Key Area 1 on "Research Coordination" – KA1

Co-chairs: Prof. Paolo Dario, Scuola Superiore Sant'Anna, Pisa, Italy
Prof. Rüdiger Dillman, Universität Karlsruhe (TH), Germany

EURON Technology Roadmaps

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1. Introduction

This documents stand as one of the deliverables due by the KA1 of the EURON Project. It reports technology roadmaps, as complementary to the research roadmaps delivered by the same KA1.

The document explains features and services in the main fields of robotics, then analyzing two specific case-studies: endoscopic and humanoid robotics.

The authors of most parts of the document are ARTS and CRIM Labs researchers, who are involved in robotics studies. The ARTS (Advanced Robotics Technology and Systems laboratory) and CRIM (Center of applied Research In Micro and nano engineering) Labs of Scuola Superiore Sant'Anna, co-responsible partner of KA1, are recognized and qualified research centers in robotics.

The selection of the case-studies is mainly based on the research topics of ARTS and CRIM Labs. Nevertheless, the same analysis can be extended to other branches of robotics. A wider and more complete vision can be given during the EURON 2 Project.

This document is made up of three parts:

- Description of the methodology adopted for defining the Technology Roadmaps
- The case-study of a robotic pill for endoscopy
- The case-study of humanoid robotics

For each case-study, the following points have been analysed:

- Identification of main market guidelines
- Robotics system characteristics
- Functions analysis
- Technology roadmaps per component

2. Description of the methodology adopted for defining the technology roadmaps

This section outlines the methodology that has been adopted for defining the present technology roadmap. The methodologies adopted in the EU-funded Nexus project has been used as an inspirational source for this purpose.

The guidelines of this methodology are:

- Identify functions in the application areas where the technology of interest could add value
- Identify current requirements and specifications
- Predict future functionality
- Forecast device trends
- Identify key devices required to guarantee the functionality
- Identify appropriate solutions that the technology considered can provide
- Identify technological development

The methodological guidelines for collecting information, that is necessary for creating technology roadmaps, are the following:

- Brainstorming sessions
- Literature Studies
- Internet Research
- Conference and technical meetings
- Evaluation of other roadmaps
- Interview with other experts

See Figure 1 and Figure 2 for a graphical representation of the adopted methodology.

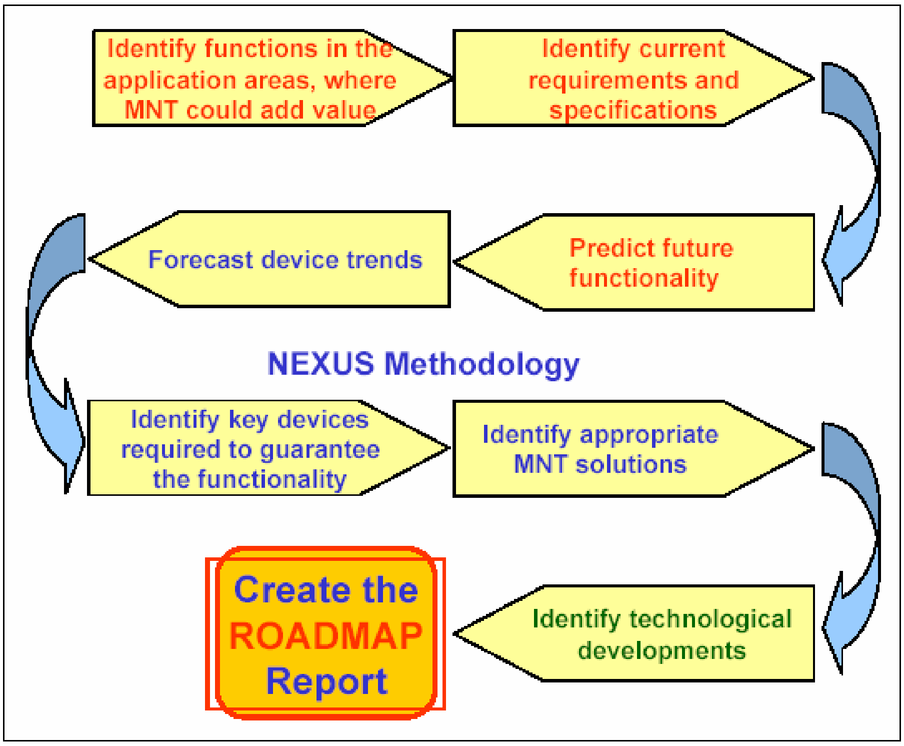


Figure 1: Methodological guidelines for creating Roadmaps [from the Nexus Project]

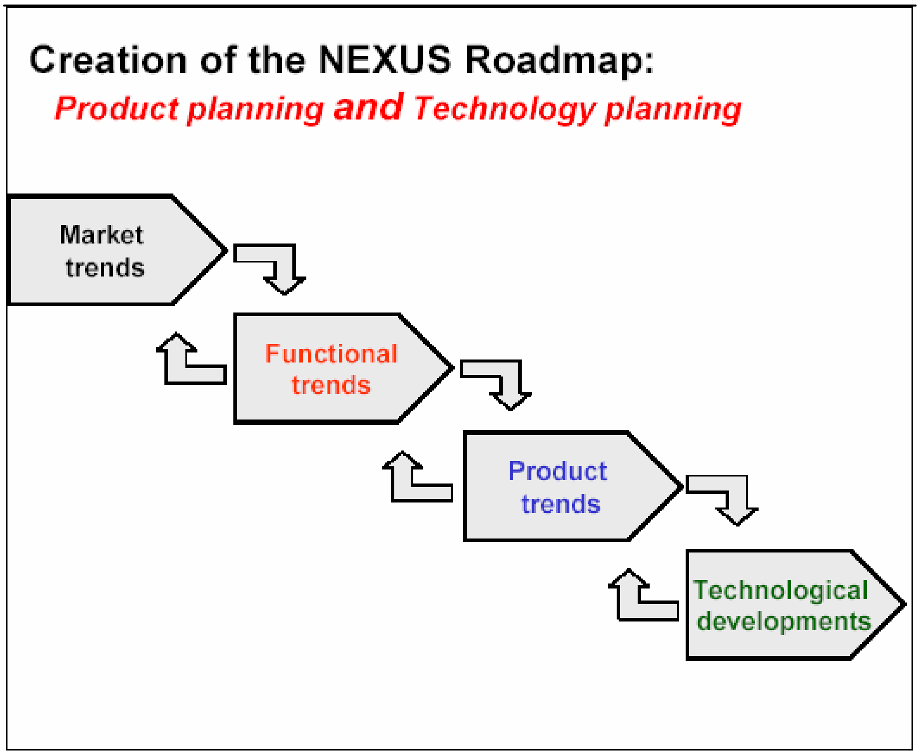


Figure 2: Product and Technology planning[from the Nexus Project]

In the following sections we present technology roadmaps related to the two case studies, concerning endoscopic and humanoid robotics, respectively.

3. The case study of Surgical Robotics: Endoscopic Micropill

3.1. Introduction to the Surgical Robotics Market: medical robotics and computer assisted surgery

Information technology plays a key role in an ever-widening range of human activities, including surgery. Computers, working in tandem with a variety of microprocessor-enabled equipment and instruments, support and facilitate the work of the surgeon and have brought a level of safety and precision to surgery that would have been inconceivable just a few years ago.

These computers, electronic equipment, and instruments are referred to collectively as medical robotics and computer assisted surgery (MRCAS) or, more dramatically, "the Operating Room of the Future." Their intended function is not to replace the surgeon, but to support the surgeon with enhanced dexterity, visual feedback, and information integration.

Study background

MRCAS is used in a growing number of operating rooms around the world, largely as a result of the growing popularity of minimally invasive surgical (MIS) techniques. Minimally invasive or "keyhole" surgery is an alternative to traditional open-incision surgery in a growing number of procedures. MIS utilizes special instruments that can be inserted and manipulated through small incisions (sometimes no more than a few millimeters long) under remote optical or video guidance, greatly reducing patient trauma and recovery times.

The need to perform delicate surgical procedures, safely, in tight spaces where the surgeon cannot see directly, has created a growing market for devices that act as extensions of the surgeon's eyes and hands: remote imaging, data processing and feedback, and robotics. This market is already estimated at more than half a billion dollars annually, and is growing faster than the overall surgical equipment market.

Because the use of these products is increasing so rapidly, there is a pressing need to develop an up-to-date base of market information, in order to better understand the dynamics of the market for MRCAS devices and equipment. Although several research reports on the computer-assisted surgical market are in print, all are at least two years old, a long time in such a fast-moving field. Most of the available studies of the surgical robotics market either treat robotics as part of the broader market for minimally invasive surgical equipment and/or are four or more years old. Meanwhile, MRCAS technology has been evolving, as have the medical and economic environments in which it is used. Populations are aging, increasing demand for a wide range of age-related surgical procedures such as heart and orthopedic surgery. Technological advances have expanded the range of surgical procedures that can be performed using minimally invasive techniques, making them accessible to even more people.

The structure of the hospital industry, the main user of MRCAS, is changing, as hospitals consolidate and other health care options such as walk-in surgical clinics become available to consumers. Private and government health insurers around the world are becoming more cost-conscious, forcing hospitals to re-evaluate their capital spending plans but strengthening the case for technologies that can reduce the cost of surgical procedures. Medical malpractice suits continue to be common in markets like the United States, and technologies that increase the precision and accuracy of surgery have obvious appeal. This report attempts to give management readers the information and analysis they need to understand and deal with these issues.

3.2. The state of the art and the market

Medical technologies to make endoscopy of the gastrointestinal tract and of other difficult access regions of the human body have been progressing very much over the last few years. Market and industrial research are dominated by Olympus, Karl Storz, Boston Scientific and Ethicon. Endoscopes are evolving in terms of miniaturization, flexibility, image quality and functionality, such us the possibility to perform biopsy and localized drug-delivery. On the other hand, typical commercial systems for endoscopy are wired and they do not differ so much from endoscopes developed 10 years ago.

The most impressive breakthrough in the last years is the introduction of wireless capsular devices for endoscopy, such as those developed by Given Imaging Ltd (http://www.givenimaging.com/) in Israel, by RF Norika Laboratory in Japan (http://www.rfnorika.com/) and by the Intelligent Microsystem center in South Korea (http://www.microsystem.re.kr/main_eng/menu04/sub_menu01.asp#01). All the above systems are a few (2-3) cubic centimetres in volume and they include mini-visualization CMOS cameras, mini-batteries (except for the NORIKA capsule which is powered by external electromagnetic fields), and RF image transmitter.

In the meantime, other capsules have been developed by some medical companies for monitoring pH and pressure in the stomach and oesophagus (e.g. BRAVO system by Medtronic). However, they are passive sensors, which are attached by suturing or elastic rings to the mucosa for performing all-day measurements.

Also in Europe a research group at the Center of Transfer for Microtechnologies (Besançon, France) is involved in a project for the development of an intestinal microcapsule with multiple functions, both diagnostic and therapeutic (http://www.ctm-france.com/html_en/frame.html). At the Massachusetts Institute of Technology a microfluidic module has been developed for microcapsule drug delivery (http://www.mchips.com - J.T. Santini, Jr., M.J. Cima, R. Langer. "A controlled release microchip," Nature, Vol. 397, pp. 335-338, Jan 28, 1999). In both cases, however, there are no locomotion or navigation mechanisms. This consideration increases the need for the development of a capsule locomotion, because it would evidently augment the clinical potential of such systems.

The Given Imaging capsule, already tested in many hospitals, is essentially a CMOS camera endowed with batteries and telemetry circuitry, which propels in the gastrointestinal tract by exploiting the natural peristalsis and takes pictures during its travel. These pictures are recorded by an external receiver and are analysed in order to re-build off line the capsule pattern.

The main advantages of the NORIKA capsule as regards to the Given Imaging capsule or the Korean capsule should be the following:

- the NORIKA capsule uses a high resolution CCD for imaging;
- it comes with an external *wearable* system for the production of a strong electromagnetic field;
- it can rotate inside the body thanks to the action of the magnetic field.

On the other hand, the NORIKA capsule is not yet available and all the technical information are published just on the web or on divulgation papers. Currently the RF

System Lab distributes a free charge NORIKA mock up kit to medical doctors interested to consider possible applications of the pill by having a look to its shape and dimensions.

Developing endoscopic capsules really useful from the diagnostic and therapeutic point of view means developing complete microrobotic systems.

Capsules developed until now are passive devices without (or with limited) autonomous propulsion which carry on just visualization sensors. Major problems form the medical and the technical point of view should be faced with in order to develop microrobotic capsules.

In the following paragraph, as an example, two problems will be illustrated for endoscopic microcapsules: the first one is related to autonomous locomotion and the second one to localization.

The first problem is related to the *autonomous locomotion* of capsular devices. Medical diagnosis is not effective if the medical doctors have no possibilities to stop the capsule, to go back, to turn the camera. The different tracts of the intestine may require a different accuracy of diagnosis and a passive device that takes pictures at a fixed frequency may not provide useful information to medical doctors in order to perform accurate diagnosis. This is the major limitation of the Given Imaging capsule: the medical doctor has to see off-line a video tape and he/she cannot collect more information than that recorded. On the other hand, an electromagnetic orientation system (e.g. as exploited in the NORIKA capsule) arises some concerns in terms of patient safety: the electromagnetic field necessary to produce enough torque in the capsule when it is "embedded" in the gastrointestinal tissue may be not acceptable for the safety of the human body. Moreover, locomotion by means of high intensity magnetic fields (superconducting coils or highly stable permanent magnets, as used in prototype systems by Stereotaxis Inc., http://www.stereotaxis.com) requires the patient to stay in hospital, since these devices are not portable, and can produce safety concerns.

The basic advantage of on-board locomotion systems is limited invasiveness, since no external devices for the production of strong electro-magnetic fields is required. This may result in a significant advantage when the patient has electronic implanted devices that may suffer from strong fields (e.g. pace-makers). In addition, a pill with an on-board locomotion system may be left close to an interesting intra-corporeal site for monitoring purpose even for a long time (e.g. days), without forcing the patient to wear bulky accessories. Anyhow, an easy to use, self-contained, self-propelling wirelessly operated endoscopic pill has advantages in terms of acceptability and commercial spreading ability. Finally, mass produced miniaturized devices are better affected by scale economy than mass-produced larger devices (such as wearable magnets).

The second problem related to the endoscopic capsular devices and strongly connected also to the locomotion problem is *localization*. An accurate diagnosis requires that the position of the capsule during image acquisition is known accurately.

The localization of intra-body surgical devices could be performed by means of conventional medical imaging systems such as intraoperative MRI, 3D Ultrasound, X-Rays Stereo Fluoroscopy. These methods use a laboratory (clinical) device that is non-portable, and that could not be used continuously for all the duration of the crossing of the intestinal tract.

For the tracking of the surgical instrument (non-wireless) some laboratories are using a prototype of the NDI Aurora (www.ndigital.com, not yet commercially available), which is a magnetic field based tracking system. The Aurora uses cylindrically shaped sensors that are extremely small (0.9 mm in diameter and 8 mm in length). This enables the sensors to be embedded into the surgical instruments. The magnetic field is generated by an external (extra corporeal) component.

Attempts to localize an intra-gastric transmitting capsule include spatial scanning of the patient with a receiver. The receiver and the scanning system locate the points with the highest reception and plot a track of the capsule, the assumption being that the capsule is at the location where the strongest signal is received. Also these attempts use a laboratory device that is non-portable.

In the case of the NORIKAWARP system (www.rfnorika.com), and of the patent deposited by Given Imaging (www.givenimaging.com), there is an antenna array having multiple antenna elements. The antenna array is fixed to the external surface of the patient body (like a T-shirt), and two or more antenna elements (embedded in the capsule) receive the signal from the inner part of the body. Maybe the same solution is used also in MiRO. The signal strength of the received signal is measured and the estimated location of the signal source is derived from the signal strength measurements. By analysing the potential problems of RF-based localization systems, we observe that they require homogeneous electromagnetic fields, which are disturbed by presence of metallic objects. On the other hand, X-Ray based localization systems, like stereo fluoroscopy, require patient exposition to radiation doses and hospital stay.

3.3. Expected functionalities

The expected functionalities and specifications of the endoscopic microcapsule for the analysis and therapy of the overall gastrointestinal tract can be summarised as follows:

Product	**Endoscopic microcapsule**
Size	10 mm in diameter, 20 mm in length
Specifications	• Diagnosis : image, Virtual Biopsy, Bio-signal acquisition • Therapy : Sampling(µg) , Injection($\mu\ell$) • Function: Sensing/Actuation/Information/Control/Power/Telecom • Micro Battery : 0.8Wh/cc
Element Technologies	• System integration for endoscopic microcapsule • Locomotion mechanism : forward, backward, stopping, and clamping • Bio- signal acquisition : acceleration, pH, and pressure • Telemetry with high speed reliability • Energy : high power density and wireless transmission • Position tracking

Table 1: Expected functionalities of the Endoscopic Micropill

The above specifications are the roadmap of the Intelligent Microsystem Center (IMC) in Seoul (South Korea) which embarked in May 2000 a 10-years project for the development of interventional microcapsule with active locomotion.

A conceptual scheme of the capsule is illustrated in Figure 3.

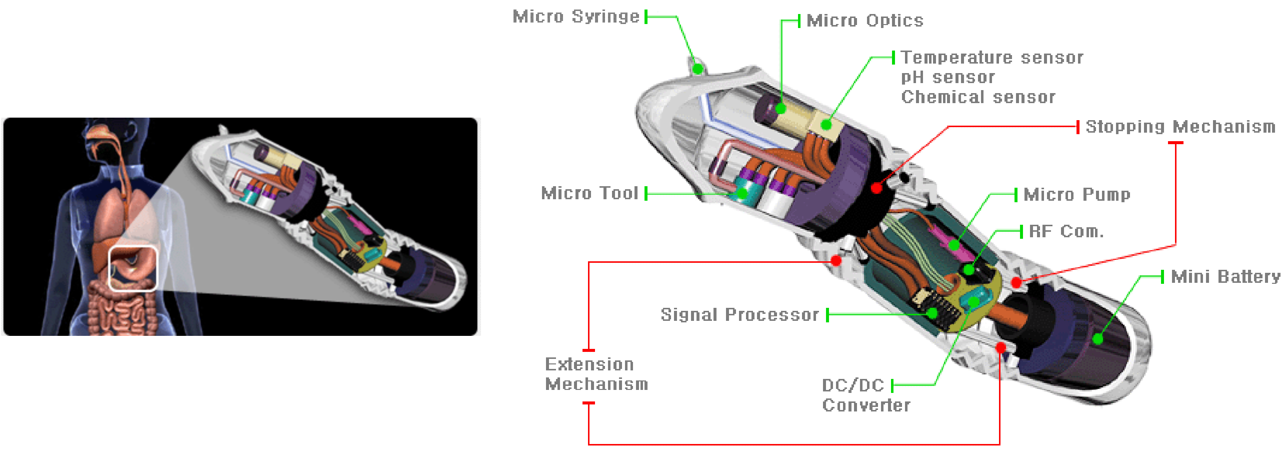


Figure 3: Conceptual scheme of the Endoscopic Micropill

Obviously, with the availability of sub-components, it is also possible to think about smaller pills, operating both alone or in cooperation with other pills. The shrinking of the size could also open interesting new applications: not only the gastrointestinal analysis, but virtually the analysis of all cavities of the human body.

3.4. The components

For making prevision about the development of the future diagnostic and therapeutic micropill, we have to consider the roadmap of its sub-components and sub-systems.

In the following paragraphs, we will explore the development lines of the following components:

- microactuators, micromechanisms and energy sources;
- endoscopic vision systems;
- telemetric systems;
- endoscopic sensor systems;
- endoscopic control systems.

1) Roadmaps for the development of microactuators, micromechanisms, energy sources

The market of Micro-electromechanical Systems (MEMS) is recently increasing his magnitude. Components for wireless communication seem to be one of the emerging fields (RF MEMS were practically still not significant in 2002), together with the sector of mechanical transduction. Regarding this last aspect, recent studies looking to next future [Yole, 2004] show that the growth is expressed by applications like:

- gyroscopes
- accelerometers
- pressure transducers.

See Figure 4 for a detailed plot of the MEMS components market.

