NAO

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Abstract

In this chapter, NAO, the most sold humanoid robot throughout the world, is introduced. Originally designed to be a domestic companion, this 58 cm tall bipedal robot was first adopted by researchers and educators. These academic communities greatly appreciate using NAO as a platform on which they can easily develop applications. Thanks to its humanoid shape, NAO changes the focus of robotic research development and highlights how human-machine interaction is a major issue for the acceptability of the robots in our daily environment. After a brief history of NAO, the kinematics, the actuators, the

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sensors, and the architecture of the robot will be presented. On top of this hardware, a software environment is also available. It is based on NAOqiOS, a specific framework which gives the user access to the robot's resources: data from the sensors and control data of the actuators as well as high-level features like walking, face recognition, speech recognition, and dialogue capabilities. The services provided by NAOqiOS are accessible in Python and C++ but also through Choregraphe, a graphical programming interface that offers a very intuitive way to develop robotic applications without deeper programming skills. Some of the applications already available on NAO are presented below. The future applications of companion robots will require tackling technological challenges as well as answering ethical questions.

Keywords
Humanoid robot · Companion robot · Man–machine interaction · Social robotics · Mechatronics

1 Introduction

In early 2000, Bruno Maisonnier was a successful banker, managing various agencies all around the world. Despite his successful career he had a hidden passion: robots. Fueled by his education at one of the most prestigious French engineering schools, Ecole Polytechnique, and his fascination for mechanics and electronics, Bruno built robots in his garage while keeping an eye on the overall progress made in the world of robotics. In 2005, he noticed a convergence point where robotic technology was mature enough and the public was starting to expect robots entering the market for their personal use. At this point he decided to quit his job and create Aldebaran Robotics, a manufacturer of humanoid robots targeted for customers. With his own money and the financial assistance of friends and family, he started to design a small humanoid robot that would become a companion for everyone; a humanoid robot aimed to improve the well-being of its user. With young engineers and interns, he built a first prototype of NAO based on strong principles that are still leading the company today: a robot should be friendly looking, kind, easy to use, and easy to program.

One year later, in 2006, the organizers of Robocup, an international competition for university students to program robots that play soccer against each other [1], were looking for a robot that could replace the robot dog AIBO as the platform for the standard league because Sony had stopped producing AIBO. Aldebaran's NAO was proposed to replace Sony's AIBO and was then selected by the event organizers. The academic teams of Robocup became the first customers of Aldebaran with a huge order: at least 5 humanoid robots for each of the 16 teams. At the end of 2008, more than 80 robots were delivered to the Robocup teams. These teams were much more than customers, they became real partners of Aldebaran, using NAO intensively and pointing out potential hardware and software improvements. Based

Fig. 1 NAO

on the experience with Robocup, Aldebaran was able to upgrade and propose its first generation of NAO to the academic market in 2009 (Fig. 1).

2 NAO

2.1 The Hardware Platform

NAO is a 58 cm tall humanoid robot with two legs, two arms, two hands, and a head with two LED colored eyes. Before going into the details of the mechatronic design of NAO, it is imperative to reiterate that the most important factor in the process of the designing NAO was the outward appearance of the robot. It was decided that no metallic parts (gears, etc.) should be visible on the robot. Furthermore, it should have no sharp edges, only smooth, rounded surfaces. At first sight, the user should want to hug the robot, not to be afraid of it. Based on this absolute rule, the design was created. Here is a short presentation of the design. A more comprehensive one can be found in Gouaillier et al. [2].

