is omni-directional owing to the isotropic behaviour of the gels. Differential swelling and hence bending of beam or plate-like shapes can be induced by charge separation techniques in some instances. Gels incorporating conductive polymers such as polypyrrole can be cast in film form over a thin and flexible conductive polymer film. When exposed to an electrical field a current passes through the EAP, promoting expulsion of solvated counter-ions. The EAP shrinks and the bi-layer structure bends. An alternating external electrical field can induce bending oscillations. Small demonstrators using this approach have been made without great difficulty but the forces that can be generated are extremely small (because of the very low modulus of the system and the necessary small thickness of the EAP to ensure a fast response)). Although the ability to induce movement by non-contacting and controllable electrical fields is attractive, these systems are still rather delicate and complex to “package” into a self-contained unit. In many respects swollen active polymer gels behave like soft elastomeric materials. In order to generate higher forces, at the expenses of reduced deformability, taking advantage of their swelling potential and virtual incompressibility, the expansion of active polymer gels must be partially confined in order to convert chemical energy into useful external work. This is analogous to the free expansion of a gas that cannot produce useful work.

Dielectric elastomer actuators exploit the electrostatic Maxwell stress experienced by all dielectrics. These are dry materials based on relatively soft elastomeric films. Essentially the device is a capacitor in which the electrodes are attached to the polymer film. Upon application of a voltage the unlike charges on the opposing electrodes attract each other which reduces the film thickness. Since such rubbers deform at almost constant volume this leads to an expansion of the area of the polymer film. Furthermore the like charges on each electrode will repel each other tending to lead to an expansion of the electrode. There is a built in amplification process since as the film thickness decreases the electric field strength increases. As a consequence the actuation is non-linear with a strain approximately proportional to the square of the applied voltage. Strains of up to 400% have been observed in acrylic elastomers exerting a pressure of ~ 7 MPa. Such systems have the highest energy densities observed for any EAP but the voltages required may be as high as 5kV.

EAPs based on conducting polymers utilise mass transport of ions into and out of the polymer. Two key requirements are an E-field driven diffusion mechanism to transport metal ions into the polymer and polymer conduction to get electrons into the polymer to generate this field. The metal ions in the polymer can then cause a shape or a stiffness change in the polymer. In both cases the polymer change can be used to generate mechanical work. Such materials have been widely fabricated as bending actuators. Polypyrrole and derivatives and polyaniline based systems have been extensively studied. However, the development of new monomers which can be used to tailor the conduction level and yield new material properties needs more research. These activator types exhibit modest strains of ~ 10% but can develop high pressures, for example, 450M Pa. However, the overall response times are relatively slow[82].

EAP type	Advantages	Disadvantages
Dry	• Can operate in room conditions for a long time • Can respond at very high frequencies • Provide large actuation forces	• Requires high voltages • Compromise between strain and stress is needed
Wet (Ionic)	• Provides mostly bending actuation (longitudinal mechanisms can be articulated) • Large bending displacements • Sustain hydrolysis at >1.23-V • Requires low voltage	• Does not hold strain under DC voltage • Operates at low frequencies (several Hertz) • Bending EAP presents a vary low actuation force

Tab. 3.2.1

3.3 DC motors

Electric motors are the most widely used electromechanical actuators. They can either be classified based on functionality or electromagnetic characteristics. The differences in electric motors are mainly in the rotor design and the method of generating the magnetic field. We can assume that the characteristics of brushed DC motors are well-known by all the RobotCub Community.

Commutator is the part of the DC motor rotor that is in contact with the brushes and is used for controlling the armature current direction. Commutation can be interpreted as the method to control the current directions in the stator and/or the armature coils so that a desired relative stator and rotor magnetic flux direction is maintained. For AC motors, commutation is done by the AC applied current as well as the design of the winding geometry. For stepping motors and brushless DC (BLDC) motors, commutations are done in the drive electronics and/or motor commands.
These motors have position feedback of some kind so that the input waveforms can be kept in the proper timing with respect to the rotor position. Solid-state switching devices

are used to control the input signals and the brushless dc motor can be operated at much higher speeds with full torque available at those speeds.
The brushless dc motor will duplicate the performance characteristics of a conventional dc motor only if it is properly commutated. Proper commutation involves exciting the stator windings in a sequence that keeps the magnetic field produced by the stator approximately 90 electrical degrees ahead of the rotor field. The brushless dc motor therefore relies heavily on the position feedback system for effective commutation. It might also be apparent that the brushless motor as described is not strictly a dc machine, but a form of ac machine with position feedback.
Modern DC brushless motors range in power from a fraction of a watt to many kilowatts. [83]