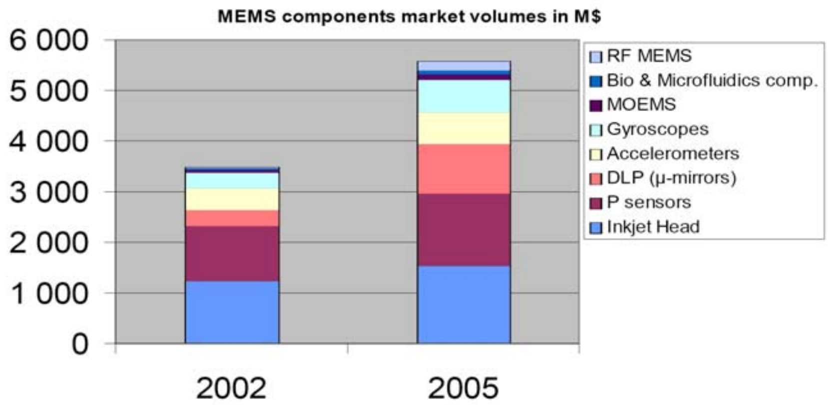


Figure 4: MEMS components market

If projections are made in the medium-long term, also **microactuators** and **micromechanisms** seem to be one of the leading fields: a symptom for that is represented by micromirrors, which are having a huge development and which are an example on how mechanical capabilities will add microsystems with new functions.

In particular in the following table a projection for the year 2020 is made on most promising components, most of which involve mechanisms:

Component	**Dimensions (volume, mm^3)**	**Power density (W/cc)**	**Energy density (J/cc)**
PZT Micromotors	2	100	-
Electromagnetic Micromotors	2	10	-
Thermal Microengines	10	10	9000
Batteries*	100	0.5	8000
Fuel Cells*	100	0.1	10000

Table 2: Projection for the year 200 related to some promising components (do not involve mechanisms.)*

New actuation mechanisms will be investigated. Preference will be accorded to actuation mechanisms that scale favourably with size. For instance, actuators exploiting surface effects will be preferred to “bulk” actuators, since they show better scaling behaviours. With this regard, fields of microengineering, conventionally considered as separate ones, will be merged or cross-linked to open new possibilities. As an example, we may consider electroosmotic effects exploited in microfluidics. The generated pressure in an electroosmotic pump is proportional to the square of the inverse of the diameter, thus having a very beneficial scaling law. The pressure generated within a 1μm capillary , filled with water, is more than 10^6 Pa. Such high pressure can be used to induce controlled deformation within a closed micro chamber. Also the applied voltage to generate the required electric field scales favourably with size.

In a long term scenario, bioinspired nanotechnology will be a fundamental driving force for the development of future endoscopic devices. Living tissues, such as those of the muscular-skeletal apparatus, integrate energetic, motor, sensory and structural functions in an intimate way, that is not currently equalled by any man-made material. In fact, microengineered devices, such as MEMS, move their steps from micromechatronics, i.e. from the harmonic integrations of separate functions defined at system level and implemented in miniaturised and logically separated sub-systems. On the contrary, bioinspiration pushes toward the development of new materials where functions are synergistically integrated and where no stand-alone module can be pointed out: energy sources, actuators and sensors are strictly, both geometrically and functionally, combined together. Nanotechnology is the enabling and key factor for the new paradigm. For instance, nanotechnologies based on self-assembly (bottom-up approach) allow to generate patterns at atomic or molecular level in a massive and parallel way. On the contrary, lithographic processes (top-down approach) currently do not allow to fabricate features below a few nm (e.g by scanning electron microscope lithography). It comes natural that future multifunctional structures will not have a separate energy source. On the contrary, they will mimic natural metabolism and they will possibly interface with the metabolism of the host organism, e.g. the human person in the case of the endoscopic robots. If we consider standard batteries, such as nickel-cadmium (Ni-Cd) or advanced batteries, such as magnesium hydride with nickel catalyst (Mg-H (Ni)) we have energy densities that are, respectively, 0.16 MJ/kg and 8.3 MJ/Kg. These values are still far from the energy density of some common food such as sugar (15 MJ/Kg) or peanuts (25 MJ/kg) or oil (35 MJ/kg). Interfacing with human metabolism will be a tremendous advantage for implantable or intracorporeal microsystems. Some efforts have been made toward this direction, but this research line is still in its infancy and it requires a strong interaction between engineers, chemists, physicists and biologists. Under this perspective endoscopic robots will more and more look like artificial insects, not only kinematically but also mechanically.

2) Roadmap of Endoscopic vision system

In a parallel way the miniaturization of surgical instrumentation and vision systems are projecting the conventional surgical interventions toward a future where the keywords are noninvasive and painless.

As regards the endoscopic procedures the most important element is the vision system. To date it is possible to single out two main directions: indirect vision (e.g. CT or MRI) and direct vision (e.g. from a camera).

Virtual Endoscopy is the simulation of endoscopic interventions using methods of Virtual Reality and Computer Graphics. Usually, 3D volume data from CAT-scan, MRI, 3D ultrasound, rotational angiography, or other sources are used to generate a 3D view of their inside. Virtual endoscopy and perspective volume rendering are constructed using data obtained from helical CT scanning and commercially available software, opening the way for exciting new clinical applications. Two methods exist for postprocessing of data: surface rendering and volume rendering. Surface rendering links the contours of selected objects in a given slice with adjacent slices. This is a faster processing system but subject to poor definition, data loss, and threshold artifacts. True perspective volume rendering allows for more detail and opacity but entails increased processing time and cost. These techniques are being studied at research centers for use in a variety of clinical applications, including inspection of the colon, tracheobronchial tree, blood vessels, urinary tract, facial bones, and sinuses. Although not yet in routine use, the techniques have been found useful in specific scenarios, such as virtual colonoscopy and virtual bronchoscopy.

Advantages and Disadvantages of Virtual Colonoscopy

Advantages	*Disadvantages*
Noninvasive	Cost*
No sedation required	Radiation exposure
Can image entire colon and localize lesions precisely	Does not allow biopsy specimens to be taken
Fast	Cannot visualize polyps <1 cm in diameter
Sensitivity equal to that of colonoscopy for lesions >10 mm in diameter and superior to that of DCBE	Cannot show texture and color details of mucosa
Less technically demanding	Retained feces can be misinterpreted as polyps

DCBE = double-contrast barium enema.

**--No reimbursement code.*

Some centers no longer consider virtual colonoscopy a research protocol and are offering it as a screening tool despite its limitations.

With continuing advances in software and hardware, virtual endoscopy offers the promise of quicker and cheaper methods of evaluation.

Finally, virtual colonoscopy may become an interesting procedure for selected indications, but not as a replacement for optical endoscopy. One of the reasons is that virtual endoscopy only provides a static geometrical information about the shape of the colon. It does not provide optical information of the surface on color and texture. This information is, however, critical for medical diagnosis, e.g. of adenoma.

As regards the direct vision by means of a camera, the most important component is the image sensor.

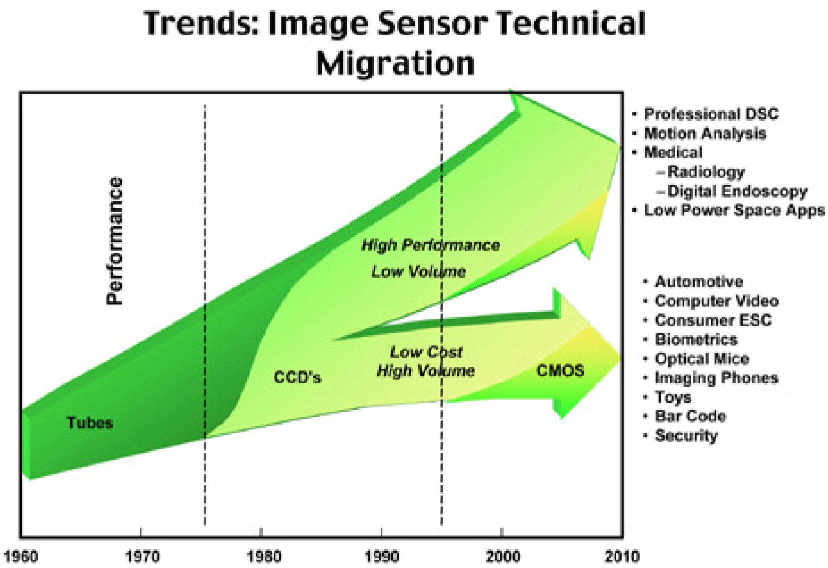
CCD (charge coupled device) and CMOS (complementary metal oxide semiconductor) image sensors are two different technologies for capturing images digitally. While they are often seen as rivals, CCDs and CMOS imagers have the same strengths and weaknesses that make them suited for different applications. Neither is categorically superior to the other, although vendors selling only one technology often claim otherwise. The choice depends far more on the application...and the vendor.

Over the last few years, CMOS sensors have become increasingly common. They are being used in medium and large format digital backs, in professional digital SLRs, as well as some consumer cameras.

Both CMOS and CCD sensors are made of silicon. They have similar light sensitivity over the visible and near-IR spectrum. At the most basic level, both convert incident light into electronic charge by the same photo-conversion process. However, CMOS sensors can be made of the same silicon material as other computer chips. That means all the electronics can be embedded onto one chip, reducing production costs, space requirements and power consumption. With CMOS, it's possible to produce entire digital cameras on a single chip.

CMOS sensors also have individual picture elements, but, unlike a CCD, the conversion of the electronic signal to a digital value is completed within the individual photo sensor. That makes it possible to read-out the values of the individual sensors in a single step, rather than having to step the electronic signal off of the register, as is the case with CCDs. In the last few years the technology limitations have been overcome to make CMOS a viable alternative to CCD. The quality gap between images captured with CCD sensors and images being taken with CMOS sensors is narrowing rapidly. That is especially true as digital camera resolutions grow. CMOS sensors don't suffer from the decrease in the signal-to-noise ratio as resolutions increase. That means higher resolution digital cameras can be produced without having to increase significantly the supporting electronics.

CMOS sensors are also used in many of the miniature cameras for space missions. To further increase the quality of the images that these tiny CMOS-based cameras can capture, NASA is working on what's called hybrid imaging technology (HIT). Theoretically, HIT merges the best of CCD and CMOS technology, in hopes of coming up with a new technology that's better than either. Once implemented, the resulting technology should have higher resolution, better scalability and reduced power consumption. NASA is also working on another type of sensor altogether. Under contract to the space agency, the Jet Propulsion Laboratory in Pasadena, California, is working on what's being called an SOI (silicon on insulator) sensor. SOI sensors are extremely thin, just 1 micron, and could be applied to almost any flat surface. Because of their light weight and low power consumption, they could be used for a wide range of applications. These sensors should be available commercially by the end of the decade. This could be another revolutionary step in digital imaging.



"We believe we have a true breakthrough in image quality that brings CMOS image sensors to a very important point for image applications where CCD have been predominant," said John Carey, product engineer for Hewlett-Packard.

3) Roadmap of Telemetric systems

Telemetry Scenarios. From PAN to WPAN

According to analysts, 60 percent of all key electronic products will be portable by 2006 and many will need connections to other devices [Toshiba Wireless Market Forecast]. The new wireless economy will probably enable us to have all our medical and financial records available at the click of a button. Thus an increasing interest is devoted in connecting together different electronic devices in a Personal Area Network (PAN), centred around the final user. These PANs can be part of wider frames, from LANs (Local Area Networks) to WANs (Wide Area Networks), where personal data, like identification and medical information, can be sent over the WWW in order to facilitate daily activities and diagnostic issues. The technological challenge of the next future will be the "wire replacement", that means the migration from wired to wireless networks: thus PANs will become WPANs (Wireless PANs), from LANs to WLANs and so over. All these W-Networks will enjoy the ease of re-configurability, given by the absence of wires.

Pervasive Healthcare

Pervasive Healthcare (PH) will be another keyword for future research. PH may be defined from two perspectives: first, it is application of pervasive computing (or ubiquitous/proactive computing, ambient intelligence) technologies for healthcare, health and wellness management; second, it is making health care available everywhere, anytime – pervasively. Developments in sensor and more generally measurement technology make it possible to obtain health related information from wearable or embedded sensors also in out-hospital conditions, in our daily life. Ubiquitous communication based on mobile telephone networks, (wireless) local area networks, and/or some other wireless technologies makes possible anywhere, anytime transfer and access of all kinds of information – like measurement data, person-to-person communications or health information. Mobile communication gadgets provide ubiquitous user interfaces for the users (from health care professionals to citizens). [IEEE EMB source] Thus, in order to achieve PH, wireless sensors networks has to be integrated inside existing PANs, using the communication infrastructure already present.

Domotic

Stating from In-Stat/MDR "Home Networking Revenue Forecast", the silicon solutions market in the domotic frame will grow from 650M€ of 2002 to more than 1G€ within 2007, following the positive trend of WLANs (Wireless LANs), of IEEE communication protocols, such as 1394b (FireWire), 802.15.1 (Bluetooth) and 802.15.4 (ZigBee), and of other kind of standards, like HomePlug (www.homeplug.org). At the end of 2003 the number of domestic network inside Western Europe increased up to 4.5 millions, starting from 2.8 millions registered in the same period of 2002. Following that trend, it is possible to predict that this number will reach 15 millions within the end of 2007. The basic condition to meet in order to achieve an ambient intelligent is the development of a domestic network able to link sensors, actuators and terminals over a common communication bus. The overall system has to be robust and very simple to be used, such as to serve also the needs of elderly or disabled people. Wireless networks will enable to connect different sensors, spread all over the domotic house and/or placed inside or outside user bodies, in order to monitor both the different home environments, both the health condition of the inhabitants.

Technologies; IEEE Standards

Beyond the well known Wi-Fi or WLAN IEEE 802.11 standard, a continuation of standard Ethernet communication in the 2.4GHz radio band that has been primarily designed to replace Ethernet, for the convenience of human users with laptops or similar cable-less systems, we have to consider the 802.15 WPANs standards. The most famous is the 802.15.1, also known as Bluetooth, that shown in these recent years its difficulties to become dominant in the market, mainly because of the complex architecture and the high energy consumption. An emerging and very promising new protocol is the 802.15.4, that will be known in the next few years as ZigBee, from the name of the alliance of companies (www.zigbee.org) working together to enable reliable, cost-effective, low-power, wirelessly networked monitoring and control products based on the IEEE 802.15.4 standard. The main difference between ZigBee and Bluetooth is the data rate: low data rate for the first, and high for the latter. For a wireless sensors network a low data rate, that means low power consumption, is usually the best choice. This make ZigBee (and similar protocols like Wireless USB, proposed from Cypress, www.cypress.com/ad/wusb3) a suitable technological solution for the wireless sensors networks of the future.

Last but not least the IEEE 802.15.3, also known as Ultra Wide Band (UWB), where the information are transmitted using a very large transmission band (the signal band exceeds one quarter of the carrier frequency). For a generic user application the UWB allows a power saving of 10000 times if compared with the technology used in nowadays mobile phones.

RFID Sensors

RFID stands for Radio Frequency IDentification. At a simple level, it is a technology that involves battery-less tags, that emit radio signals if stimulated with a RF impulse, and devices, called readers, that stimulate the tag and pick up the response signal. The diffusion of RFID tags on goods of every kind is nowadays a reality and, from a IDC (International Data Corp.) study, the market of RFID devices will grow up to 1.3 billions of dollars within the end of 2007, from the 91.5 millions reached on 2003.

A great technology challenge for RFID in the next future will be the enlargement of the working range, actually reduced from materials standing between the reader and the tag. For this reason, researchers are working on better performing antennas and more sensitive readers. Another problem that RFID has to face is the high cost, compared to the barcode tags: actually a RFID tag has a mean cost of 20-30 dollar cents; this means that a radical and pervasive diffusion of this technology can be obtained only with a unit cost of 5 cents or less, that will be reached within 2010, stating from IDC market forecasts. Another actual weak point of RFID is the absence of a unique standard, but this problem will be overcame in the very next future.

The killer application, in our opinion, will be the integration of sensors in the RFID tags: this will add to the big advantages already present, like battery-less operation and flexible package, the capability of monitoring the environment, obtaining a virtually everlasting sensor node.

Conclusions

The possible long-term scenario regarding the Endoscopic Radiopill, from the point of view of the telemetry architecture, can consist in a set of biocompatible RFID sensors implanted along the digestive tract (or all inside the human body) for a long range of time (several years). Each sensor would be capable to measure a different and critical physiological parameter. Every time there will be the need to acquire the sensors readings, a battery operated radiopill can be swallowed by the user: the pill would stimulate the RFID sensors and should acquire the sensors readings along the gastro-intestinal tract. Once the data will be acquired, the radiopill will send them over the WPAN by RF communication. Using the domotic network infrastructure these information can be analyzed, organized and sent to the family physician. In case of a severe pathology is found, the medical doctor can take control of the endoscopic radiopill and tele-operate a real time minimal invasive operation exploiting the surgical instrumentation present on-board of the pill.

4) Endoscopic sensor systems

Scenario

At present, commercial micro-capsules for endoscopy have two important characteristics: they are passive and, excluding local drug delivery, they have pure diagnostic purposes as they are only able to achieve an effective visualization of the small intestine (M2A Plus microcapsuleby Given Imaging, 2003; NORIKA3 by RFLab, 2004). Future robotic pills will not only be active and able to travel and stop along the entire GI tract, but two additional key-concepts are expected to drive the research in the field of micro-robots for endoscopy:

migration from diagnosis to direct intervention on the body, and the concept of continuous endoscopy, with small robotic capsules continuously moving inside the body, with monitoring and rapid intervention capabilities.

In order to achieve the ability to make on board diagnosis, therapy and biopsy, a complete sensory system showing a high degree of reliability is mandatory for such a robot, that must know its position and orientation in space, feel the environment around it, grasp tissues and manipulate surgical micro-tools. There is the need for a unified sensory system, in which all the “senses” share the same language, in order for the small, embedded, processing unit to efficiently deal with them. Other aspects that on board sensors and sensory systems must have are: extreme miniaturization and flexible support.

The sensory system will include vision, touch and physiological parameters detection (such as pH). Touch is a key point for the robotic capsule, both for sensing the surrounding tissues (with a tactile skin all around the capsule body) and for palpation/grasping. In particular there is the need for sensorized micro-hands, covered with highly dense tactile skins.

Enabling technologies

The main driving factor for the integration of sensors for the robotic pill application will be the strong miniaturization of the devices. In order to equip the microrobot with sensory capabilities, it will be essential to develop a diffused and pervasive sensory system. Nanotechnology (whose definition given by the Merriam-Webster Dictionary, 1987, is “the art of manipulating materials on an atomic or molecular scale”) will fully supersede current traditional (silicon bulk and surface micromachining) and non-traditional (like e.g. LIGA, micro-discharge machining, micromolding) microsystem technologies for sensor development. In this way miniaturization of devices will not depend on the limits of current photolithographic technology (electron-beam photolithography reaches dimensions of no less than some nanometers).

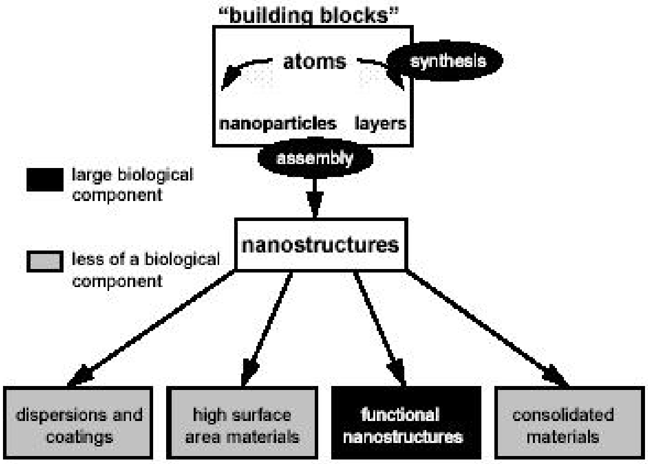


Figure 5: Biological aspects in nanotechnology (L. Jelinski “Biologically related aspects of nanoparticles, nanostructured materials, and nanodevices”)

Nanotechnology building blocks are at the moment being thoroughly investigated in order to be assembled to provide an enormous range of possible structures. Chemical synthesis and biotechnology are the enabling key factors to combine these building blocks to produce new materials and structures that have not yet been made in nature. These self-assembled materials often have enhanced properties as well as unique applications. Different nanostructures are obtained through the “bottom up” approach, and advances in biological science may have a large impact as shown in the scheme below.