NAO has a total of 25 degrees of freedom (see Fig. 2): two in the neck (yaw and pitch), five in each arm (roll and pitch in the shoulder, yaw and roll in the

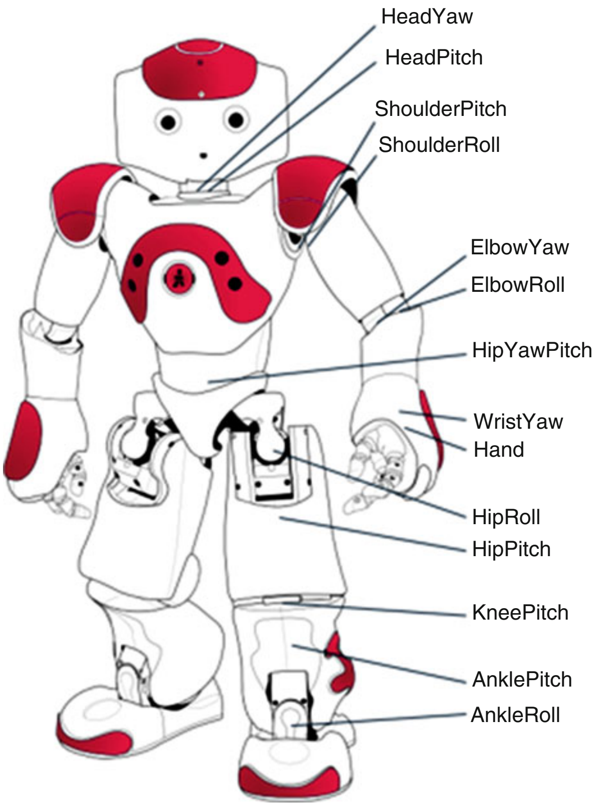


Fig. 2 Kinematics of NAO

elbow, and yaw in the wrist), one in each hand (open and close the three fingers together), and five in each leg (roll and pitch in the hip, pitch in the knee, roll and pitch in the ankle). The 25th degree of freedom is the hip yaw that is shared by the two legs. The yaw motion of the two legs is mechanically synchronized. The rotation axis of these two joints is inclined at 45° toward the body. This mechanism replaces the classical set of three active rotary joints as seen in most humanoid robots (see Fig. 3): the horizontal axis rotary joint at the waist and the rotary joints of vertical axis for each leg hip. The coupling of the pelvis joints prevents the trunk from rotating along the vertical axis (yaw rotation) when both legs are supporting it without creating a problem with walking and other movement related behaviors. The proposed mechanism also presents several advantages. Only one motor is required to drive the pelvis, instead of three in the classical design, this allows a reduction in manufacturing costs and saves space in the lower part of the torso. In addition, this structure helps better distribute the power between the hip roll joint and the pelvis joint and creates a specific motion style to the NAO humanoid.

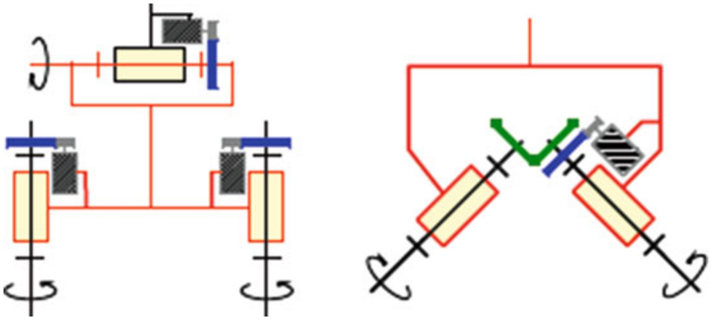
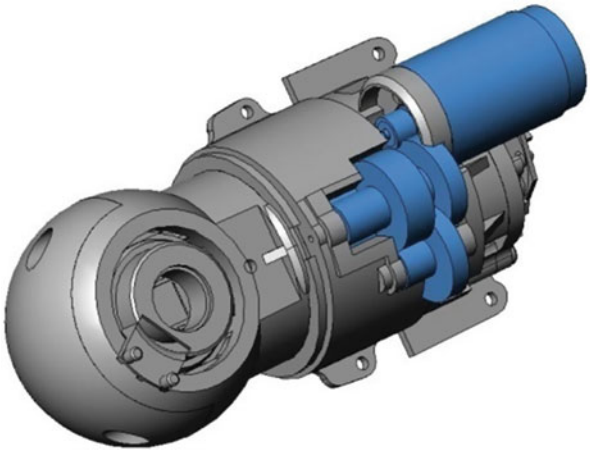