3.3.1 Comparison between BLDC and brushed-DC motors

A brushless DC motor (BLDC) is a DC electric motor that uses an electronically-controlled commutation system, instead of a mechanical commutation system. Thanks to this, BLDC motors offer several advantages over brushed DC-motors, including higher reliability, longer lifetime (no brush erosion), elimination of ionizing sparks from the commutator, and overall reduction of electromagnetic interference (EMI).
BLDC's main disadvantage is higher cost, which arises from two issues: first, BLDC motors require high-power MOSFET devices in the fabrication of the electronic speed controller. Brushed DC-motors can be regulated by a comparatively trivial variable-resistor (potentiometer or rheostat), which is inefficient but also satisfactory for cost-sensitive applications. BLDC motors need a more expensive integrated circuit, called an electronic speed controller, to offer the same type of variable-control. Second, when comparing manufacturing techniques between BLDC and brushed motors, many BLDC designs require manual-labor, to hand-wind the stator coils. On the other hand, brushed motors use armature coils which can be inexpensively machine-wound.
BLDC motors are robust and low-noise just as asynchronous motors. They have a better dynamic performance than DC commutators motors. The constant development in the field of electronics and of magnet technique reduces on the one hand the cost and improve the properties on the other. More and more DC commutator motors are being replaced by BLDC motors. BLDC motors are able to reach more than 30,000 rpm, to cover a speed range up to 1:3000 and to generate torques between 0,02 Nm up to 100 Nm. Their life time amounts to several 10,000 hours. Typical data are given in Table 3.3.1.1

Nominal voltage V	Nominal speed rpm	Nominal torque Nm	Nominal output power W	Efficiency %	Inertia gcm²	Weight kg
24	5000	0.02	10	60	30	0.5
24	5000	0.057	30	65	70	0.9
42	3000	0.032	10	65	20	0.3
42	3000	0.095	30	65	200	1.0
42	3000	0.32	100	70	1400	2.5
230	3000	0.095	30	40	200	1.0
230	3000	0.32	100	45	1200	3.0
230	3000	3.18	1000	65	2000	5.0
230	5000	0.38	200	50	400	2.0
230	5000	1.15	600	60	600	3.0

Tab. 3.3.1.1

BLDC motors are considered more efficient than brushed DC-motors. This means for the same input power, a BLDC motor will convert more electrical power into mechanical power than a brushed motor. The enhanced efficiency is greatest in the no-load and low-load region of the motor's performance curve. Under high mechanical loads, BLDC motors and high-quality brushed motors are comparable in efficiency.
On the other hand, electronic drives in BLDC are bigger and more complex; this aspect is critical in a multi DoFs application as the iCUb is. The space gained thanks to BLDC's better performances could be wasted by the room required by the electronics. Moreover the control of each motor will become more complex [84].

3.4 Fluidpower motors

The characteristics of fluid servosystems are examined below, with particular reference to systems which permit continuous control of one of the two physical magnitudes which express the fluid power: pressure and flow rate. In general, pressure control is carried out in cases in which it is necessary to create a determined force or torque law, while flow rate control is used to carry out controls on kinematic magnitudes such as position, speed, and acceleration. Continuous control of a force or of a speed can be effectively realized with a fluid actuation device, with evident advantages compared with electric actuation, such as the possibility of maintaining the system under load without any limitation and with the aid of adequate control devices, the possibility of carrying out linear movements directly at high speeds, without devices for transforming rotary motion to linear, and the possibility of having high bandwidths, in particular in hydraulic systems, as these have limited dimensions and therefore low inertia.