Current nanotechnology research and market development are a considerable promise for a future strong added value across a broad range of industrial and medical applications where attributes of nanotechnology offer significant performance advantages including:

- low power consumption
- small size
- high specificity, sensitivity, and reproducibility.

All these features are crucial for the development of an advanced sensory system for robotic capsule.

Several companies (among which: Nanomix, www.nano.com; Nantero, www.nantero.com; Nanocs, www.nanocs.com; Nanosys, www.nanosinc.com) are actors in this scenario and their nanotechnology research is based on a central element which is the carbon nanotube. These individual molecules respond to chemical changes at the molecular level and it has been demonstrated that sensors can be tuned to respond selectively to a variety of chemicals, including some which are difficult to detect with traditional sensors.

Individual or a small collection of single-walled carbon nanotubes can be used as miniature chemical and biological sensors to detect molecules in a gas or in solutions with ultra-high sensitivity. The detection mechanism of these tiny nanosensors is based on chemical interactions between the surface atoms of a nanotube and adsorbed molecules. Up to three orders of magnitude change of the nanotube resistance is detected within a few seconds of electron donating or withdrawing molecules adsorbing onto the nanotube.

The nanotube-based chemical and biochemical sensors have several unique features:

- Direct electrical signal detection and readout;
- Extreme sensitivity and superior response;
- High density.

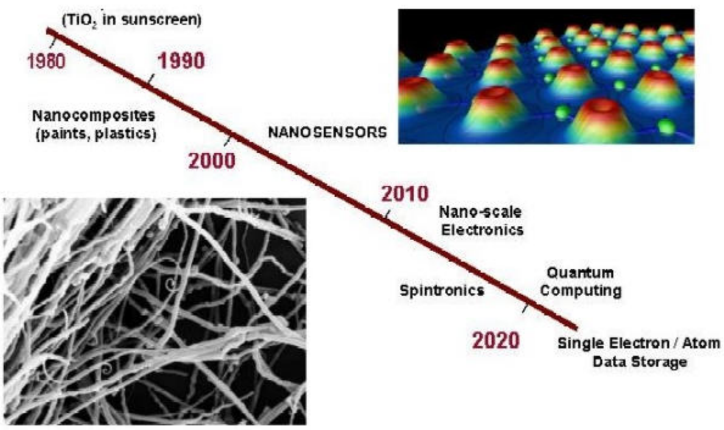


Figure 6: Nanotechnology commercialization trend (www.nanomix.com)

Some applications of nanotechnology have long been on the market, such as nanoscale additives to sunscreen, others are many years from commercialization, such as single-electron transistors and quantum computing.

According to Moore's Law, formulated in 1965 by Gordon Moore, the number of transistors per integrated circuit would double every 18 months. This has been proven in the past as the graph illustrates for transistors, and Moore predicted that this trend would hold for the next ten years.

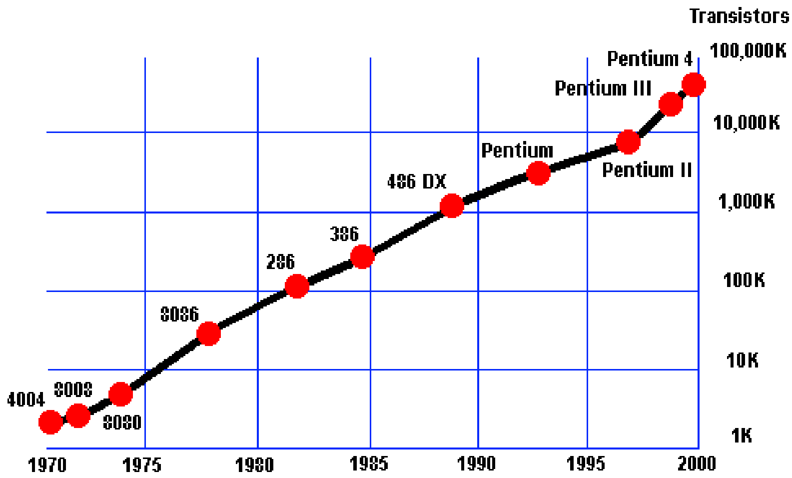


Figure 7: Intel Moore law for transistors (http://www.pctechguide.com/02procs.htm)

Advances in "bottom-up" fabrication nanotechnology will enable further miniaturization and new nanoelectronic device development, as illustrated in the graph.

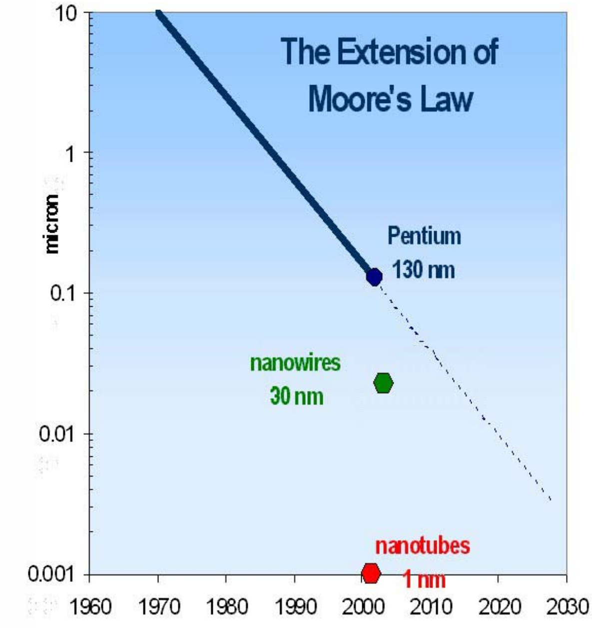


Figure 8: The extension of Moore Law (www.nanomix.com)

A future nanotechnology trend will be the integration of nanoelectronics with nanosensors. Obviously, in order to “build” these nanomachines, rules for nano-assembly of bio-nano-pieces are necessary. The long term goal is to develop novel and revolutionary biomolecular machine components and sensors that can be assembled and form multi-degree of freedom nanodevices that will be able to transfer information from the nano to the macro world.

As with any new technology, much work must be done to convert a first demonstration into a commercial product. Large-scale manufacturing techniques must be developed, and product reproducibility and reliability must be ensured.

<u>Conclusions</u>

A possible long term scenario for the endoscopic pill from the sensors point of view could consist of a set of capsule robots able to propel not only in the GI tract, but also in narrower districts of the human body, such as in mini-vessels, in the respiratory system and so on. The interaction between these nanomachines and the tissues will have a different nature from the interactions which we are used to. They should be based on chemical stimuli and molecular configuration changes rather than on mechanical forces and traditional sensing signals.

These nanomachines will be normally fixed to the walls of cavities of the human body, like big vessels, stomach and bronchial tubes. At predetermined intervals they could move and monitor the conditions of these organs: wall conditions (stiffness, roughness, ulcers, vessel diameter), pH and other bio-chemical parameters, presence of localized infections or obstructions. In high risk patients robotic pills could be used to find tumors in early development stages. In relation to the body part to be monitored, pills with different sensor configurations could be used: for example a pill for vessel monitoring could host pressure sensors, ultrasound proximity sensor; a tactile skin could wrap the pill.

Telemetry will be used to transmit data to an external control unit, or to an internal master unit, which could coordinate the swarm, or decide if a measured situation is dangerous enough to alert the family doctor: the master unit could also make a “surgeon” unit approach the area and perform the intervention.

5) Endoscopic control systems

Robot control scenarios

This is a huge field. In the following we will try to split the analysis into three main sectors: single robot, multiple robot and robot swarms.

Single robot control

Key features that autonomous robots must have, in order to actively interact with an unstructured environment are ***learning*** and ***adaptation***. Many strategies were developed; among them are:

- reinforcement learning: rewards and/or punishments are used to alter the parameters of a controller;
- neural networks, where learning occurs as the result of alterations in synaptic weights;
- evolutionary learning, using genetic algorithms;
- learning from experience;
- inductive (training sets are used to generalize or specialize the controller).

In the last years, the animal kingdom has been an important source of inspiration for both robot structures and control architectures, capable of reacting to a dynamic environment. Among biologically inspired robots, ***legged robots*** are particularly interesting for robotic pills that must move inside the human body; adaptive central pattern generators have successfully been used for such robots.

Trends

In order for a robot to be really autonomous it’s mandatory that it can deeply interact with the environment and learn from it. The first step in this process is ***perception***; the development of a complete sensory system (both proprioceptive and exteroceptive) will be mandatory [A.I. Selverston, in Ayers 2002]. The dimensions of the sensors are decreasing day by day, and miniaturization seems to be a limitless process: dealing with large amounts of ***analog signals*** will be a challenge, and control strategies managing information from thousands of sensors need to be developed.

We expect that artificial ***neural network*** technologies will play an increasing role in robotics, in particular, in situations where the environment in which the robot has to move is unknown or only partially known.

The use of ***genetic algorithms*** to optimize robust pattern generators appears to be one of the most promising approaches, since genetic algorithms do not require computing a gradient of the cost function .

Multiple robot controls

Instead of evolving a centralized control on a single robot, a multiple robots solution with a distributed control and less complexity for each unit can be the best choice to perform certain tasks. A multi-agent robotic system merges multiprocessing, parallel system design and distributed artificial intelligence together with ethological study of cooperative societies.

Swarm control

Swarm intelligence (SI) leads the multi-agent robotic system concept to its extremes. SI is a novel approach to solve distributed problems, which takes inspiration from biology examples provided by social insects, like ants or bees. In these cases a robust and efficient group behavior is the result of a small set of simple interactions among individuals and between individuals and the environment.

Advantages of robotic swarms:

- scalability,
- flexibility,
- distributed sensing and action capability;
- increased robustness of the system.

Following the trend of technology towards micro and nano range, we conjecture that swarm intelligence could represent a fundamental approach to the development and control of micro and nanorobots. The main challenge for research in Swarm Intelligence is to succeed in finding the right and simplest behavior of the individual unit starting from a desired swarm target.

A dramatic impact of a similar robotic control is foreseen in particular for biomedical application (e.g., examine and medicate human body from inside):

- *Pervasive monitoring*: a micro robotic swarm could navigate inside the human body monitoring in continuous different health parameters and transmitting between each other and outside useful information.
- *Tissue repairing*: swarm could cooperate in repairing internal damages (e.g., internal bleeding). A swarm behavior is necessary for a faster (-> parallelism) and effective action.
- *Detection and removal of tumors and viruses*: cooperative behavior is necessary for nano-robots to perform similar tasks in a reasonable time and with a high level of system robustness. Their behavior could be inspired to "biological swarm" like white corpuscles, implementing the so called “Immune system” control strategy.

Conclusions

The next generation of control schemes will probably consist of hierarchical structures mixing

- data conveyed from thousands of analog sensors organized in biologically inspired sensory systems and processed by parallel chips,
- knowledge from rough a-priori models of the environment,
- codified behaviors,
- neural controllers, whose parameters are continuously tuned by genetic algorithms.

There are several possible long-term scenarios regarding the swallowable Endoscopic pill, from the point of view of the control architecture:

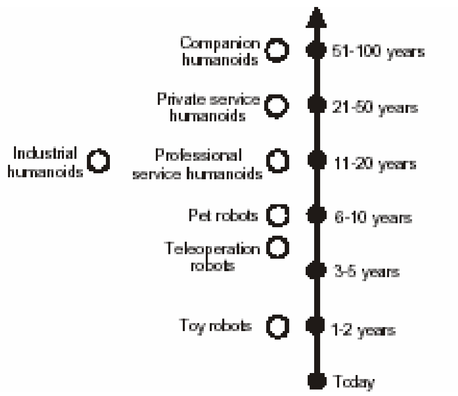
- a single legged pill will probably be “driven” by a central pattern generator for locomotion, whose parameters will be updated in accordance with the information on the environment (exteroceptive), on the pill status (proprioceptive), and coming from telemetry, provided by many sensory channels (visual, tactile, inclination, chemical,…);
- small groups of intelligent cooperating robots will be controlled by distributed architectures. The microcapsule system would guarantee several advantages, and in particular would let a differentiation of the robots' skills (not possible to integrate on a single robot), a multiple vision system (increased robustness), possible cooperation on the field (biopsy or in-situ analysis). Finally, several robots acting simultaneously would let a faster and more accurate inspection (which could also eventually mean a cheaper operation);
- by using a even larger number of more simple robots (a swarm), even more visionary targets could be achieved, as mentioned before.

4. The case study of Humanoid Robotics

4.1. The state of the art and the market

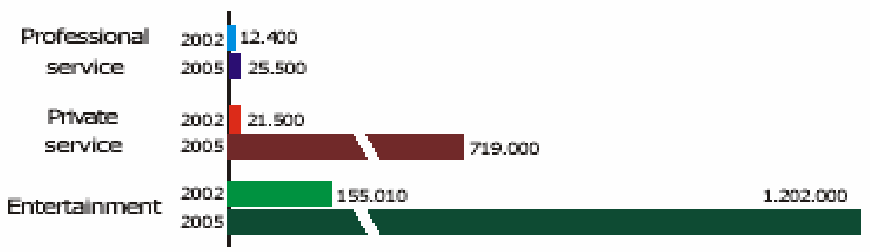
Humanoid Robotics is an example of rapid evolving robotics. A rush between some important Japanese industrial companies is ongoing for developing more advanced humanoids and the results are demonstrating that the competition in research activities is very efficacy. At this moment, humanoids are able to walk straight, lateral, up and downstairs, to sit down and raise up, to kick a ball, to follow a target, to make gestures, to dance, to play the trumpet, the piano and other instruments, to interact with human, and so on. The top humanoid platforms (not the entertainment ones) demonstrate the potentialities of such research activities but they still cost too much for becoming market products and, more especially, they still reproduce only very few capabilities of their natural model, the human.

In the next 10-20 years this gap will be probably filled. Humanoids will be provided with the main features that distinguish the human by the other animals: the hand and brain capabilities. The present humanoids demonstrate that the technology has already reached a good quality level, especially in terms of transmission and actuation components. New design paradigms have to be used for developing the future generations of “more human-like” humanoids. Some research groups are already working in order to achieve this objective collaborating with neuroscientists for going literally beyond robotics. The human learning, cognitive, predictive, perceptive neurophysiologic models are going to be “translated” into new robotics models. In the next 10-20 years, the humanoids will integrate the new components and the new bio-inspired neural models and amazing results are expected. The future humanoid will be a real human companion, assisting or substituting him/her during the daily living activities. It will be able to cook traditional dishes, to clean the home, to make shopping, to help elderly people during their walking, and so on. Probably, it will be also provided with additional capabilities (a kind of “super-humanoid”) for example an additional arm or a super vision system and so on. Such humanoids will be characterised by a sophisticated artificial intelligence and probably a kind of conscience will be autogenerated. The ethical issues are being faced by a multidisciplinary community of researchers, scientists, theologists, politicians, and institutional representatives in order to define a common strategy. Will we be able to avoid the “Bladerunner” concept of humanoid considering him a friend and not a slave?



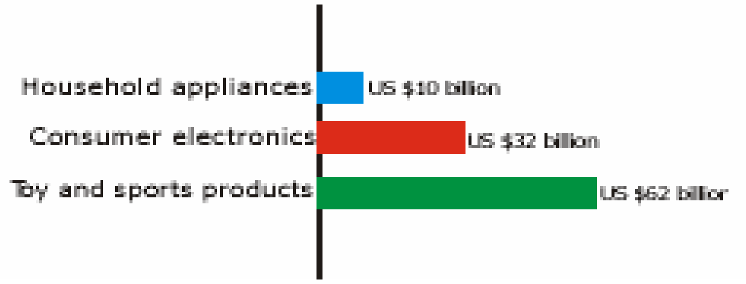
Even though robotic solutions for personal care and home assistance have been designed so far to respond to well-identified user needs, humanoid robots seem to be the general-purpose solution of the future for this growing need.

The World Robotics 2002 study published by the IFR/UN ECE [22] presents statistics for the current number of robots used in the different fields (see the picture below).



Worldwide numbers of service robot units in use

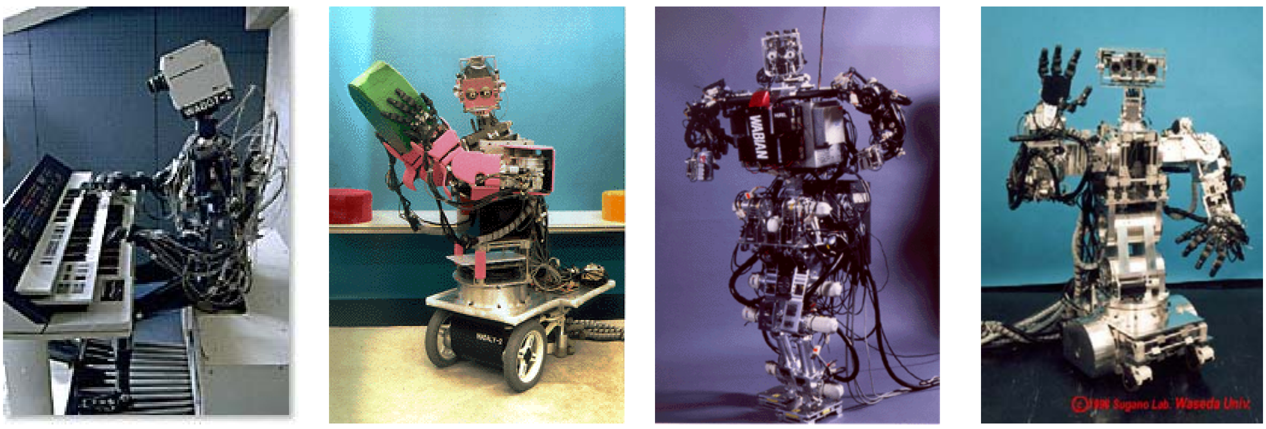
The U.S. census 2000 report [23] gives explicit numbers for the different product groups. Although these numbers are only showing the US domestic market, the overall market sizes are roughly the same in other developed countries.



US domestic sale figures for the year 2000

Humanoid robotics is fast and widely developing world-wide and currently represents one of the main challenges for many robotics researchers. In Japan, this trend of current research is particularly evident. Many humanoid robotic platforms have been developed in the latest years, most of them with an approach especially focussed on the mechanical, or more in general, hardware problems, in the attempt to replicate as closely as possible the appearance and the motion ability of human beings.

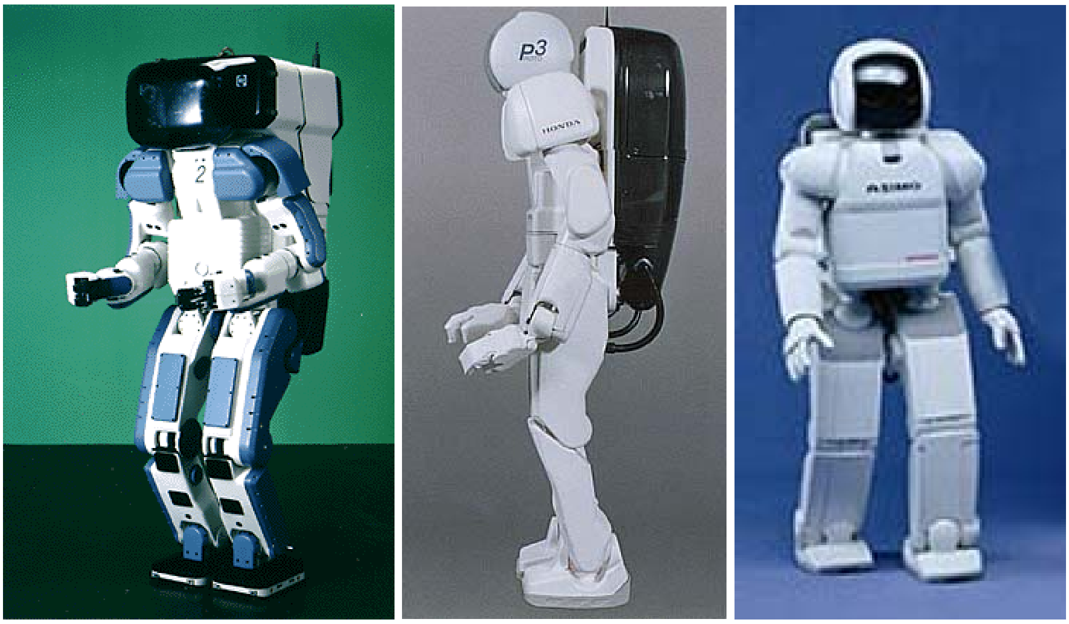
Impressive results were achieved by the Waseda University of Tokyo since 1973 with the WABOT system and its later version WASUBOT, that was exhibited in playing piano with the NHK Orchestra at a public concert in 1985 [1]. The WASUBOT system could read the sheets of music by a vision system and could use its feet and five-finger hands for playing piano. The evolution of this research line at the Waseda University has led to further humanoid robots, such as: Wabian (1997), able of walking on two legs, dancing and carrying objects; Hadaly-2 (1997), focused on human-robot interaction through voice and gesture communication; and Wendy (1999) [2,3]. Figure 9 illustrates some of the humanoid developed along this evolution.



a b c d

Figure 9: Waseda Humanoid Robots: a) Wabot-2, the pioneer piano player, b) Hadaly-2, c) Walking Wabian and d) Wendy

What is even more impressive in the scene of Japanese Humanoid Robotics research is that big companies are also devoting considerable efforts to this objective. The outstanding example is the Honda Humanoid Robot, whose current version is called ASIMO (see figures below), which absorbed a dedicated Honda team in a research effort for over 13 years. ASIMO presents very advanced walking abilities and fully functional arms and hands with very limited capabilities of hand-eye coordination for grasping and manipulation [4].