Fig. 3 *Left-hand side*: classical set of three rotary joints, one horizontal axis rotary joint at the waist, and two vertical axis rotary joints for the legs. *Right-hand side*: coupled inclined axis rotary joints for the NAO pelvis

Fig. 4 Two DOF cylindrospheric module used in the neck, shoulder, and elbow of NAO



If the very first prototypes of NAO were based on servo motors; the integration of these actuators would not be compatible with the very strong constraints that Aldebaran aimed for on the physical appearance of the robot. For this reason, specific actuators, based on DC motors, gears, and position sensors were created. 10 degrees of freedom in NAO rely on the same type of actuation module called the cylindrospheric module (Fig. 4). This module includes two motors that provide two perpendicular motions. This module is very compact and makes the integration of motorization very easy. This module is used in the shoulder, at the elbow, and in the neck of NAO. This modularity is an important aspect to consider when regarding the goal of mass production for NAO.

Another constraint that led to the design of proprietary actuators was research in backdrivability. Classically, humanoid robots use harmonic drives which provide high reduction ratio in a small volume, but are not backdrivable. This means that a shock in the limb is not "seen" by the motor but supported by the mechanics.

Considering that a small and affordable humanoid robot, like NAO, should be able to fall several thousands of times without breaking, the backdrivability of the actuators is an important feature. Using spur and planetary gears, the backdrivability is acceptable.

Each joint is equipped with a position sensor, Magnetic Rotary Encoder or MRE, that is used to evaluate and control the position of the joint in the robot. The resolution of the MRE is 4096 points per 360° range. On the leg joints, a second MRE is implemented to accurately measure the real position of the motor (before the reduction, that is, between 130 and 201 depending on each joint). This is a way to improve the accuracy of the position control and the estimation of the speed.

The architecture of control is distributed, rather than being all on one main system. The main CPU (ATOM Z750, 1.6 GHz) is in the head, and it is connected through a USB bus to an ARM-9 microcontroller located in the chest. The ARM receives the position command for each joint computed by the main CPU and transmits them through a RS485 bus toward DSPIC microcontrollers located in the limbs of the robot. Each DSPIC is in charge of the local servoing of two joints. It implements a PID position control and safety controls to prevent any trouble of communication that could generate erratic motions of the joints that could damage the motors or the gears or hurt someone.

But a robot is not only made of actuators and proprioceptive sensors. NAO is also equipped with other sensors to improve the observation of its own state, the environment, and the user. An inertial measurement unit (IMU), located in the trunk and consisting of a three-axis accelerometer and three-axis gyrometer, can be used to detect disturbances that can affect the balance of the robot (push off, slope) and that would not be detected by the proprioceptive sensors. The last sensors used to evaluate the current status of the robot are the pressure sensors located in the soles of each of the feet. The four FSR (force-sensing resistors) under each foot allow the robot to detect if the foot is on the ground or not and can give an estimation of the position of the center of mass and of the center of pressure. Mechanical bumpers on the "toes" can also detect a collision of the foot with an obstacle.

With classic exteroceptive sensors, NAO benefits from two sonars on his chest with a range of 3 m and a field of view of 60° each with a small overlap in the front of the robot. Two 1280x960 pixel color cameras, located in the chin and in the forehead, complete the robotic sensing equipment of NAO. Because the robot is dedicated to interact with people, NAO is also equipped with devices which allow very intuitive communication with humans: four microphones (around the head), two loudspeakers (one in each ear), tactile sensors (three on the head and one on the top of the hands), and plenty of LEDs (around the eyes, around the ears, on the chest, on the feet, and on the head) that can easily communicate information to the user. Thanks to all these devices, the users can talk, touch, look, listen, and move to interact with the robot in whichever way they prefer.