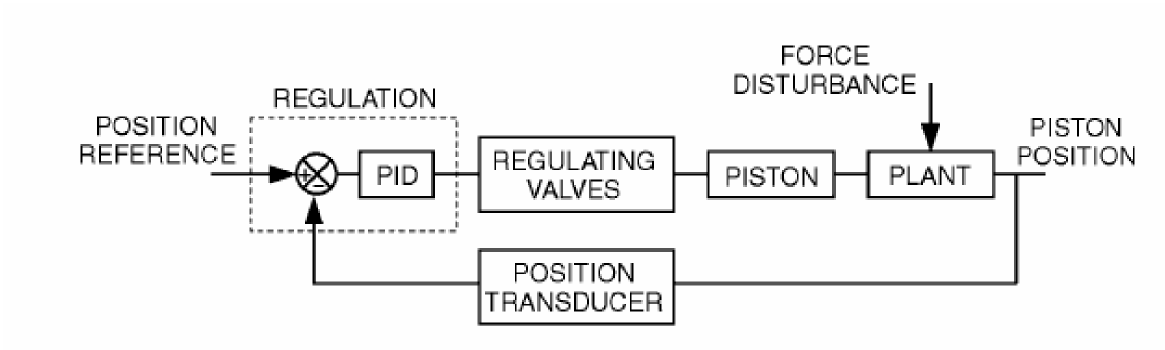


Fig. 3.4.1

Fluid actuators, whether they are linear (cylinders) or rotary (motors) are continuous systems as they can determine the positioning of the mobile component (of the rod with respect to the cylinder liner; of the shaft with respect to the motor casing) at any point in the stroke. Performance of the usual cylinders and motors is currently highly influenced by the action of friction (static and dynamic) developed by contacts between mobile parts. This action, in pneumatic systems in particular, gives rise to the well known phenomenon of stick-slip, or intermittent motion at very low movement speeds, due to the alternation of conditions of friction and adherence in the motion of the mobile element in the actuator.
Given the nature of the friction itself, the presence of devices suitable for sustaining the mobile components of the actuator and maintaining the correct pressure conditions, such as supports and gaskets, gives rise to nonlinear conditions in the equilibrium of the actuator, increasing the level of difficulty in obtaining high precision in positioning the system. To overcome these problems in specific applications it is necessary to use actuators without seals, for example, with fluid static and/or fluid dynamic bearings.
If, on the other hand, it is necessary to have continuous control of the position and force transmitted, it is necessary to use devices which are not digital now, but which are continuous, such as proportional valves and servovalves, or it is necessary to use digital devices operating with control signal modulation, for example those of the PWM (Pulse Width Modulation) type.

Two large classes of fluid servosystems are usually present in current applications: hydraulic servosystems, in which the operating fluid is a liquid (which it is assumed as a uncompress/perfect fluid), and pneumatic servosystems, in which the fluid used is compressed air. The working pressure in hydraulic servosystems is typically comprised between 150 and 300 bar, while in the case of pneumatic systems, the pressure values are generally below 10 bar.
As we can see in figures 3.1 and 3.2, hydraulic servosystems have a high power to weight ratio, comparable to piezoelectric actuators, and the same efficiency DC motors have (>0.9). In the pneumatic ones these parameters are lower; particularly efficiency is 0.3 to 0.4. On the other hand, hydraulic servosystems require huge and heavy compression machines to operate. Air is a power source easier to find and manage.

Eventually, properly using fluidpower drive systems requires suitable sensors. The most important variables to be measured, either for monitoring or as control variables, are pressure, flow, and stroke (or turning angle). Comparing to DC motors (current and turning angle), these devices require one more variable to be controlled.

3.4.1 McKibben Artificial Muscles

The MacKibben artificial muscle is a low cost pneumatic muscle actuation source with a high power/weight ratio and safety due to its inherent compliance. This type of actuator was firstly used by McKibben [85]. Since then several other groups had noted the potential of this form of actuation ([86], [87], [88], [89]) and it has been adopted in applications in the area of bio-robotics ([90], [91], [92]) and rehabilitation ([93], [94]). The McKibben artificial muscles are constructed as a two-layered cylinder, an internal rubber tube covered by a braided shell, figure 3.4.1.1. Usually within the actuator a pressure sensor is incorporated to monitor the internal state of the muscle. The complete unit can safely withstand pressures up to 700KPA (7bar). The detailed construction, operation, and mathematical analysis of these actuators can be found in ([87], [88], [89], [95], [96], [97]). The experience obtained from the employment of this type of actuator in various robotic platforms from bipedal / quadrapedal systems to haptic and industrial applications reveals a number of beneficial characteristics of this type of actuator which are listed below [98].