(a) (b) (c)

Figure 10 The Honda Humanoid Robots (a) P2 and (b) P3, and (c) the current version, ASIMO. Even if the robots are presented here in the same size, the real size was consistently reduced during the evolution: height went down from the P3's 160cm to the ASIMO's 120cm, and weight was reduced from the P3's 130kg to the ASIMO's 43kg

To help eliminate hefty production costs in developing "partner robots," the government of Nikkei, companies and academia are combining efforts to standardize parts and components, which should open the doors to volume production. Partner robots are designed to cooperate with humans, helping in social activities such as assisting elderly, nursing care and keeping public security, instead of serving merely as industrial tools.

As part of its three-year program through fiscal 2005 to reinforce basic technologies for robots and metallic molds, the Japan Small and Medium Enterprise Corp., affiliated with the Ministry of Economy and Trade, is working together with robot/parts makers and researchers to unify standards to make them smaller and less expensive. One of the two panels at the corporation is tasked with reducing motor, gear and servo amplifier sizes to reduce the overall engine size of a robot, while the other panel engages in developing a small and high-performance robot sensor of 2-3cm in diameter, about one-third the size of the existing models. If the panels attain their goals, both types of parts could begin to be sold this year for prices about 70% below those of conventional parts, sources at the corporation said. High production costs have hampered the spread of partner robots. One engineer said, "It would be hard to limit the prices of partner robots to affordable levels of several hundred thousand yen each because the shipments of robots are less than 1% of those of home appliances and because the necessary parts have to be procured from various suppliers."

Yoichi Shimosasa, submanager of security equipment development section at Sohgo Security Services Co. (2331), who is a member of the sensor panel, said, "We, as robot developers, have proposed the specifications of partner robots and parts suppliers always respond very quickly to our proposals," voicing expectations for the successful development of low-cost sensors. The security firm has only sold two C4 robots since it started marketing the security device in April 2002. The robot failed to draw demand due to the expensive price tag of 9.5 million yen, though it has multiple functions, such as memorizing the layout of a building for patrolling and sending pictures to security control rooms through its built-in camera. The C4 robot is costly because it incorporates about 50 sensors, which at the high-end cost around 100,000 yen each. If the price of a sensor is lowered to 30% of present levels, it would cut back on robot prices remarkably.

Efforts to standardize robot software are also underway at other government-affiliated organs, including the New Energy and Industrial Development Organization and the National Institute of Advanced Industrial Science and Technology. They are working to create a common format for software to control the robots movements. If it becomes possible for several ready-made software titles to be integrated, robot development would be streamlined significantly as currently companies have to develop software from scratch.

A group of about 10 robot-related firms, including Fujitsu Ltd. (6702) and Iwata Corp., has developed the RoboLink Protocol, which can link robots made by different manufacturers, based on the assumption that more than one robot will be used at offices and homes in the future. The group is seeking to improve the performance of software by adopting an "open source" approach in which it releases related information on a Web site and invites public opinions online, as was the case with the Linux operating system. A Fujitsu official said, "An open and spontaneous approach is necessary for software development beyond the collaboration between the government and businesses." *(The Nikkei Business Daily Thursday edition, April 2004)*.

It is worthwhile to outline how these systems are developed in Japan with a special focus on the mechanical, kinematic, dynamic, electronic, and control problems, with minor concerns for the robot behaviour, their application perspectives, and their acceptability.

Most progresses in humanoid robotics in Japan have been accomplished without focussing specific applications, and maybe this is one of the main peculiar features of this area of robotics, especially in that country. Nevertheless, among the possible applications of humanoids envisaged by researchers in this field, even in a long-term perspective, assistance to human beings is one of the most common. In Japan, the long-term perspective of application of humanoids concerns all those roles in the Society in which humans can benefit by being replaced by robots. This includes some factory jobs, emergency actions in hazardous environments, and other service tasks. Among them, in a Society which is fast and steadily increasing its average age, personal assistance is felt as one of the most critical ones.

On the market landscape, some products are being proposed as first attempts of introduction of robots in the society. Such introduction has been pursued in Japan gradually, starting from entertainment pet robots, such as the popular Sony AIBO, to arrive to the first robotic devices able to provide some simple services, like the recent Papero and the Temsuk housekeeper.

The Sony AIBO dog was launched at the end of 1998 by an Internet limited sale and all the 3,000 available items were bought in 20 minutes. This was especially a demonstration of how robotics was ready to be attractive also from a commercial point of view. Following the AIBO experience, many other pet robots, sometimes simpler and cheaper, were proposed on the market with a relatively good success. Examples are the robotic toys produced by Tomy and other toy companies.

While Honda was putting its ASIMO humanoid on the market, other small humanoid robots were also proposed as hi-tech entertainment products. For instance, Sony launched the SDR-3X and Fujitsu the HOAP-1. More recently the Pino humanoid robot became very popular in Japan and it is successfully sold together with a variety of gadgets. In addition to the commercial aspects, one of the peculiarities of Pino is that it was designed so as to be assembled with no-specialised off-the-shelf components and materials and with an open software platform, in order to favour humanoid robotics research especially for young researchers and students.

These robotic toys are now opening the way to the first commercial personal robots, i.e. still entertainment robots with some 'helpful' functionality: the novel Papero (by NEC) is a small mobile robot with a non-anthropomorphic pleasant shape, with big eyes and speech and audition capabilities. It can recognise some faces, welcome guests and take messages for other people. On this line, the Temsuk housekeeper has a more anthropomorphic shape, resembling a feminine household figure, and is intended to provide simple services around the house.

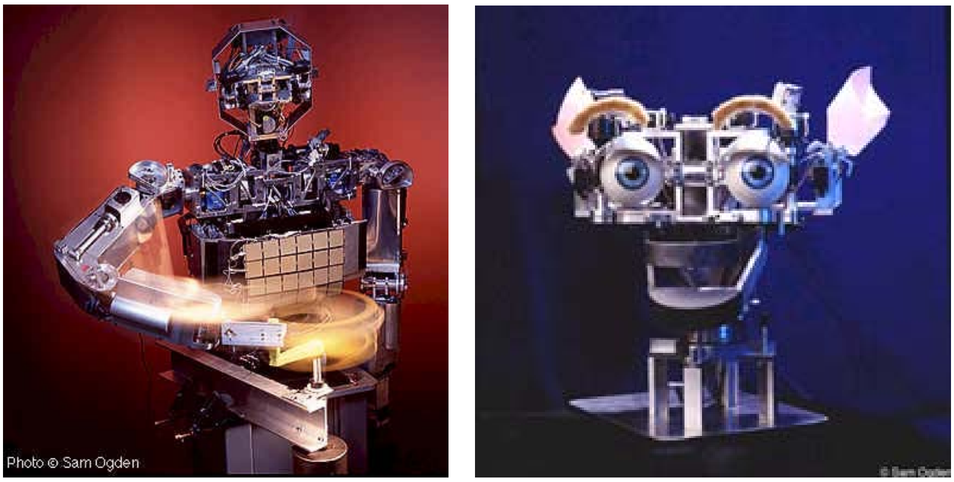
Figure 11 (a) The new Sony AIBOs (named Latte and Macaroni); (b) the Sony SDR humanoid; (c) the popular Pino humanoid

Figure 12 More helpful robots: (a) Papero and (b) the Temsuk housekeeper

In the USA, the research on humanoid robotics received its major impulse within the studies related to Artificial Intelligence, mainly through the approach proposed by Rodney Brooks, who identified the need for a physical human-like structure as prior for achieving human-like intelligence in machines [5]. Brooks' group at the AI lab of the MIT is developing human-like upper bodies able to learn how to interact with the environment and with humans. Their approach is much more focused on the robot behavior, which is built-up by experience of the world.

In this framework, research on humanoids does not focus on any specific application, as well. Nevertheless, it is accompanied by studies on human-robot interaction and sociability, which aim at favoring the introduction of humanoid robots in the Society of Humans.

Still at the MIT AI Lab, the Kismet robot has been developed as a platform for investigation on human-robot interaction. Kismet is a pet-like head with vision, audition, speech and eye and neck motion capability. It can therefore perceive external stimuli, track faces and objects, and express its own feeling accordingly.



(a) (b)

Figure 13 (a) The MIT's COG Humanoid Robot and (b) Kismet.

At the market level, in the USA robotics diffusion is fostered through entertainment applications, as well. In the latest 10 years a big impetus was given by Sarcos, which develops and commercializes entertainment humanoid robotic systems, such as Sarcoman, which can be remotely controlled by a human operator and used in shows and demonstration.

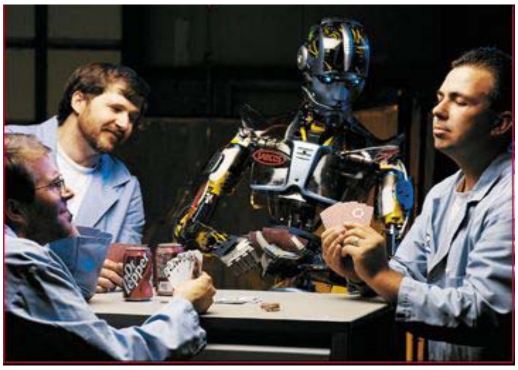


Figure 14 Sarcosman

Humanoid robotic personal assistants are still at the research level, in the USA.

At the Intelligent Robotics Laboratory of the Vanderbilt University, ISAC is a humanoid robot designed and built as a research platform for service robotics. The humanoid system also provides a test-bed to develop new technologies for human-to-robot and robot-to-human communications, including audio, visual, and gestual methods.

The Nursebot project (Personal Robotic Assistants for the Elderly) is an inter-disciplinary multi-university research initiative focused on robotic technology for the elderly that brings together researchers from the University of Pittsburgh and Carnegie Mellon University. The goal of the project is to develop mobile, personal service robots that assist elderly people in their everyday life. A first prototype is named Pearl and, when fully developed, it will be able to assist elderly people in their homes, allowing them to live independently longer before they need for the full time care of a nursing home. Pearl can perform such routine tasks as opening a jar, reminding people to take their medication or calling for help if they fall.

Figure 15 Two images of Nursebot

Europe is more cautiously entering the field of humanoid robotics, but can rely on an approach that, based on the peculiar cultural background, allows integrating considerations of different nature, by integrating multidisciplinary knowledge from engineering, biology and humanities.

Generally speaking, in Europe, research on robotic personal assistants has received a higher attention, even without the implication of anthropomorphic solutions. On the other hand, in the European humanoid robotics research the application as personal assistants has always been much more clear and explicitly declared. Often, humanoid solutions are answers to the problem of developing personal robots able to operate in human environments and to interact with human beings.

Personal assistance or, more in general, helpful services are the European key to introduce robots in the society and, actually, research and industrial activities on robotic assistants and tools (not necessarily humanoid) have received a larger support than research on basic humanoid robotics.

While robotic solutions for rehabilitation and personal care are now at a more advanced stage respect to the market opportunities, humanoid projects are currently being carried out by several European Universities.

Some joint European Projects, like the Brite-Euram Syneragh and the IST-FET Paloma, are implementing biologically-inspired sensory-motor coordination models onto humanoid robotic systems for manipulation [21].

In Italy, at the University of Genova, the Baby-bot robot is being developed for studying the evolution of sensory-motor coordination as it happens in human babies [20].

ARMAR, developed by the Karlsruhe University, is an autonomous mobile humanoid robot for supporting people in their daily life as personal or assistance robot. Currently, two anthropomorphic arms have been built up and mounted on a mobile base and studies on manipulation based on human arm movements are carried on [15] [16].

Thus, even though European humanoids are still a step before application and exploitation, they are being developed in view of their integration in our society and, meeting the need for robotic assistants already strongly pursued in Europe, they are very likely to be employed in assistance activities.

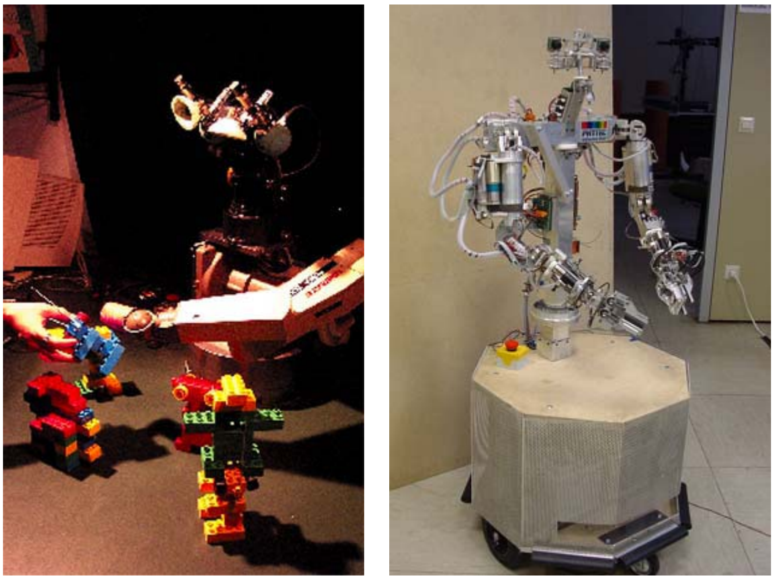


Figure 16 The European (a) Baby-bot, and (b) Armar

4.2. Components of Humanoid Robots

Considering the human body as model, we need for several new components.

First of all, we need to reproduce the wiring capability of the human nervous system. Only in the arm, for example, there are thousands of nerves that connect in parallel thousands sensors and muscle fibres to the Central Nervous System. The results of the research activities in micro-nanotechnologies and conductive and elastic new materials will be probably used for solving this problem.

Artificial skin will covered the humanoid’s body. It will embed micro-nano-tactile sensors able to reproduce the human tactile sensation of touch, texture, temperature, slippage. Micro-nano-proprioceptive sensors will be also distributed on the actuators and artificial tendons in order to reproduce the human functionality of the sensory system.

New actuators will be available in the future. In particular the artificial muscles seem to be very promising for such bio-morphic application.

The humanoid will be a real autonomous robot, able to process in real-time the information arriving from thousands of sensors distributed in its body, to learn by errors, to take decisions, to navigate in unknown environments. All this tasks need for new powerful process units and new control and cognitive SW implementation. The evolution of nano-electronics will contribute to solve the first requirement while the collaboration with the neuroscientists will generate neuroscientific models that will be used for defining new control, cognitive, and learning SW strategies useful for humanoid applications.

In the following the main components of a humanoid robot are analyzed separately in terms of state of the art, key requirements for future developments and expected advances.

1) Mechanical systems

Research on humanoid robotics allowed to achieve some of the most advanced current results in the design and development of mechanical systems (excluding the application of robotics requiring micro-mechanics solutions). Mechanical systems developed for humanoids show the best ratio between size/weight and performance. They usually show a high dexterity together with lightness and compliance.

Japan is maybe on the state of the art of mechanical systems for robots, especially with solutions replicated from biological system. The Waseda University in Tokyo, within the Humanoid Project, developed several biologically-inspired mechanical systems as humanoid components, such as Prof. Takanishi's robotic head, talking robot, Wabian walking humanoid. The arms developed by Prof. Sugano for the Wendy robot show an advanced mechanical solution (called MIA) that allows an adaptable compliance at the mechanical level, so as to provide a completely safe interaction with humans.

In Europe, studies on anthropomorphic solutions for robotics have also led to interesting and innovative mechanical systems. An interesting example of robotic arm is the 8 d.o.f. Dexter arm, developed by S. M. Scienzia Machinale srl, Pisa, Italy, for incorporation in the 'URMAD' service robotic system [28]. Its physical structure is highly anthropomorphic (see Figure 17), with the link structure reproducing the human body from trunk to wrist, and cable transmission has been adopted for joint movements. The reason of such an anthropomorphic choice mainly relies on the application the arm is addressed to, i.e. service tasks in unstructured environment involving strict interaction with humans. The anthropomorphic structure allows instinctive approaches in driving tele-operation tasks, thus reducing the training phase of operators. Furthermore, it also increases the acceptability from the user's side and enhances the possibility of integration into a domestic environment, conceived for human limbs. The redundancy of the cinematic structure of the arm facilitates dexterous manipulation, enables the arm to be configured for work at various heights above the ground, and allows the arm to fold so that its work envelope can be minimized. Cable transmission allows for achieving low weight and inertia of the distal joints; all motors of the 6 d.o.f. distal part are located in the second link which represents the trunk. The first two proximal joints are aimed at pre-positioning the distal 6 d.o.f. manipulator so as to increase the overall workspace.

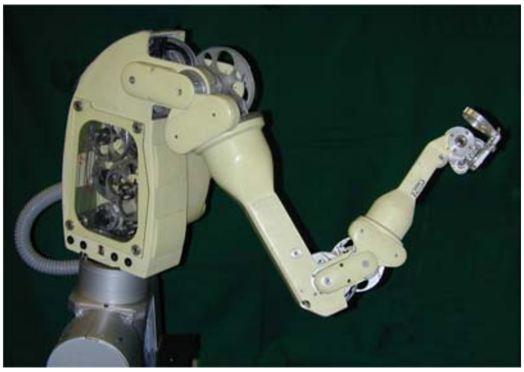


Figure 17 The Dexter robot arm

A definitely central need for humanoid robotics (as a technology driver) but also for the wide variety of future terrestrial service robot applications, are sensor-controlled light-weight arms (in contrast to the stiff and heavy industrial solutions) and articulated, multi-fingered hands, which come closer and closer to the delicate human performance. Two of these arms combined with an arrangement of a stereo camera pair tends to provide such a system with humanoid appearance for space applications and thus provokes the "robonaut" terminology (Figure 18, left). NASA has recently presented remarkable results in this context. In Europe an advanced light weight robot manipulator and a 4-finger-hand has been built by the DLR [8]. In Figure 18 (right) a robonaut concept of a free-flying service satellite is shown using components of the DLR robotics technology.

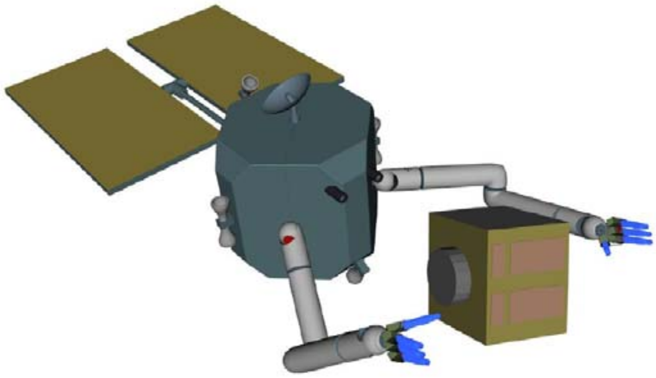
 

Figure 18 The NASA Robonaut (left) (courtesy of NASA) and a Robonaut study using the DLR light-weight robot components and multi-sensory 4-finger hand technology

Key issues for future developments are in the integrated mechatronic design approach. A mechatronically designed product relies heavily on system and component modeling and simulation to establish the optimal design tradeoffs between electronic and mechanical disciplines when subject to specific cost and performance constraints. Integrated design moves on standard goals, namely:

- to rationalise the procedures and standardise the steps;
- to automate routine developments (computer graphics, stress analysis, etc.);
- to transfer customers' demands, with transparent assessments;
- to simplify products and production processes, with optimal work-cycles;
- to modify work-cycles schedules, for minimal time-to-market;
- to provide visibility of the overall technical specifications files;
- to reach design robustness (to grant zero-defect manufacturing);
- to refer to value-chain models for measuring the return on investments;
- to perform condition monitoring maintenance with reliability margins;
- to exploit benchmarking for the adaptive designing of artefacts;
- to include quality checks, as routine tasks of the process operators;
- to enable re-engineering with design-to-costs requirements;
- to resort to paradigms shifts, for market-driven changes of the business;
- to comply with eco-requirements, ergonomic realizations, prevention of industrial accidents (sustainability).