The description of the mechatronics of NAO will be completed with a presentation of its head. The head is a very sensitive part of the robot. It holds the CPU, microphones, cameras, loudspeakers, most of the LEDS, the Wi-Fi dongle, the Ethernet and USB connectors, two Infra-Red emitters and receivers, and a fan to make sure nothing gets overheated. The weight of NAO's head is about 600 g. It's a pretty massive and sensitive part on the top of a biped robot, especially when falling is often a part of daily life. Aldebaran had a hard time making the connection between the head and the torso reliable enough to insure the possibility of easily unplugging and replugging the head for maintenance purposes while being resistant to several thousands of falls. Operating similar to the spinal cord in the human body, NAO's flexible printed circuit insures, through the neck, the connection between the brain of the robot (the CPU in its head), and its limbs (the battery and the ARM board in the chest). Like for human beings, if the neck is broken, the robot will not be able to move anymore.

Even though its size has remained the same for almost 8 years, the weight of NAO has increased in a way that would worry any other nonrobotic humanoid: the current version of NAO is about 5 kg when the original version weighed only 4.5 kg. This additional weight has been the price to pay to improve the reliability and the electromagnetic compatibility required to access wider markets. Despite the fact that some of NAO's plastic parts became metallic and magnetic shields were added, the global performance of the robot was not negatively impacted.

2.2 Implemented Features

For easy use of all the resources provided to NAO, a specific operating system runs on its CPU called NAOqiOS. Based on Linux, it has been developed by Aldebaran to provide the basic functions necessary to simply use an interactive humanoid robot. Designed as an event-based system, NAOqiOS offers all the low-level and high-level functions which give access to the robotic features through software APIs. These include the sensor data, the control of the actuators, the speech synthesis and recognition, the image processing, the face recognition, the walk, and more. It also gives access to the status of the subsystems (battery level, internet connection, etc.). As with any screen-based operating system, it offers a way to explore the installed applications list and launch them. The principle of this OS, operating system, is to make the development of applications for interactive humanoid robots accessible to people who are not robotics experts. The list of all the features provided by NAOqiOS is given in the online documentation [3] but the most important ones are presented in this paper to illustrate the way they make the development of interactive robotic applications easier.

2.2.1 Gait

The most important feature for a bipedal robot is, of course, the walk. If the user gets a biped robot that cannot walk, he would be upset based on the expectation of the legs. Aldebaran implemented an omnidirectional walk based on the classical approach of ZMP [4]. Thanks to this the robot is able to walk in any direction. It is possible to change the length, the height, and the speed of NAO's steps. The maximum speed of the walk is 40 cm/s. The current version of the walking algorithm does not use the information of the inertial sensor to check its balance in real time