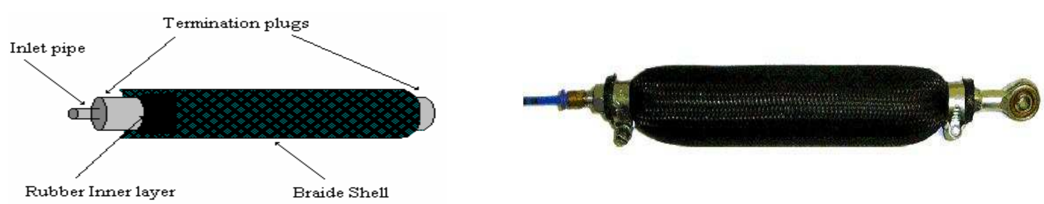


Fig. 3.4.1.1: Pneumatic Muscle Actuator Construction.

i. Actuators have exceptionally high power and force to weight/volume ratios >1kW/kg.
ii. The actual achievable displacement (contraction) is dependent on the construction and loading but is typical 30%-35% of the dilated length - this is comparable with the contraction achievable with natural muscle.
iii. Being pneumatic in nature the muscles are highly flexible, soft in contact and have excellent safety potential. This gives a soft actuator option, which is again comparable with natural muscle.
iv. Force and position control using antagonistic pairs, figure 3.4.1.2, for compliance regulation is possible. This is once more comparable with natural muscle action. Joint motion/torque on the joint is achieved by producing appropriate antagonistic torques through cables and pulleys driven by the pneumatic actuators. The two elements work together in an antagonistic scheme simulating a biceps-triceps system to provide the bi-directional motion/force.
v. Easy construction and great control over the actuator dimensions, forces and general performance allowing them to be tailored to the application. This muscle can be made in a range of lengths and diameters with increases in sizes producing increased contractile force.

vi. The actuators are highly tolerant of mechanical (rotational and translational) misalignment reducing the engineering complexity and cost.

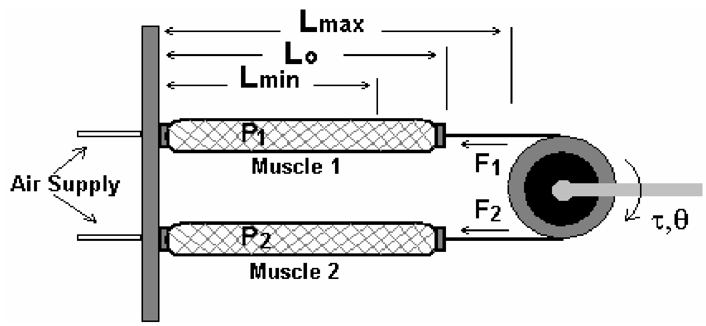


Fig. 3.4.1.2 Antagonistic pairs of muscles.

The main disadvantages of this type of actuator include:

i. Lower Bandwidth when compared to electrical motor drives: Although this usually considered as an actuator limitation the actuator bandwidth is directly related to the flow capability of the air supply valve.
ii. Lower accuracy than that obtained by motorised systems Controllers developed for the muscle systems have shown them to be controllable to an accuracy of better than 1% of displacement.
iii. More difficult control when compared to the control of conventional electrical motors
iv. Need for additional pneumatic power source.

3.5 Actuation in other Robotic Platforms

The SdA of Humanoid Robotic Platform has been analyzed; two main groups can be identified. In the first one *mobile robotic platforms* (as Sony QRIO e Honda ASIMO) can be found. They are reliable and have a complete body; nevertheless their hands have only one or two DoFs. Thus they are not suitable for exploration and cannot be considered as *cognition tools*. The latter group consists of "incomplete" platforms but provided with dextrous hands.
It is easy to understand the iCub is a *unicum* among all robotics platforms. It could belong to both the two groups. Making possible to obtain such different requirements is one of the toughest goals of this Project as the tasks the iCub is required to perform are quite various. Table 3.5.1 gives an overview of the specifics of the main humanoid platforms of the two groups described.