Another crucial aspect is computer simulation. Computer simulation has to deal with a series of packages, each one corresponding to the particular view of the problem, to be investigated. At the design-development stage, several production facilities are compared in terms of enterprise policies; at the management-fitting stage, several production plans are assessed in terms of delivery requests. The monitoring of value forming, by respect with cost build-up, is performed in virtual reality, to establish comparative enterprise forecasts and to anticipate achievements or drawbacks of (actually) selected production policies. The approach is particularly useful for the traditional manufacturing industry, where 'intelligent factory' set-ups are still observed with caution, since addition of technology-driven options to a labour-intensive environment cannot be accepted without having previously acknowledged the returns on investment. Then simulation, after throughout investigation of achievements and drawbacks, offers affordable commitment, making possible to rank competing manufacturing facilities and plans.

Digital mock-up, virtual and rapid prototyping technologies are becoming the engineering means to range appropriateness and lianness of competing solutions "a priori" to the realization. Rapid prototyping can be useful to produce one of a kind robotic elements.

- Intelligent manufacturing. The main factors related both to material and information flows are:
- Piece wise continuous improvement: to yield the successful effort of adapting products to consumers' wishes (increasing quality and lowering price);
- Cooperative knowledge processing: to enable a reward system granting individual and team creativity, which aims at innovating products and processes.
- Diagnostics and monitoring maintenance: to aim at company-wide quality-control, and at predictive maintenance policies. Knowledge intensive set-ups bring to exploit monitoring data: for process, to enable recovery flexibility and to promote predictive maintenance; for product, to grant intrinsic quality, selectively adapting technical specifications. Diagnostics operates on-line. Actions are taken on the processes; the products profit of results.
- Lean engineering check-up assessment: to remove material and information additions, that do not improve enterprise profitability.

2) Power System

Power supply to robots has strong requirements. In the case of humanoid robots, intended to be mobile, such requirements are strengthened by the need for portable power supply, i.e. batteries.

A key issue for future developments is the availability of high specific power lightweight batteries (fuel cells) to increase robot mobility autonomy.

A solution that can help foster the problem of power supply in mobile robots, especially if used in indoor application, is docking. Docking robots (like the MOVAID personal assistant) are equipped with a special connector by which they can physically docked to re-charging locations in their working environment.

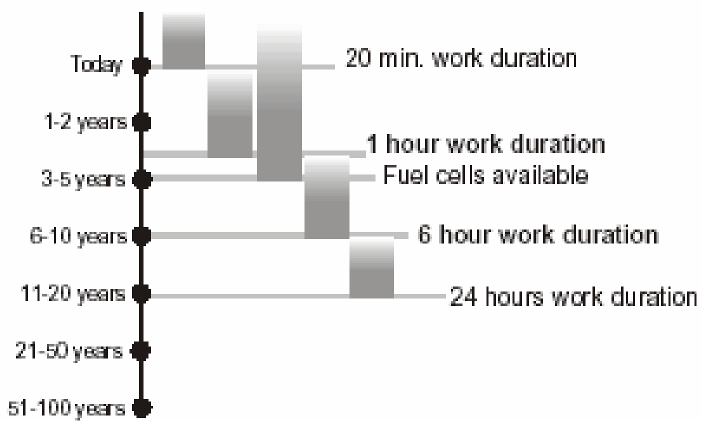


Figure 19 Predictions on the evolution of power systems in the next future [GROWTH ProRpbot Project]

3) Actuation

Actuators for robotics application have been developed by means of a variety of technologies, from the traditional electromagnetic, hydraulic and pneumatic, to the most recent shape memory alloy based, piezoelectric, magnetostrictive and polymeric [23]. Humanoid robotics, again, presents interesting state-of-the-art solutions, replicated from human/animal biology.

In humans, actuation is achieved through muscles, which are very unconventional actuators, from an engineering point of view; they are neither pure force generators, nor pure motion generators but in fact they behave like springs with tuneable elastic parameters.

Skeletal muscle fiber (a single cell) is almost identical across all mammals, as to molecular machinery, diameter, force per unit cross-section. What is variable in different muscles is the number of muscle fibers in parallel. This shows that nature has developed a modular actuator which is simply scaled up to produce more force by incorporating more muscle fibers in the muscles, and to produce wider displacements through longer fibres.

Pseudo-muscular actuators are intended to reproduce some features of biological muscles, such as large linear displacements, durability, built-in tuneable compliance, high power-volume and power/weight ratios, high force density, fast response time, convenient, high density and environmentally safe energy source, efficient energy conversion.

While traditional technology actuators represent good examples of machines converting some kind of energy, such as that given by electromagnetic, pneumatic or hydraulic processes, into a displacement or rotary movement, new technologies have provided tools for reproducing the biological muscle structure and characteristics, based on shape memory alloys, polymers, piezoelectric phenomena and magnetostriction.

Shape memory alloys (SMA) present the property of returning to an undeformed state, after a mechanical deformation, when heated, so that it has been possible to develop SMA elements to be utilized in the construction of robotic limbs. A study on SMA actuators was presented, with special regard to their application in robotics, and developed a prototype tendon-based biomorphic actuating system exploiting SMA properties. The system consists of two SMA active elements (helicoidal springs) in series in a push-pull configuration, which are pre-deformed of the same δ. The push-pull configuration allows to control the motion of the joint with the same modalities for both directions of motion, and the mechanical characteristics of the actuators to be perfectly symmetric. Temperature is the control variable for each active element.

Also the property of contractility in polymers, elicited by electrochemical phenomena and driven by external electrical stimuli, can be fruitfully exploited in the development of actuators. Casalino et al. presented a pseudo-muscular linear polymeric actuator consisting of stimulating carbon electrode fibres and contracting gel fibres bundled into a rubber container filled with a diluted NaCl aqueous solution. The proposed actuator provides strong forces and fast response, and the flexibility and low weight of carbon fibres provide minimum mechanical impediment to contraction and a favourable weight/power ratio to the actuator.

Piezoelectric materials have the property of generating a charge proportional to the mechanical stress applied on their surface and, conversely, of deforming under application of a voltage, while magnetostrictive materials change dimension in the presence of a magnetic field. Some examples exist of their application in robotics, though with poor reference to the anthropomorphic concept of muscle fibers.

Hollerbach et al. have recently proposed an extensive and accurate analysis of different actuator technologies, comparing different performance of artificial actuators to human muscle performance.

According to Hollerbach's analysis, as to macro-motion actuation, among traditional technologies electromagnetics show the lowest stress, while pneumatics and especially hydraulics show the best performance in comparison to muscles. Among newer technologies, polymeric actuators show similar stress as muscles and good maximum strain, while SMA have the best stress but low efficiency. As to micro-motion, piezoelectric and magnetostrictive actuators show very good stress characteristics, similar to hydraulics, but low strains.

However, the above mentioned actuator media have to be included into complete actuation devices, which may realize each material potential to varying degrees. A comparison has been presented by taking into account some selected actuators incorporating the considered technologies, which show different degrees of success. Traditional technology actuators mainly respect the performance outlined for the actuation media, while SMA and polymeric actuators show little worse performance, especially regarding the power/mass ratio. Also for piezoelectric and magnetostrictive actuators power/mass ratio is low, maybe due to the problem of scaling up their very small motion.

An interesting solution adopted for different robotic realisation is cable transmission, which allows more anthropomorphic movements of joints and lighter mechanical structures. The Dexter anthropomorphic arm is produced by SM (Pisa, Italy), based on this principle, as well the Marcus prosthetic hand. More recently, prosthetics and robotic hands have been developed at the ARTS Lab of the Scuola Superiore Sant'Anna based on this principle.

Key issues for future developments are:

- electric linear motors for linear motion generation: full integration into the mechatronic design;
- deep analysis and modelling of servo actuation modules, taking into account friction, backlash and other non-linearities;
- new concept and miniaturised actuator;
- highly compact, small sized and high torque-generation motors.

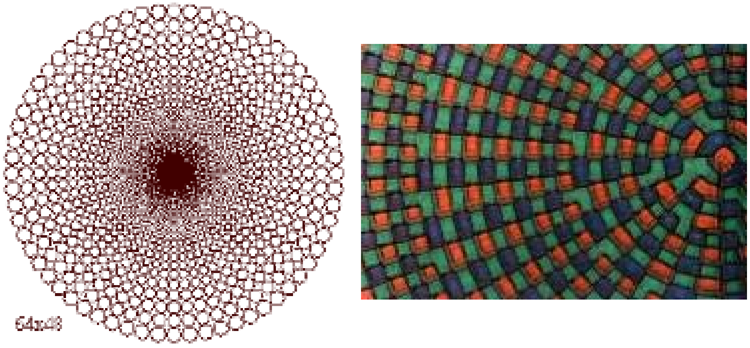
4) Sensor Systems

As for anthropomorphic sensory systems for robotics application, the state of the art can be illustrated by taking into account the five human sensor modalities: vision, touch, hearing (and even smelling and taste, though their implementation in robotics is currently limited).

Anthropomorphic sensors for artificial vision

Artificial visual sensors have achieved a high level of performance, in terms of image resolution, acquisition speed, and miniaturization. The traditional approach to the development of visual sensors has never been anthropomorphic, but rather based on the classical arrangement of the sensing device in rows and columns.

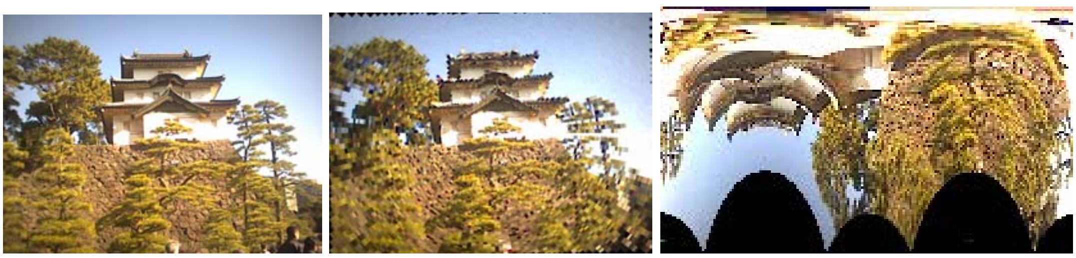
Recently, however, visual sensors inspired by the structure and functionality of the human retina have been proposed. The retina-like sensor proposed by Sandini et al. has a circular physical layout and a space-variant disposition of active sites, with consequent space-variance in resulting image (see figure below). The sensor is composed of photocells located on the radii of concentric circles; the same number of cells is located on each circle, so that they result in a higher density in the central area.



(a) (b)

Figure 20 (a) Geometry of the retina-like sensor and (b) layout of the central part of the color CMOS sensor

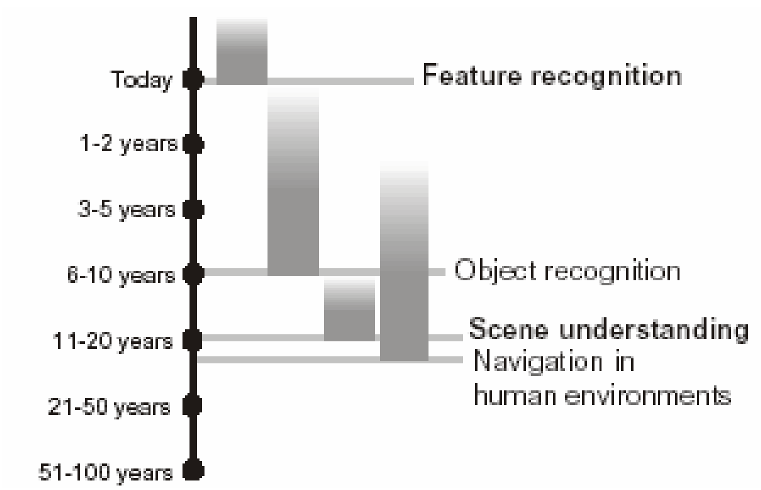
The retina-like arrangement of sensor sites drastically reduces the amount of data of a single image, corresponding to the degradation of peripheral areas of the image. A cortical projection can also be extracted by retina-like images, replicating the mapping that is done in humans from the retina to the visual cortex. Figure below illustrates a simulated retina-like image and its cortical projection, showing how the amount of data, and therefore computational burden, is reduced.



(a) (b) (c)

Figure 21 (a) A traditional image, (b) a retina-like image corresponding to the same view, and (c) its cortical mapping

In the following picture, a prediction is proposed of the evolution of the functionality of vision systems for humanoid robots.



Predictions on the evolution of the functionality of vision systems [from the GROWTH ProRobot Porject]

Anthropomorphic sensors for artificial touch

Human touch is a very complex mixture of different perceptions, fused or integrated at different levels. The sensation that humans perceive when touching an external object is the combination of cutaneous sensing, coming from external stimuli, and kinesthetic sensing, reporting the positions and motions of the limbs and the force exerted by muscles. The dividing line between these two modes is not always distinct, however, as cutaneous information is used in kinesthesia. The simultaneous use of cutaneous and kinesthetic sensing is referred to as 'haptic' perception. The different human cutaneous sensors are miniature and integrated into one support, the human skin, so as to give a global perception of the features of interest of the object in contact. Main sensor modalities perceived by human touch are contact, pressure, force, torque, thermal, dynamics.

The replication of the different human sensor modalities has been achieved by different groups world-wide, through a variety of different technologies, but what still represents a demanding challenge in robotics is the replication of the features of the human skin, i.e. miniaturization and integration of different sensors into one support.

Technologies for biologically-inspired sensors aim essentially to merge sensing and processing capabilities in order to obtain a smart, adapting, intelligent device.

An integrated miniature fingertip has been developed at the ARTS Lab of the Scuola Superiore Sant'Anna for application in dextrous hands. Different sensors have been integrated into one sensory system, including a miniature control electronics, so as to be physically assembled in an anthropomorphic fingertip, with sensors on the external surface and processing electronics inside. The resulting sensory system is an integrated anthropomorphic sensitized fingertip with contact, dynamic and thermal sensory capabilities and data acquisition functionality.

The proposed solution includes three different types of sensors:

- a 'Tactile Array' sensor, to determine contact pattern;
- a 'Dynamic' sensor, to detect micro-vibrations due to stick-slip movements;
- a 'Thermal' sensor, to detect thermal characteristics of object material.

The Tactile Array sensor is based on Force Sensing Resistor technology (supplied by Interlink Electronics Europe). The sensitive site disposition follows fovea-like design concept in an area of spatial high resolution implementing the concept of 'focus of attention'. The sensor has a maximum resolution of about 1 mm at the centre of the sensor. 8 rows and 8 columns define a pattern of 64 active sites.

The Dynamic sensor is based on a bimorph piezo-ceramic element, generating a signal related to applied strain. In order to limit possible damages to the dynamic sensor during grasp operations, the sensor stick can glide into the fingertip structure: the dynamic sensor is capable of sensing tiny tangential components of the applied forces. However, if a large normal force is applied, this might result in a damage of the dynamic sensor. In this case, the sensor element may slip into the fingertip structure thus protecting automatically.

The Thermal sensor is composed of a pair of resistors fixed together and embedded into thermal conductive rubber. One resistor generates thermal power to warm-up the assembly; the second resistor is a thermal sensor, NTC type, that allows to detect the temperature variations originated by heat being transferred from the fingertip sensor to the touched object.

The tactile signal acquisition and processing electronics are incorporated in the fingertip frame. A rubber cover protects the fingertip sensors. Integrated fingertips with rubber cover are shown in Figure 22.

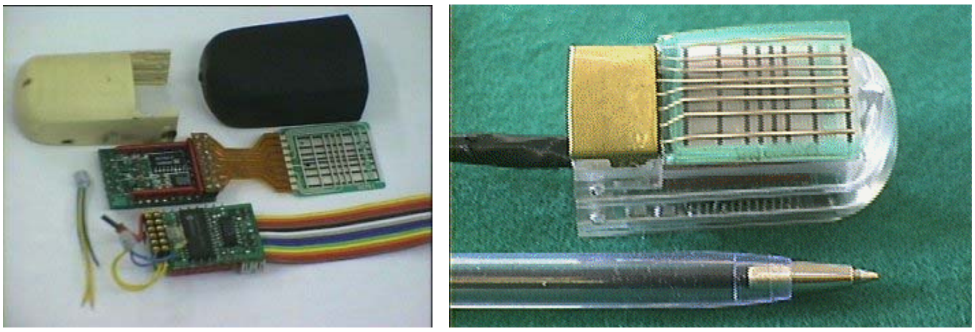


Figure 22 Integrated fingertip

But the state of the art of artificial tactile sensing needs to be described at the lower level of the technologies for fabricating microsensors. Nowadays, the degree of development of such technologies is quite dissimilar. However, microsensors that measure physical parameters are common in the market, as they have reached mature technologies at a high state of the art. The main traditional technologies for microsensor fabrication are: (1) Silicon bulk micromachining and (2) Silicon surface micromachining.

By exploiting bulk micromachining, mechanical devices are fabricated by selectively removing material from a silicon wafer which is used as substrate. Membranes, cavities, masses and bridges are the basic mechanical structures etched (isotropically or anisotropically) by this technology. Most pressure and accelerometers sensors rely on this technology that is usually fully compatible with microelectronic circuit fabrication.

Surface micromachining allows the fabrication of low thickness structures by the deposition and selective etching of thin layers of appropriate materials on a silicon wafer which serves mainly as a support. Selective etched layers are called sacrificial layers and they permit the fabrication of free-standing membranes, beams or mobile parts separated from the substrate by very thin air gaps. Surface micromachining is also IC compatible in some cases, and even with bulk micromachining. Therefore, the main advantage of silicon technologies is the possibility to combine sensing and processing capabilities in a reliable way and often at low cost. In fact, many industrial IC lines can be used for or can be converted into lines for sensors fabrication.

Other techniques derived from precision machining or from hybrid fabrication technologies are now developing for sensor applications, although they are not yet ready for a large scale production. For example LIGA, micro-electro discharge machining and micromolding techniques allow the fabrication of high aspect-ratio microstructures made out of polymers, ceramics, metals etc. The possibility to machine materials different from silicon can represent an important opportunity and can open new scenarios for microsensors. The main open problem is that these “hybrid” and “precision machining derived” techniques are not compatible with IC fabrication, although some improvements have been done for incorporating processing layer in the device (e.g., SLIGA technique).

Sensing effects can be obtained also with conductive polymer composites whose mechanical properties are closer to those of biological tissues. Electrically conducting or semiconducting polymers have attracted a great deal of interest applied as sensing layers in sensors. There are two types of conducting polymers:

- polymers that are intrinsically conducting or can be made so by doping;
- composites that contain an electrically insulating polymer matrix loaded with a conductive filler (conductive rubbers).

In general, by applying force or pressure to a conductive polymer composite, the filler concentration locally changes and the resistivity changes too. By exploiting this effect (and side effects connected), force and pressure sensors can be fabricated, with the advantage to be easily integrated in biomimetic devices. In fact, conductive polymers and smart polymer gels can be used also as actuators for biological applications and substitutions (e.g., artificial muscles).

A further dissertation would be necessary to illustrate the peculiar features of the manufacturing technique called Shape Deposition Manufacturing (SDM), a machining technology developed at the Stanford University. SDM is not a technique to fabricate specifically sensors and precision structures, but it is a “manufacturing philosophy” which allows to integrate sensors and actuators in many complex structures with a strong biomimetic approach.

The basic SDM cycle consists of alternate deposition and shaping (often, machining) of layers of part material and sacrificial support material.

This cycle of material deposition and removal results in three key features:

- building parts in incremental layers allows complete access to the internal geometry of any mechanisms;
- this access allows to embed actuators, sensors and other pre-fabricated functional components inside the structure;
- by varying the materials used in the deposition process, it is possible to spatially vary the material properties of the mechanism itself.

A completely different approach is attempting to engineer biological, cell-based, tissues in vitro to restore, maintain, or improve tissue functions (including sensing function). Instead of fabricating artificial devices for sensing and actuating substitution, “tissue engineering” [18] aims at growing tissues in a physiological environment. First of all, the development of functional tissues requires to fabricate a bioresorbable 3D scaffold where seeding cells in static culture. Then cells proliferate and differentiate in a dynamic environment (e.g., spinner). Growth of mature tissue happens in a physiological environment (bioreactor), until surgical transplantation. All these steps are quite critical but, from an engineering point of view, the fabrication of an effective scaffold is a very interesting problem. Photolithography is often used to pattern biomolecules on glass substrates which mediate cell adhesion. However, other scaffold materials are being investigated for tissue engineering:, including ceramics, polyimides, polyphosphazenes and natural polymers such as collagen.

Force/pressure/tactile sensors

Measuring force essentially means measuring the displacement or strain induced by force in an instrumented deformable structure (e.g., membrane, cantilever).

Due to their simple construction and wide applicability, mechanical sensors play the most important part in MEMS and MST (Micro System Technology). Pressure microsensors were the first ones developed and used by industry. Miniaturized pressure sensors must be inexpensive and have a high resolution, accuracy, linearity and stability. Pressure sensors are largely used also as force sensors: by considering the area where load is applied it is possible to shift between force and pressure measurements. A few examples which represent well the state of the art in the field of microfabricated contact sensors are presented in the following sections.

Piezoresistive pressure sensor

Pressure is most often measured via a thin membrane which deflects when pressure is applied. Either the deflection of the membrane or its change in resonance frequency is measured, both of these values are proportional to the pressure applied. These mechanical changes are transformed into electric signals. Pressure sensors usually employ capacitive or piezoresistive measuring principles.

Figure 23 shows the design of a typical piezoresistive pressure sensor. The piezoresistors are integrated in the membrane, and change their resistance proportionally to the applied pressure. The resistance change indicates how far the membrane is deflected and the deflection is proportional to the pressure.

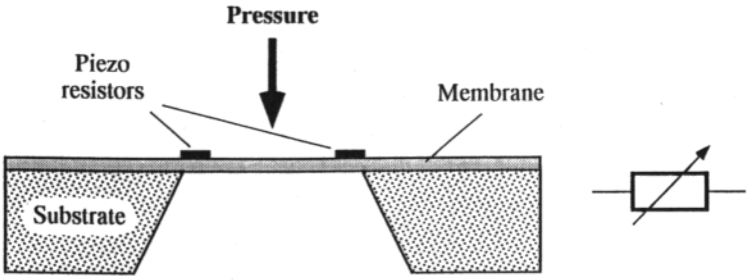
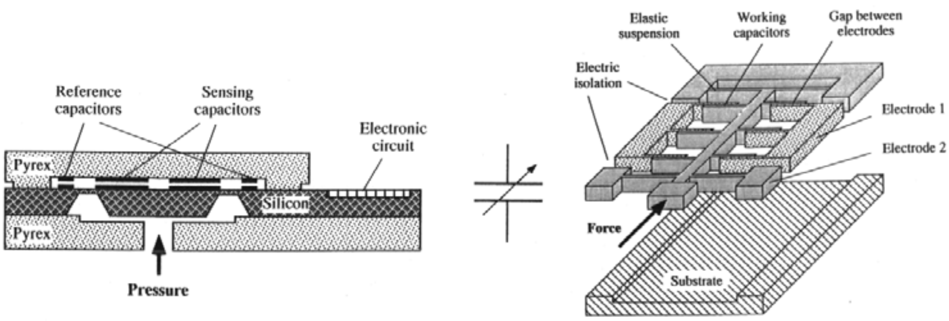


Figure 23 Schematic of a piezoresistive pressure sensor

Capacitive pressure sensors

Capacitive sensors make use of the change of capacitance between two metal plates. The membrane deflects when pressure is applied, which causes the distance between the two electrodes to be changed. The capacitance change is measured and the pressure value can be calculated from the amount of membrane deflection. Figure 24 (a) shows a silicon-based capacitive pressure sensor with integrated CMOS components including sensor, transformer, amplifier and temperature compensator. The sensor chip has a dimension of 8.4 mm x 6.2 mm.

Another example is shown in Figure 24 (b). The electrodes are made of a planar comb structure. Here, the applied force is exerted parallel to the sensor surface. The sensor element mainly consists of two parts: first, a movable elastic structure which transforms a force into a displacement, and second, a transformation unit consisting of the electrodes which transform the displacement into a measurable change of capacitance. By the separate measurement of the capacitance changes on both sides a high linearity and sensitivity is obtained. Compared to piezoresistive sensors, capacitive sensors have no hysteresis, a better long-term stability and a higher sensitivity. However, the advantages of capacitive pressure sensors go along with higher production costs.



(a) (b)

Figure 24 Silicon-based capacitive pressure sensors

Resonance sensor for measuring pressure

In both of the sensing principles introduced above, the sensor signal is generated by a deflecting membrane or a displaced mass. It is also possible to get a signal from a change of resonance frequency of the membrane caused by the pressure. The main advantage of this measurement principles is that the transmission of the measured value in form of a frequency is practically noiseless and the signals can be digitally processed. An example of pressure resonance sensor is shown in Figure 25.

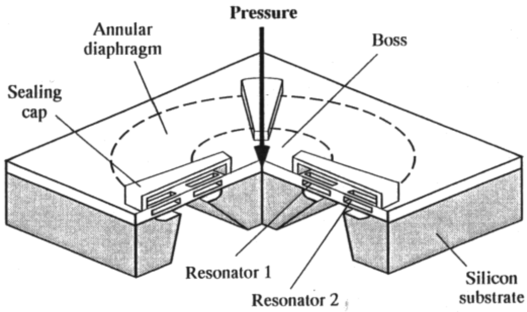


Figure 25 A pressure resonance sensor

The device consists of a silicon substrate, a diaphragm and three transducers equally spaced on the annular diaphragm. Each transducer consists of two resonators which oppose each other. If a pressure is applied to the diaphragm, the deformation causes the resonant frequencies of the resonators 1 and 2 to increase or decrease respectively. The frequency difference between the two resonators serves as the output signal of the sensor. The sensor has the following dimensions and performances: a diaphragm diameter of 1.2 mm and a thickness of 3 μm; a resonator length of 100 μm and a thickness of 0.5 μm; a maximum diaphragm lift of 0.7 μm; a pressure range of up to 1000 Pa; an accuracy of a.a1 Pa and a slight non-linearity of 0.1%.

Mach-Zehnder interferometer

Many physical quantities can be measured by optical sensors, making use of the change of light which is sent through fiber optical cables. A so-called Mach-Zehnder interferometer is proposed as a pressure sensor (see Figure 26).

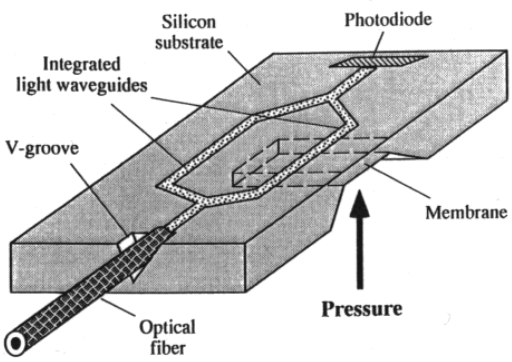


Figure 26 Schematic of the Mach-Zender interferometer

Laser light is brought into the device by a fiber optical cable. The light is split and channeled via two waveguides to a photodiode. One of the light branches crosses a microstructured membrane which can be exposed and serves as a reference signal. When the sensor membrane is actuated by pressure, the waveguide deforms and changes the properties of the light beam. The modulated light beam has a different propagation speed than the reference light beam, resulting in a phase shift which is registrated by the integrated photodiodes. A sensor prototype with four membranes produced an output signal of 14 μV/mbar and the entire chip size was 0.3 mm x 5 mm and the size of the individual membranes was 200 μm x 200 μm.

Array of tactile sensors

The key aspects of the neurophysiology of touch consist in the representation and coding of spatial and temporal patterns of mechanical stimuli, as perceived by various mechanoreceptor population.

One example of sensor which tries to imitate the human skin is shown in Figure 27. The sensor consists of three main layers. The lower or "dermal" layer is a relatively thick layer (110 μm) of PVF_2[1] (or PVDF). This corresponds to the dermis of the skin, and it measures pressure applied at the surface of the sensor. This layer is bonded to a printed circuit board patterned with an array of electrodes, which allows for the detection of location as well as magnitude of sensation. The second layer is made of conductive rubber, which is used to enhance the recording of applied force by adding an additional output as a result of applied force. The top or "epidermal" layer is a thin film of PVDF (about 60 μm), and is used to measure small variation in pressure. This layer can be used to sense slippage, texture, or lighter tactile contacts. The final element of this tactile sensor is a layer of resistive paint between the rubber and the epidermal layer. This layer can be electrically heated so that when the sensor contacts an object, heat is drained off and this can be measured by the pyroelectric effect of the upper PVDF layer.

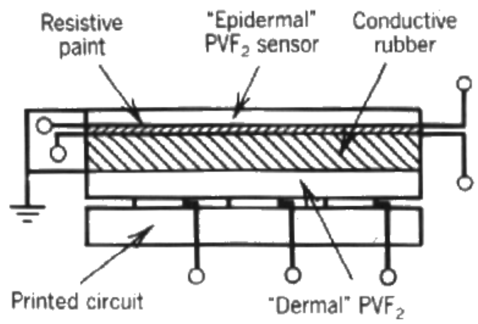


Figure 27 Sensor incorporating PVDF

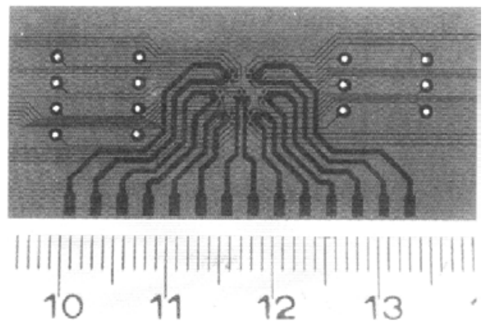


Figure 28 Layout of the kapton film used

This sensor alone, however, is a poor replication of the human tactile system, as it can sample data only on one point at time, thus making impossible the accurate sensing and reconstruction of local indentation profiles (fine-forms) that is one of the key aspects in which the sense of touch is superior to vision. In order to overcome this problem, thus making a better replication of the human tactile sense, in recent years a variety of technological solutions have been proposed to obtain high resolution bidimensional maps of contact displacements of forces.

An example of a sensor array which attempts to emulate the piezoelectric texture of the biological skin uses an array of synthetic polymer (PVDF) elements. In this array the 42 sensing elements are assembled in seven small hexagonal zones (see Figure 27 and 28), each containing 6 polymeric crystals. These crystals have been cut along appropriate axis,

[1] PVF_2 = POLYVINYLIDENE FLUORIDE.

in such a way that each crystal presents a piezoelectric response to one particular direction of the stress field.

Another example of tactile sensors is the “KIST Tactile Sensor” developed in the authors’ laboratory (see Section on Prosthetic applications).

A further example is a capacitive tactile sensor. In this case, polymide is used, which is highly flexible and has excellent electrical, mechanical and chemical properties. The sensor consists of a polymide base to which a 4 mm^2 inner electrode is deposited. Over this there is an outer electrode separated from the inner electrode by a 25 μm thick air gap. When a force is applied, the capacitance changes allowing the force and location of the force to be determined. The entire signal processing circuit could also be integrated on the substrate.

Position and speed microsensors

Position and speed microsensors are essential for many applications, especially for use in automobiles, robots and medical instruments. Position and speed control is also a major concern in microrobotics in order to determine the exact position of the end-effector at any point of time.

Magnetic sensor to measure angular displacement

In robotics it is necessary to exactly control the movements of the robot arms and legs or other components having rotating joints. A classical sensor consists of a rotor which has a row of teeth on its bottom. The rotor faces a stator which contains several Hall sensors and electronic circuits. A permanent magnet is located under the Hall sensors, producing a magnetic field. When the rotor moves, the teeth passing by the Hall sensor change the magnetic field. This change is picked up by the Hall sensors and they produce voltage signals. The developed prototype of the sensor matrix was produced on a GaAs substrate having a 1 μm thick silicon dioxide layer. The prototype is about 4 mm long and can measure the rotational angle with an accuracy of 0.028 degrees at temperatures between –10°C and +80°C.

Inductive position sensors

Inductive position sensors combine the advantages of silicon integration and inductive sensing principle. Using coil-on-chip technology, the bulky coil windings of the related resolvers and LVDT's are reduced to the size of a silicon chip. In the same package, an application specific integrated circuit (ASIC) provides signal conditioning and a robust interface, suitable for motion control and industrial control applications. An example of inductive position sensor is illustrated in Figure 29.

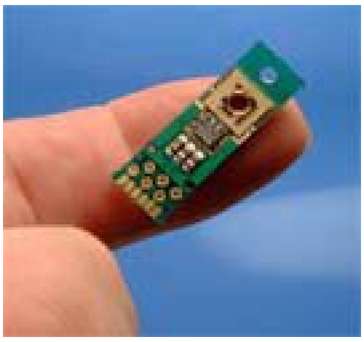


Figure 29 Inductive position sensor

Vibratory Microgyroscope

The gyroscopes are used to detect orientation in space. The standard gyroscope technology presents the following drawbacks: (1) Too Expensive; (2) Too bulky (volume, mass); (3) Too high power consumption; (4) Limited Lifetime. MEMS technologies could provide for a low cost solution with the capability to merge sensing and processing functions in a synergetic way.

An innovative gyroscope was developed at the University of California at Los Angeles – UCLA -(see Figure 30). This is a silicon micromachined vibratory microgyroscope and depends on the Coriolis force to induce energy transfer between oscillating modes to detect rotation. The advantages of this approach are the following: (1) Inexpensiveness; (2) Compactness, (3) Low power consumption, (4) Non-wear/Long lifetime, (5) Negligible turn-on time, (6) Large dynamic range.

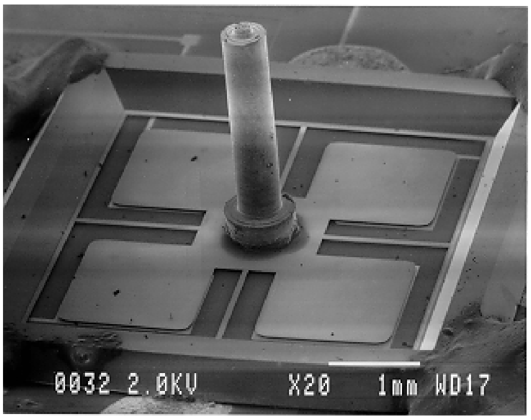


Figure 30 The gyroscope developed at UCLA [30]

Implantable joint angle transducer (IJAT)

Joint angle transducers for biological applications are particular important for implantation and prosthetics. A permanent magnet can be implanted in one bone of an articulating joint and an array of Hall-effect sensors can be implanted in the opposing bone. The sensor array consists of three Hall-effect sensors arranged in an equilateral triangle (see). As the joint is moved, the relative position and orientation between the sensors and the magnet changes, producing sensor voltage changes related to the joint movement. The IJAT allows measurement of wrist position in two degrees of freedom, flexion/extension and radial/ulnar deviation. The IJAT is sufficiently small in size to allow implantation in the wrist joint, does not restrict the joint movement, and transduces up to 135° of wrist motion.

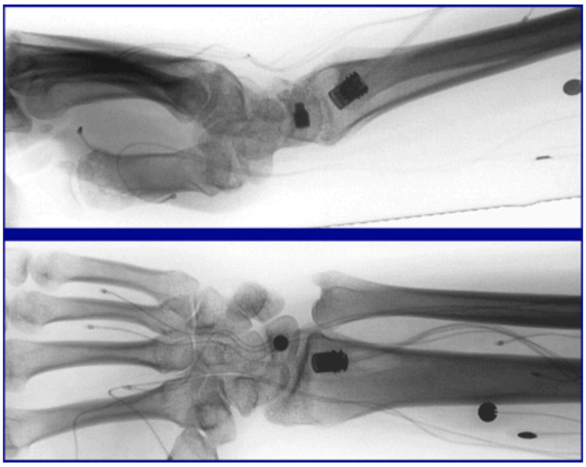


Figure 31 Xerographic picture of the IJAT

Anthropomorphic sensors for artificial smell

Smell and taste are very similar in biological systems, as both are characterized by an overall sensation upon the reception of a complex mixture of odour and taste producing chemicals and are both multidimensional qualities accounting for shape, size and charge of the received molecules. Of the two senses, smell is maybe the best studied and the one receiving most attention in research. Many examples of artificial odour sensors have been proposed [16]. Here we discuss some representative ones.

Pelosi and Persaud have investigated the gas sensing properties of a number of conducting polymers, finding out that the concentration-response profiles are almost linear over a wide concentration range, thus simplifying computational methods for information processing. This characteristic, together with fast response and high stability, make such polymers suitable for designing an artificial nose. A prototype multi-gas sensor based on conducting polymers was developed, consisting of an array of up to 20 different types of conducting polymer elements, each one designed to enhance differences in response to particular classes of molecules. Each sensor element undergoes a change in resistance on exposure to a vapour, and the response pattern of the array as a whole is characteristic of a particular odorant. The pattern of resistance changes is compared and matched with odorant patterns stored in a memory to reveal the nature of gas.

Hatfield et al. presented an integrated approach to an artificial nose based on conducting polymers as well. Their approach is based on the identification of specific chemicals by means of arrays of sensors of different specificities. The compound of interest is identified when the entire response pattern of such an array is identical to a stored pattern, thus simulating the behaviour of olfactory sensor arrays in biological systems. An integrated artificial nose was developed by exploiting Application Specific Integrated Circuit (ASIC) techniques in conjunction with arrays of conducting polymers.

Anthropomorphic sensors for artificial taste

Important results in the field of artificial taste have been achieved by Toko, who, starting from the study of the five basic tasting qualities in humans, proposed an approach based on the utilisation of similar materials, i.e. lipid membranes, as transducers of taste information. Lipid membranes have been found to discriminate between basic taste qualities and to detect interactions between taste substances.

A taste sensor with multi-channel electrodes has been developed by using lipid membranes as transducers of taste substances, achieving a good imitation of human sense of taste. The multi-channel sensor is composed of several kinds of lipid/polymer membranes for transforming information of substances producing taste into electric signals which are input to a computer. The sensor output shows good capability of discrimination among molecules which have different taste qualities, and also good performance in taste integration, i.e. the suppression of effects occurring for example between sweet and bitter molecules. The proposed sensor has been fully characterised and experimental results have been presented on the taste of common foodstuff such as beer, sake, coffee, mineral water and vegetables. The sensor has been also used for the reconstruction of a taste map by a neural network model with mean field output which reflects the collective behaviour of groups of output elements. It was shown that the neural network model could learn taste mapping, thus introducing the further anthropomorphic feature of learning capability.

5) *Interfaces*

The discussion over the state of the art of interface in robotics is quit difficult because these are developed as a part of a the special application. A rough classification as follows can be made:

- Basic research
- Industrial application

In research, early interaction interfaces for robot systems were developed on topics like manipulation as teaching robots or mobile robotics as command input. The interaction level raised for textual input/output to multi modal communication through speech, gesture etc. Special input / output devices were developed on areas like tele – robotics, humanoid robotic etc. Most HCI Projects all over the world are developing methods of interaction, but even if some of them are considering robots as application target for their research, they use a general approach that leads to a lack of reliability. Another research area that deals with human communication interfaces is based on Virtual Reality technologies. In the last 6 years many national projects have stared on this topic mainly concerning on basic research. Encouraging results were achieved and based on these new research projects were set up in the past one or two years dealing with the integration of VR in industrial applications.

In most industrial applications, the robots have to be manually programmed by teach-pendant, or by trained experts using special programming languages. Since all robot positions should be given exactly, e.g. as the so-called "tag points", such an interaction modality is on the explicit level. In recent research robots, such an interface is extended to the implicit level by adding simple human-perception technologies and automatic planning modules.

The state of the art is discussed by classifying different input and display modalities as follows:

Input Modalities:

Teach panel: First intelligent interfaces in robotics were developed by the robotic industry with the scope of reduce the costs for programming these systems. Starting point were primitive keyboards witch enabled the user to incremental move the robot on keystroke. More comfortable devices were the 3-D or "Space" mouse which allowed the user to position the tool centre point (TCP) of the robot easily over 6 degree of freedom (DOF). Last developments for robot input devices leads to the integration of several input canals like keyboard, touch screen and space mouse in to one panel.