DoMs (Hand/Arm/Total)	Pourpose	Actuation	Transmission	Hand dexterity	Mobility req.ts
Humanoid Robot Promet HRP-2 (1/ 6 / 30)	Entertainment	DC motors	n.d	Grasping	Walking; Lie down to stand-up
Honda ASIMO (1/ 5/ 26)	Entertainment	DC motors	n.d	Grasping	Walking; climbing stairs
Sony QRIO (1/ 5/ 38)	Entertainment	DC motors	n.d	Grasping	Walking; dancing; managing uneven surfaces
Robonaut (17 / 7 / n.d.)	Working tool	DC motors	Gears, flexible shaft	Manipolation	no
DLR (13 / 7 / -)	Working tool	DC motors	Gears	Manipolation	no
Shadow (22 / 7 / -)	Research tool	Pneumatic artificial muscles	Direct, cable	Manipolation	no
WE-4RII (6 / 9 / 59)	Entertainment (emotional)	DC motors	Gears, belts, cable	Grasping	No

Tab. 3.5.1

DC motors are indeed the favourite choice and there are lots of reasons to justify it. First of all, this technology is well-known and has been improved all over the years. There is a wide range of models in size and power. They have not a high power to weight ratio (see figures 3.1 and 3.2) but they don't need huge power sources as fluidpower actuators do; their efficiency is high too (>.9). We have to point out that the robots of the first group (green) use battery packs; this is extremely important for mobile platforms. Last but not least, controlling this kind of motors is easier as the output is linear.
In second group we find the only humanoid platform that uses Pneumatic Artificial Muscles. The Shadow arm and hand are the only research tool of the list. The hand has the highest overall number of DoFs and fingers are cable driven with an agonistic/antagonistic muscle strategy. As we can see in Fig. 3.1, pneumatic air muscles are the technology closest to real muscles characteristics; thus it is well-known as these artificial muscles have a dynamical behaviour (contraction and compliance) much closer to real muscles than DC motors do. From a cognitional point of view, they probably are the best tool available. Anyway, as the iCub is an open platform, we have to consider the platform modularity as mandatory; to this purpose DC motors are more suitable.

4 The selection of the appropriate Cub-Technologies

According to the state of the art depicted above, we made a preliminary selection of sensors and actuators. In the meanwhile we sketched an *ad hoc* solution.
As shown in 3.6, two categories of Humanoid Platforms have been identified. The iCub requirements cover the most of the characteristics of both the two groups. The iCub is what we properly call *a unicum.* The problem is several specs address the design toward different approaches. E.g., one critical issue is manipulation as it hardly coexists with advanced mobility.
So we tried to find out an equilibrium point. In Table 4.1 a task-oriented comparison between the advantages of Hydraulic and Electromagnetics drives is shown. If we consider that the main differences between McKibben artificial muscles and Hydraulc Systems are a quite lower efficiency (see Fig 3.2) and an intrinsic compliance, Table 4.1 can be adopted also for a McKibben – DC motor first comparison.

Hydraulic drive	Electromagnetic drives
higher energy density	better control response
smaller mounting space	higher efficiency
higher accelerating ability	easier maintenance
lower cost	easy adaption to different conditions
easy generation of linear motion	the same energy type for sensors, control electronic and actuators
problem: leakage	

Tab. 4.1

The actuator selection has been made taking in account characteristics as easy adaptation to different conditions, better control response and, last but not least, the advantage of using the same energy type for sensors, control electronics and actuators. DC motors were eventually chosen.
For the iCub platform the main concerns regarding electric motors will be those of selection for purpose. At the very least the motor must be capable of matching the power requirements of the driven load. In all cases, therefore, the motor power available should be enough to cope with the anticipated demands of the load. Other requirements are the need for the motor to have enough torque available on start-up to overcome the static friction, accelerate the load up to the working speed, and be able to handle the maximum overload.
Concerning the sensors, obviously the selection must take in account the actuation and the transmission. Due to the use of DC motors, we need rotary sensors.
The rotation of the motor (or gearbox) shaft is related to the joint rotation. The encoder is the simplest choice, but due to the wiring problems and the limited range of motion of the joint (less than 360°), an hall effect sensor is more suitable. Where the dimensions are in the right range, a wounded potentiometer could be used (although the friction is a

problem for the lifetime of the sensor). When the joint are underactuated, the position of the motor shaft is not sufficient to know the joint positions. The underactuated finger will be endowed with Hall Effect sensor in the joint.
Due to the use of the tendon transmission, we need a tension sensor. *Ad hoc* strain gauges sensors will be designed for: finger tendon and main joint tendon. Commercial 6 axes load cell will be integrated in the main joints.
For the tactile sensor we planned to test different technologies: QTC sensors are promising (but expensive); some Kapton sensors are already available and manufactured by one of the partners. Other technologies will be investigated: magnetic sensors as the Hall Effect sensor in the head-on configuration.

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