Industrial Teach Panel

Force Torque Sensors: Further classical teach devices common to industrial applications are several force-torque sensors within the so- called zero-force-control. (Using force/torque sensors on manipulator wrist and/or using the physical model, the robot can be set to free-floating mode and be taught by human manually guiding.)

3D Interaction via Space Mouse

This method allows the worker to place the manipulator itself to the key points for performing the trajectory. Newer developments on this field are dealing with new exhausting force sensors, which are covering the robot like an artificial skin. These devices enable the development of more comfortable programming methods like Interactive Programming or Programming by Demonstration (PbD). The use artificial skin increases the safety of robots and makes them useable for human environments.

Laser pointer and 3D pointing tools: In industrial application pointing tools like laser pointer are often use for marking significant points for proceeding with the robot. One typical application is welting robots used in the car industry. Further on pointing devices are used for marking pieces for performing assembly tasks. Precise and flexible robot programs can easily be generated, if these devices are used in addition with other input devices like speech or text.

Voice input: Voice recognition as digital dictating is an available technology with acceptable success-rate if the speaker is close to microphones, the environment is not noisy and the speaker does not use extremely spontaneous and strong emotional expressions. Such a voice recognition can be even speaker-independent after adding adaptive methods. After the voice recognition, understanding of natural language instructions relies on more complex linguistic analysis and the availability of robot skills at different levels. In most projects investigating simulated robot agents or real robots, natural language interfaces have been used as the ``front-end''. If constrained natural language is used to realize a limited number of robot operations, special steps can be taken, e.g. by pre-defining the grammar or by only recognising nouns in an instruction and listing the possible actions based on an a-priori knowledge database.

Voice input via Headset

Visual Perception: Visual detection of human body and gestures: In close and limited range of multiple cameras, more user information can be detected such as WHO is speaking (face ID), WHERE such as 3D head pose / gaze (accuracy of 3 degrees), pointing hand, and sound localisation, and WHAT (operation sequences). Two underlying methods are skin colour segmentation and template matching. The detection is not robust under extreme illuminations or in a background with similar colours or patterns. For detecting complex motions of face and body in real environments, the marker-based animation is the prevailing technology. Such systems are applied in virtual and humanoid robots to capture and imitate human movements.

Tactile and motion capture: Sensors such as data glove or suits are used for capturing human motions and poses. These informations are used either direct for control of robots or indirect by integrating extracted key features into a cognitive process. As example programming by demonstration uses the estimated hand pose in combination with visual or/and magnetic trackers as an input device for teaching robots. Dynamic grasping forces during a teaching phase can be detected by employing tactile sensors like Force Sensing Resistor (FSR). These are mounted on a data glove and increase the

Motion catpure via Data glove, -suite

amount of information from human demonstration. An other very important research area which deals with this kind of input is the developing of humanoid robots, were humanlike movement is one of the basic topics.

Display of Robot States:

Video, audio and force: Traditionally feedback devices like video displays and primitive audio messages are commonly used in industrial application for programming robots. These are included in modern teach panels. Modern panels include high resolution (touch) displays for representing online simulation of robot movements. Furthermore in several laboratories head mounted displays are used for three-dimensional environment representation. Based on broadband communication channel, the video, audio and static force information can be transmitted from a remote site or via Internet to the user. However, the time-delay is still a problem for dynamic tele-operations.

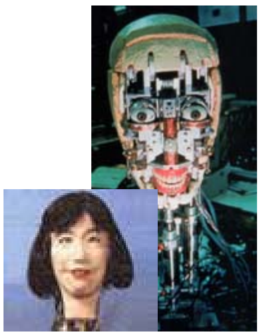
Graphical output via 3D displays

Haptic devices for physically reflecting 3D forces, and expensive versions which additionally reflect the 3D torques are commercially available, but they are limited to gross position, force and torque information. No dynamic tactile information representing texture, indentation, thermal, etc., can be captured and displayed.

Forcefeedback devices: Phantom Force Grasp

Speech output: Beside industrial applications speech output represents the most intuitive or natural way for man-machine interaction. Text-to-Speech (TTS) technology can generate natural-sounding synthesised voices even if they are still emotionless. Speaking is often realised by using prepared sentences or simple production rules. Few sophisticated language production modules can be found in human-robot communications. Especially in office, service areas speech generators are widely-used. In research, the human robots developers are using and integrate speech for long years in their systems. Evidently speech generators are vitally important for handicapped people as a native communication cannel.

Emotions: Face robots are developed in several laboratories, which employ multiple DOFs to control eyebrows, upper and lower lip, etc. Facial skins are also used to make facial expressions more realistic. Static facial expressions of emotions like surprise, fear, disgust, anger, happiness and sadness can be realised and recognised as more or less real. Some toy robots use the body motions to express simple emotion types. No dynamic facial expressions similar to humans can be found.



Expression of emotions

HMI

Many of the current intelligent robot systems are dealing with multi modal communication for intuitive interaction. In this context methods for fusion of several input/output canales like speech, gestures, tactile information are demanded. Beside perceptive tasks, there is obviously the need of integration of cognitional abilities, in order to enable natural complex man-machine interaction. The modelling of communication and interaction tasks in terms of actual context, domain etc. is crucial for this propose although most actual systems have not considered them so far.

Though most interfaces for robotic systems are based on personal computers, in the applications where robots are supposed to interact with not-specialised users, more natural or more usable interfaces have been developed. This is for example especially true in the field of rehabilitation robotics, where special needs are to be taken into account. In this framework, a variety of solutions exist, able to fit the wide range of residual abilities of the potential users.

In order to enable a disable people to make use of the PC or for environment control, lots of devices have been developed so far. The PC is always considered the principle aid for enabling disable or elderly people to make use of a wider class of services, such as phone/fax, TV, VCR, Internet, office automation tools, etc.,

In a rough categorisation, the interfaces for disabled people can be divided into Special Keyboards, Special Mouses, Voice Control Systems, Scanning Systems and Alternative Input Devices.

Special Keyboards are keyboard purposely designed for disabled users, such as Expanded Keyboards, Reduced Keyboards and Reconfigurable Keyboarsd. Expanded Keyboards, to be used by people with difficult in performing fine movements, differ from normal keyboard since they have larger keys. The Reduced Keyboard, to be used by people with fine movement ability and unable to manage large working area, have small keys on a small surface. Re-configurable Keyboards allow redefining keys position and dimension according to the user preferences. Finally, special masks allow to protect standard keyboards from involuntary movements. In Figure 32 are shown some examples of the three categories of keyboard.

Figure 32 Examples of Expanded Keyboard, the WinKing Keyboard, Reduced Keyboard, the WinMini Keyboard and Reconfigurable Keyboard, the Intellikeys keyboard.

As special keyboards, Special mouses replace standard mouses and they can assume different shapes. Figure 33 shows two examples of Special Mouses. The third of them, MouseMover, allows the user to control the mouse by moving the head. A small reflective round surface is placed on the head of a user (on his forehead or on the eyeglasses). A special infrared device, placed in front of a PC, is able to detect the changes in position of this surface, caused by the head movement, generating the correspondent movement of the mouse on the screen.

Figure 33 Examples of Special Mouse: EasyBall, JoyMouse and MouseMover..

For the users that lack the ability to use a keyboard, Voice-Control System and Scanning Systems exist. Voice control systems allow the user to control mouse, keyboard and software applications through voice commands and they consist of a microphone, a voice recognition software and of a voice synthesiser.

Scanning system usually consist of a small keyboard with an array of keys that can be scanned so that the user can select the desired key by means of a single-function alternative input devices, such as a switch: in order to speed up the action, usually the user first selects the raw containing the desired key, for example by pushing on a switch, and then he/she selects the column in the same way.

The Gewa Remote Controller or the James II, depicted in Figure 34, are two scanning system. They consist of a remote controller with a specific number of keys. Each key is associated with a special command such as to switch on/off a light or a plug, to answer to a voice phone, or to open/close a motorised window/door. The user can push directly the key or he/she can make use of an alternative input device to select the appropriate key using the scanning facility.

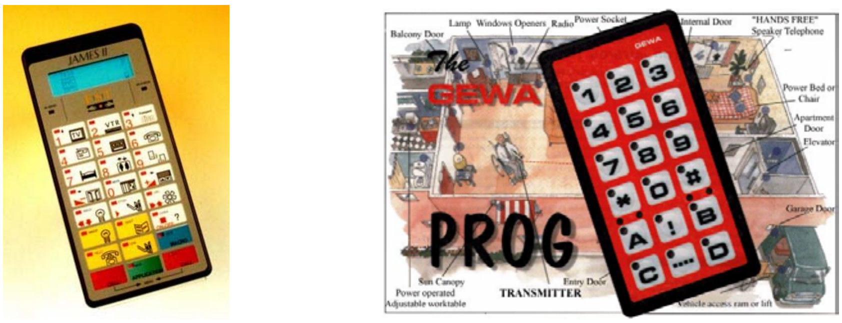


Figure 34 The infrared Remote Controllers James II and Gewa.

The alternative input devices used in the scanning systems instead of the keyboard usually are devices that have the same function of a single key and they differ form the activation procedure. Pushing, shaking, touching or breathing can activate them. Figure 35 shows various examples of alternative input devices.

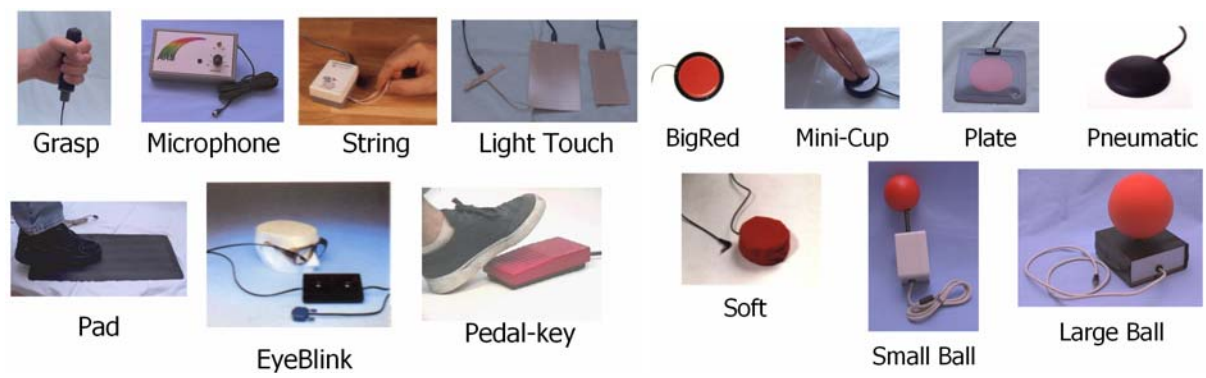


Figure 35 The Alternative Input Devices.

The Virtual Scanning Keyboard is based on the same principle of the scanning systems: a Virtual Keyboard consist of a software application running on a PC and emulating a standard keyboard. In the same way, the user selects first the proper row and then the proper column by means of an alternative device connected to the PC. In Figure 36, an example of a virtual keyboard is shown.

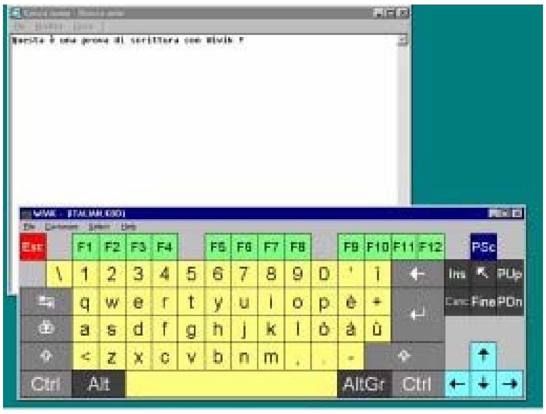


Figure 36 The layout of Wivik2,the user select the raw and the column with a special input devices and the selected character appear on the Notebook application.

The M3S project deserves to be mentioned especially, which tried to provide a standard for fitting any input interface with technical aids for disabled people []. This was aimed to prevent disabled users to change interface for any new technical aid and, instead, to allow them to use their best-fitted interface for any device.

As human-machine interaction grows there is an increasing need for friendly interfaces. Human-machine oral communication as a means of natural language interaction is becoming quite common. Interpretation of human gestures can, in some applications, complement such communication. A significant amount of work has already been done in this relatively new research field. The first systems operated over synthetic images based on segments and joints to model a human body. Many systems operate from marks over the human body that can be either visual, magnetic, etc. The use of special clothes with identifiable colours is another alternative solution, as well as the operation over a specific plateau.

The work at the Automatic Control and Computer Engineering Department at UPC, operates from the analysis of images obtained from the setting, by tracking an operator who is not specially dressed for the task or equipped with specific identifying elements. The tracking starts by automatically detecting the operator's position in the setting thus getting the three dimensional position of his arms. It is also possible to restrict the active search area to a predefined area of the setting to reduce the error probability by avoiding the detection of unwanted moving objects and to decrease the search time. The system then interprets the operator's postures, movements and gestures that are significant enough to be interpreted as control commands. Figure 37 shows the simplified model used to detect and track the human body elements: head, arms, hands, and body.

The later gestures interpretation process, from a sequence of human body postures, provides the data for the coding of different robot orders.

Operations and experiments performed with existing systems have clearly shown that the state of the art control technology has to be extended in two different directions:

since many tasks cannot be pre-planned or are unknown in its structure, the user should be enabled to perform the task manually under remote control. The key technology for manual control is telepresence. It has to provide a sufficient degree of immersion, e.g. that the operator receives stereo images and kinaesthetic feedback for dexterous manipulation. Recent developments have shown that haptic feedback is possible when advanced direct communication links are used;

on the other hand many tasks are repetitive and/or are time consuming when performed manually. The methodology of task directed programming has been developed to program and control robots when performing tasks under such conditions. This methodology has to be extended such that dexterous complex tasks, e.g. the grasp of known or unknown objects is supported using autonomous modes that e.g. automatically generate safe grasps using the robots sensor system.

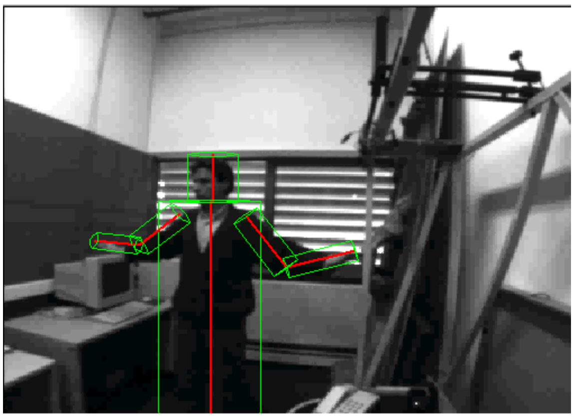


Figure 37 Detection and tracking of the human movements for robot teleoperation from human gestures.

The development of these technologies is even more essential since they are key issues in other robotic application domains, as well. **Telepresence** and **autonomy** are e.g. key technologies in minimal invasive surgery robotics and the robotic assembly systems of MEMS. In the first application the surgeon performs dexterous operations like by-pass heart surgery with the robot system, not necessarily remote, but with the same degree of immersion as required in space robotics. Again the autonomous execution of parts of the task becomes essential to reduce operation time and to increase the overall feasibility of the system.

Core interface technologies are listed as follows:

- Seamless communicator. Interfaces will be closely coupled with planning and monitoring. If the nature of tasks cannot be fully predicted, they are automatically decomposed into more elementary actions. Ideal action needs to be inferred based on motion and action planning while considering the context and the human preference.
- Active intention detection based on multiple cues. Speech, gesture, motion sequences (human demonstrations) will be integrated and combined with contexts, knowledges and personal preference. The cross-modal interplay will be investigated. Since the system resources are limited, sensory input needs to be selected by using factor analysis, signal synthesis and tracking focus of interests.
- General human perception. Human motions are captured without using artificial markers. Wide-range, active camera configurations are applied in human recognition and precise gaze perception, also by low-quality input and occlusions. The robustness of the voice input in real environments should be significantly improved. This task is even more challenging if non close speaking microphones are used.

- Grounded learning of multisensor events, sequences and human activities. The long-term-memory is learned from the short-term-memory so that symbols, sequences, names and attributes are anchored in the real sensor/actuator world. To enable the arbitrary transition between digital measurements and concepts, symbolic sparse coding, granular computing, fuzzy sets and rough sets will be investigated and integrated. The sensor capability can be extended by using linguistic modelling of human perception human perception and sensor fusion so that information which is difficult to measure, incomplete or noisy can be perceived. Learning on the higher level should be conducted to select action strategies and to generate intelligent dialogs. This will need the tight integration of more components and more knowledge. The combination of grounded learning and communication will make the human-robot interaction work like interaction with a child which will be really entertaining.

6) Control & behavior

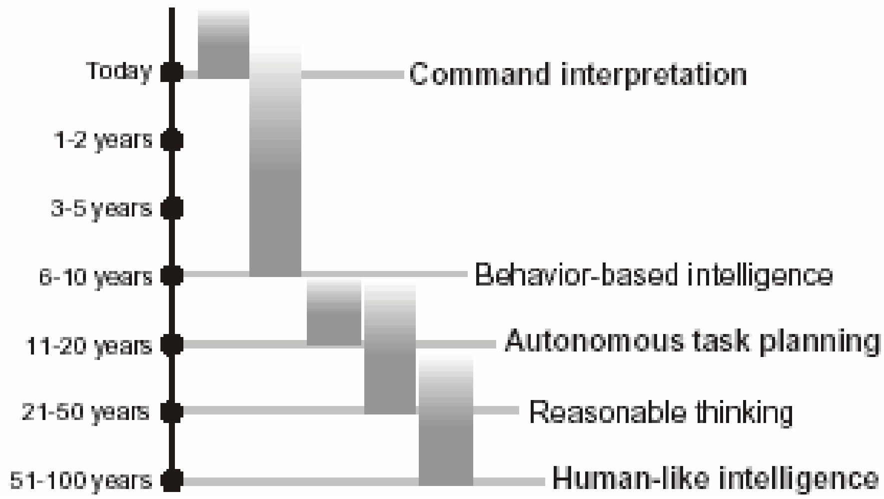
In the new scenarios of application of robotics, beyond the traditional manufacturing context, new control schemes have been conceived to comply with the new requirements, both technical and related to acceptability. For example, adaptable compliance has been proposed for robots interacting with humans in personal assistance tasks [].

Techniques for the grasp control and optimisation, detection and exploitation of slippage conditions, interaction with known and unknown environments, consideration of only the linear case or the general 6-dimensional linear/rotational case and so on have been proposed in the literature by a number of researchers active in this field in the last decades. Just to mention a few names: Salisbury, Howe, Cutkosky, Bicchi, Dario, Hirzinger, Melchiorri, Dai, Kerr, Erdmann, and many others.

Non-linear, model based, hybrid and impedence control systems are used to improve the robot performances.

Open source and open architecture, multi level, distributed control systems to allow for easy interconnection and communication.

In addition to this, the cognitive capabilities of humanoids robots need crucially to evolve. A possible roadmap is shown in the following picture (from the GROWTH ProRobot Project):



7) *Computing*

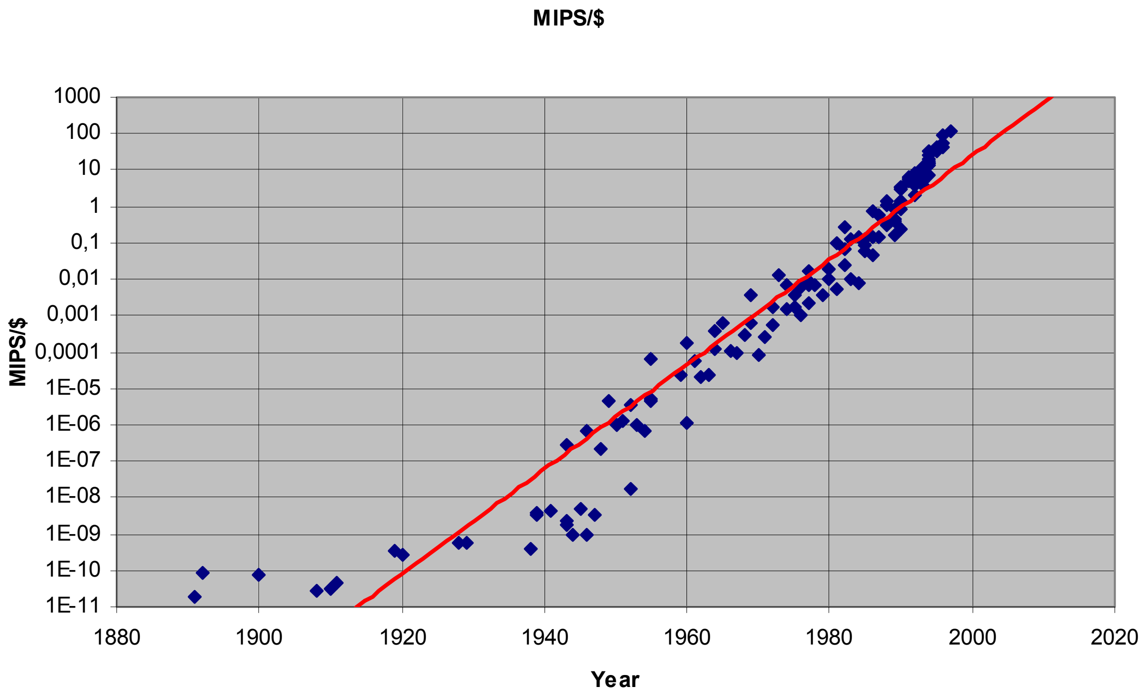


Figure 38 CPU development, MEMORY, networking costs

8) *Communications*

The communication channels between system components are the glue that holds any large system together. In the case of autonomous robot systems, we do not only need to define protocols between software components in a network. There are also requirements with regard to location and locomotion, and communication between robot systems and the human operator. Since an autonomous robot system is by definition a ubiquitous-computing system, there is not only the question of communication protocols but also of the medium on which data is transmitted, and also the wish for integration with domotics/intelligent-house systems.

Facets of communication

Teleoperation

The most direct way of robot control, Teleoperation, is by implication the most robust way, and therefore to be preferred for some extremely critical tasks. It is also, however, the task that requires the most direct and latency-free communication system, and therefore only to be performed when a very reliable and real-time capable data link is given, which is often not the case in non-professional (and especially wireless) environments. Luckily, in household tasks and many other common manipulations there is often not the need for the preciseness of control that only teleoperation grants.

Robot-environment communication

Almost all robot tasks require a more or less precise knowledge of the environment. This requirement is often met by pre-constructed models and maps, whose accuracy cannot be guaranteed in a real-world scenario. On the other hand, on-line refinement and update of environment models by robot sensors alone is often impossible due to sensor inaccuracies, limited viewing angles etc. Therefore it is desirable to be able to use sensing capabilities of the environment, such as surveillance cameras etc., to integrate their measurements in the robot's model.

Environmental sensing capabilities can be managed either by a global facility manager system, in which case the task of querying such sensors is reduced to general inter-systems communication processes, only enhanced by location-based service lookup. They can also be self-contained in local cells, down to one camera alone, in which case the communication process itself becomes location-based; this needs to be reflected in the chosen wireless protocol.

Distributed computer / robot systems

Multi-agent operation is a vast field of research, which covers loosely-coupled cooperation tasks such as communicating the traffic density in crowded walkways with other robots, as well as tightly-coupled tasks such as handing a package from one mobile robot's manipulator over to another one's. Communication systems take account of this diversity by presenting different paradigms (task and dialog queues, notification centers, direct messages, out-of-band urgency data) to the robot developer.

Diagnosis, maintenance, remote servicing

Next to the "normal" mode of system operation, a second set of modes must be presented that will usually stay hidden from the normal user: those used to diagnose and maintain the system. This is not only extremely helpful during system design and development, but it is a requirement for day-to-day system use to enable human operators to quickly scan the system for incorrectly-operating modules, track down and correct errors and in the worst case shut down the system if secure operation cannot be guaranteed.

Technologies

Wireless LAN

Wireless LAN, standardized by IEEE as standard no. 802.11 and sub-standards, is a continuation of standard ethernet communication in the 2.4GHz radio band. It has been primarily designed to replace ethernet, for the convenience of human users with laptops or similar cable-less systems. Wireless LAN is purely an ISO Layer 1 (Transmission layer) specification.

Being rooted in Ethernet, it bears solutions for only very few of the higher-level problems that are inherent in robot communication: All transmissions are best-effort, therefore there can be no real-time or quality-of-service guarantees, there is no mechanism for privacy since all packets are seen by all hosts on the network, etc. By features alone, Wireless LAN would make a very poor choice for robot applications.

This shortcoming is more than made up for, however, by the extremely high level of distribution of Wireless LAN. It is ubiquitous, cheap, has fairly good range and excellent driver support by all operating systems, and since it is basically Ethernet, it can be hidden very well underneath TCP/IP, which means that all standard network-aware applications, including network file systems such as NFS or SMB, will work over Wireless LAN. Additionally, applications (robots!) can first be developed cable-bound to a high-performance network; no change has to be made to the software when switching from cable to wireless networking.

Due to its long-range nature, Wireless LAN has no direct location-discovery possibilities. It is possible to determine which access points are within range, as well as the approximate signal level to each, but this is a much too inaccurate system to be used for triangulation.

All in all, Wireless LAN is a mediocre to good choice for facility-level networking and therefore ideal for multi-robot or robot-environment interaction on long ranges.

Bluetooth

This relatively new specification has been developed for close-range networking and extremely low power consumption. By its developers, Bluetooth is targeted mainly at mobile-phone and peripheral-device networking uses.

Bluetooth has a few very interesting features for mobile-robot applications: It has transmission-speed degradation, so it can transmit data very fast at short ranges (up to a few meters), but also has a low-rate high-range mode. It can be used to discover other Bluetooth devices within range, and since this range is very short (at acceptable transmission ranges), it can be used to determine location-based services very easily.

Bluetooth has not yet reached a very high level of pervasion outside of the mobile-phone market, but this will surely come. It is also not quite as easily integrated as Wireless LAN, but since its uses are much more narrowed, it will play an important role in the future.

CORBA

CORBA is an open standard (defined by the Object Management Group, OMG) for software-component communication. It is language-independent (which is very interesting for robot applications, which tend to be extremly low-level at the actuator control side of things and extremely high-level at the AI side) and uses the object-oriented paradigm to define software components. A software component implements an interface to be used by its peers, which must be defined in a special interface definition language. This allows for very easy and fast construction of very large systems, and the clear interface definition makes things type-safe and secure.

Unfortunately, the CORBA specification contains no statements regarding real-time communications or elegant handling of no-connection incidents (which happen often in wireless and/or mobile applications), and most implementations of the specification are rather weak in these respects. There exist a number of "Real-Time CORBA" implementations, however, and most other shortcomings can be worked around quite elegantly given a basic understanding of CORBA and the underlying networking technologies.

CORBA implementations exist for almost all relevant computer languages.

RPC / SOAP

Remote Procedure Calls are a non-object-oriented variety of the CORBA theme. They have existed in various implementations and sub-concepts for a long time (UNIX's network file system, NFS, is an example for a RPC-based application). SOAP is a Microsoft specification for remote procedure calls, the characteristic trait of which is that the procedure calls and their arguments are formulated in XML and use the HTTP port 80 for communication. The advantage of this is that SOAP communication pierces most network firewalls, and many SOAP components can be queried and/or controlled by a standard WWW browser.

In our understanding robot assistants should communicate and interact in a “human-like” way and therefore should take into account both shape and mobility of the human body, the performance and versatility of the human senses as well as the natural operating environments. Robot assistants represent a generalization of industrial robots characterized by their advanced level of interaction and their ability to cope with natural environments both at homes and shop floors, see Figure 39.

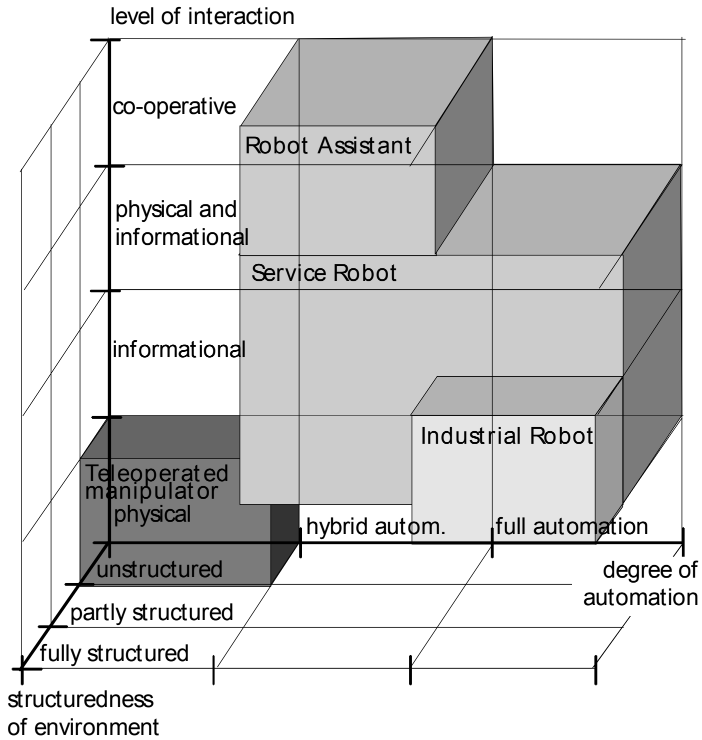
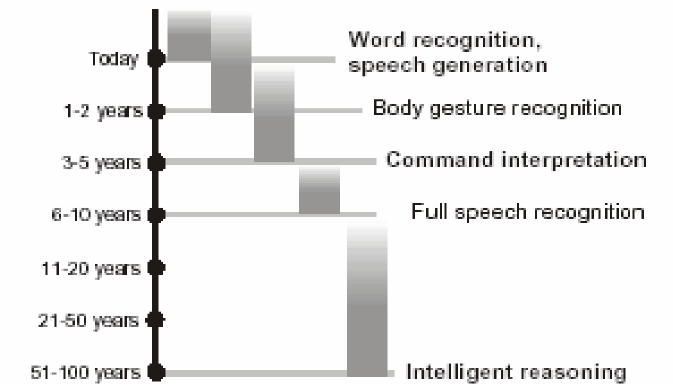


Figure 39 Context of robotic assistants relative to tele-operated manipulators, industrial and service robots

Five technical fields have been identified in the MORPHA initiative for developing and putting manufacturing assistants into practice:

Channels of Human-Machine Communication. User and robot assistant should co-operate and safely interact even in complex situations. This implies that the assistant understands the user intent through natural speech, haptic or graphical interfaces.

1. Scene analysis and interpretation. Effective co-operation depends on the recognition and perception of typical production environments as well as on the understanding of tasks in their context.
2. Learning and self-optimizing. Effective assistance not only requires technical intelligence of the robot but also a knowledge and skill transfer between human and robot. A typical example of learning is programming by demonstration.
3. Motion planning and co-ordination. During human-machine interaction motions have to be planned and quickly co-ordinated. For motions without physical user contact skills such as avoiding obstacles, approaching a human, presenting objects etc. have to be performed. In the more difficult case of physical contact with the user typical skills would comprise compliant motion, anthropomorphic grasping and manipulation.
4. Safety, Maintenance, Diagnoses. A suitable safety concept must account for the integrity of the system just as it must account for the integrity of its surroundings. External events affecting the proper function of the system and internal error conditions must be identified and classified according to their inherent risk factors [12-15].



Predictions on the evolution of communication [GROWTH ProRobot Project]

6) Architectures

Mechatronics

There are many different kinds of autonomous robots, both in research and in industrial use. The main differences are to be found in means of locomotion (fixed, bipedal, quadrupedal or hexapedal walking, differential drives, omnidirectional drives, tracks, etc.) and in the kinds of actuators used, such as industrial robot arms, light humanoid arms etc. There seems to be little doubt with current research that a robot that is humanoid "from the belt upward", i.e. consists of a torso with two humanoid arms and (perhaps) a head, is to be preferred for most tasks for both its versatility and end-user acceptance.

Locomotion is a different matter: The humanoid form of bipedal locomotion is still very difficult to implement in a reliable, accurate and fast way. Therefore, most robot systems still use wheeled driving, with all the problems in rough terrains that this encompasses. The problem is not too big in human-made environments since most building floors can be assumed to be sufficiently flat. The problem of stairs etc. remains, however.

Sensory networks

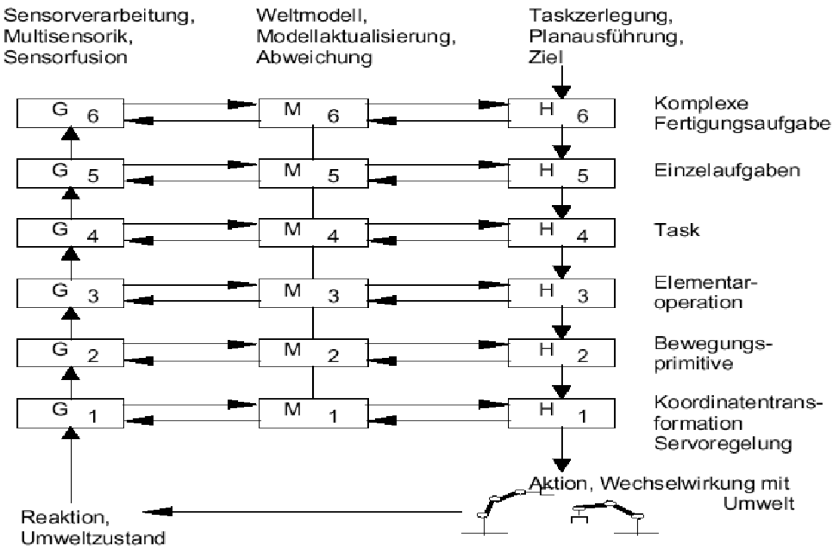
An autonomous robot needs to react to the environment in a fast, predictable and conclusive manner. Therefore, it must continuously use its on-board sensors to scan the environment for obstacles or targetable objects. Sometimes, what a robot "sees" with its sensors means that the current goal cannot be achieved directly: A person blocking a robot's way, for example, will hinder its task to drive to a certain position. If we define a current "main goal" for the robot, there are also at any time a number of "sub-goals" (or constraints) that must be fulfilled with higher priorities, and that can override the main goal temporarily. There may even be certain sensor readings that must be given a higher priority than others: A laser scanner may not see a glass door, but an ultrasonic sensor will!

Subsumption Architecture

This is the "classic" approach for robot system software design, pioneered by Rodney Brooks. The basic principle is to structure robot software akin to a living being's brain, with its main goals and reflexes. Subsumption architecture is built in layers, each of which gives the system a set of pre-wired behaviors. The higher levels build upon the lower levels to create more complex behaviors. The behavior of the system as a whole is the result of many interacting simple behaviors. The layers operate asynchronously and accept input from separate sensoric systems.

NASREM

First developed by NASA for a telerobotics system, NASREM models a hierarchical multi-sensor and multi-behaviour architecture similar to the ISO network-layer model. There are several layers, each made up of a sensor-processing, world-modelling, and a task component. The lowest layer gets its input from the physical sensors into its sensor-processing component and delivers actuation commands to the robot's actuators. The second layer gets its input from the first layer's output and sends actuation commands to the first layer's task component, and so on (see picture). This model builds layers of abstraction upon the robot's hardware and therefore allows rapid construction of very complex behavior by building upon the simpler behaviors provided by the layers below.

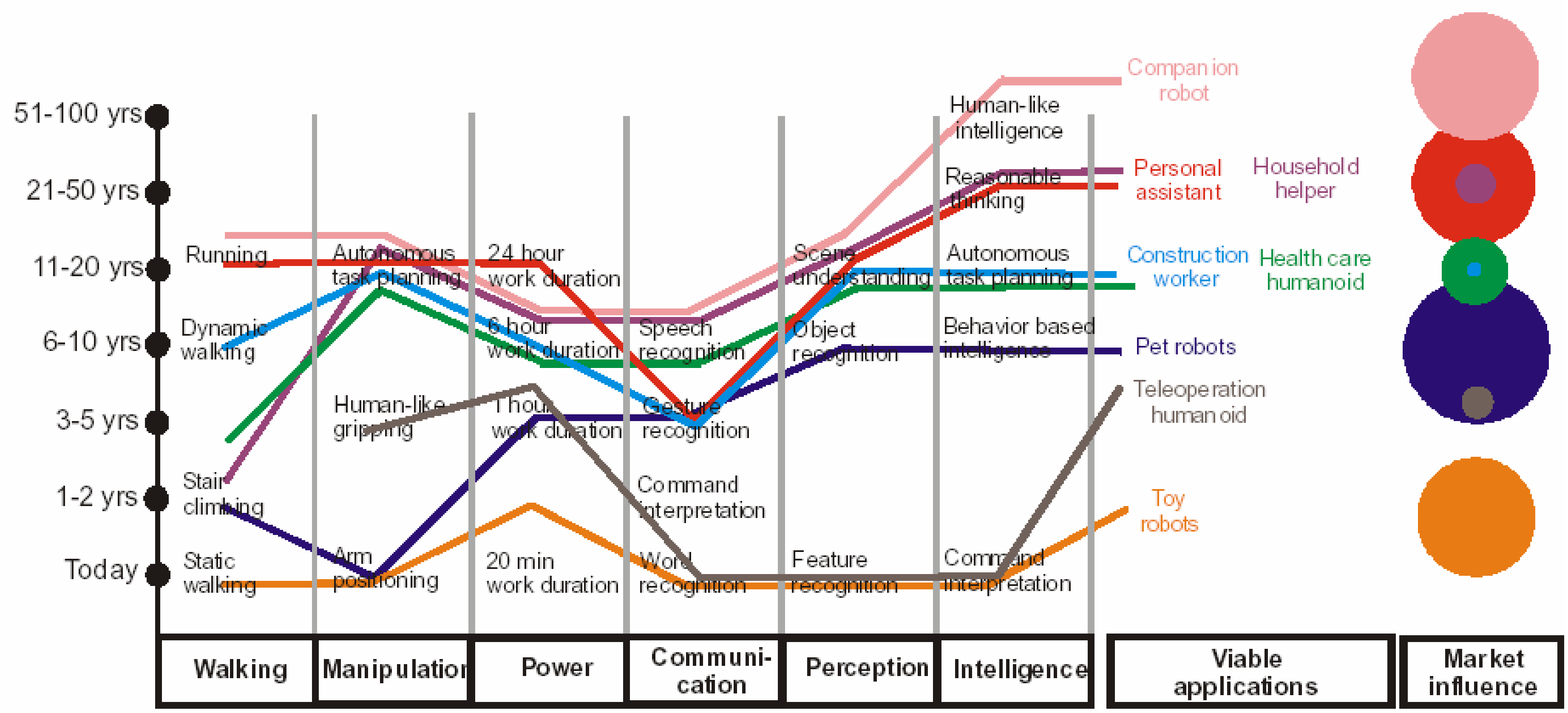


ProRobot – Predictions for the future development of humanoid robots

The ProRobot project “Paving the Way for Humanoid Robots” is funded in the Competitive and Sustainable Growth (GROWTH) Programme by the European Commission with project no. G1MA-CT-2002-00015. The project aim was to define a humanoid robotics roadmap.

The project results are reported in an article written by Ralf Regele, Wolfgang Bott, Paul Levi, of FZI Forschungszentrum Informatik, Mobility Management & Robotics and are enclosed in the Annex A.

The complete humanoid robotics roadmap is below and it shows the final overview of the development of humanoid robots in the future, the technical component roadmaps, the economic application profiles and the scenario prognoses were combined to a single roadmap diagram.



51-100 yrs
21-50 yrs
11-20 yrs
6-10 yrs
3-5 yrs
1-2 yrs
Today
Running
Dynamic walking
Stair climbing
Static walking
Autonomous task planning
Human-like gripping
Arm positioning
24 hour work duration
6 hour work duration
1 hour work duration
20 min work duration
Speech recognition
Gesture recognition
Command interpretation
Word recognition
Scene understanding
Object recognition
Feature recognition
Human-like intelligence
Reasonable thinking
Autonomous task planning
Behavior based intelligence
Command interpretation
Companion robot
Personal assistant
Household helper
Construction worker
Health care humanoid
Pet robots
Teleoperation humanoid
Toy robots
Walking
Manipulation
Power
Communi-cation
Perception
Intelligence
Viable applications
Market influence

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