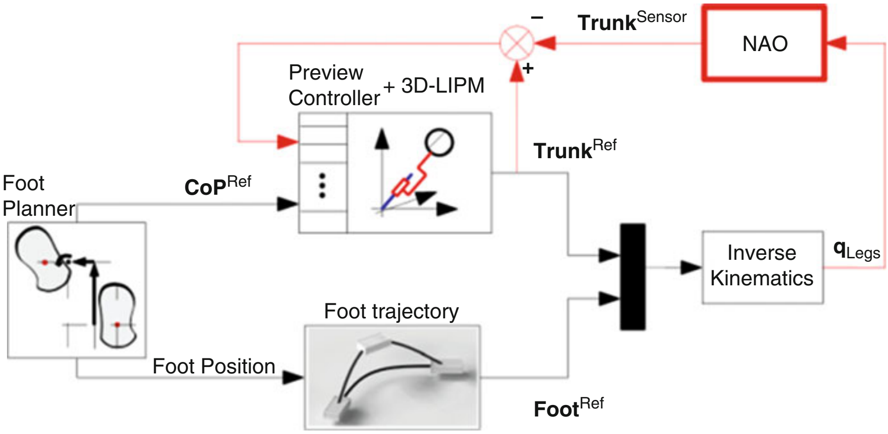


Fig. 5 Closed-loop walking algorithm

except for fall detection. But, nevertheless, the robot does not walk with a total open loop on position [22]. At each command cycle, the algorithm looks at the actual position of the joints to check if the real position is the same as the expected one and computes the next motions based on the current real position, not on the expected one. What could make a difference between the real position and the expected position if the control of each joint is good? The principle of the reliable walk that has been implemented on NAO (described in Fig. 5) is to have a joint control that is not too stiff and that allows for some error between the command and the measurement. The size of this error will be a way to observe the good execution of a motion. For instance, if the robot walks on a flat surface, the trajectory of each foot can be followed easily because it is planned for a flat surface. If the foot lands on top of a small obstacle, the contact will happen sooner than expected. If it finishes its trajectory toward the expected level, it has to carry the weight of the robot when it was not supposed to. The low stiffness of the control will make the error increase between the required position (on the ground) and the real one (on the obstacle). The walking algorithm will take into account that the 2 feet are not on the same plane to compute the next step of the robot. The robot is able to step over small obstacles (about 0.5 cm). This is equivalent to a 1.8 m tall human stepping over an object of 1.6 cm height.

The control of the stiffness, that has just been illustrated to get a reliable walk, is very useful in other situations and became a smart feature that application developers appreciate. Changing the stiffness of a joint is a way to use the backdrivability of the mechanism that has been evocated before. We noted previously that backdrivability could be used to prevent unexpected shocks. For instance, when NAO detects it is falling (and that a shock will probably occur), he takes a pose that protects the fragile parts of its body (the head and the hands) with its arms and then goes to a very low stiffness in each joint. When the shock happens, the joints are soft and fold under the weight of the robot instead of trying to maintain their position and end up breaking gears in the actuators. The low stiffness is also used to manipulate the limbs of the robot during the programming phase or when the robot gives its hand to a child to walk with him. Its arms become passive and determine the direction in which the child pulls the robot to move. The walking algorithm takes this input as the required walking direction. The proprioceptive position sensors of the arm become exteroceptive sensors.

2.2.2 Speech

When you meet a biped humanoid robot, you first expect that it can walk (similar to a human) and then that it can talk (also like a human). Speaking and listening are essential features of NAO. With the emergence of companion robots, vocal interaction with the robots has become a new research field within robotics. The verbal interaction with machines is a classical problem in telecommunication but it raises very specific problems when it is applied to robots. If the user is far from the robot microphones, the signal coming to the microphones is weak, the reverberation can be significant, the environment can be noisy (TV, music), etc. Furthermore, the robot itself generates noise when it moves and when it talks and this can disturb the perception of the audio signal. Also the robot's processing power is limited while it's processing a signal because this is CPU intensive. Last but not least, if you want to sell robots all over the world, your robot should speak and understand all the languages of the world.

Aldebaran partnered with Nuance for language processing, for Text-to-Speech (the robot pronounces written sentences generated by the application), and for Automatic Speech Recognition (the robot translates a pronounced sentence into a written text that can be interpreted by the application). The Nuance software allows the robot to potentially understand and speak up to 19 different languages in two different modes. In the embedded mode, a list of words, sentences, and contextual grammar is given that the robot should be able to recognize. The robot will find the most probable words in this list corresponding to what words the robot was able to recognize. In a well-known interactive situation, the embedded mode gives a better recognition rate with lower CPU consumption but with no chance of recognizing nonpredefined words, sentences, and grammar. With the remote mode, there is no limit to what the user could say; the speech is free and the user can say anything. The audio signal is sent to the cloud for Nuance servers to send back, within less than a second, a complete written transcription of what was said. This second solution seems very interesting, if we consider that there is no problem with the Wi-Fi connection to reach the cloud, but that makes the application much more complicated: the robot is supposed to be able to talk about anything. On the other hand, if free-speech recognition offers results in any dialogue situation, the result's confidence is not optimized to the interaction context. To optimize performance, an open question asked by the robot will require free-speech recognition ("What did you do today?"), where an oriented question prefers local speech recognition ("Do you prefer potatoes or beans?").

In addition to speech recognition, a complete dialogue engine is offered to application developers. The aim of this dialogue engine is to provide a tool to describe the content of complex, efficient, natural, and realistic dialogue. A good robotic dialogue should possess the following characteristics: the human user has numerous word choice options, the robot can vary the words it uses in a same situation, and the dialogue can refer to variables and external information, such as sensor data, and can trigger robotic animations. A specific syntax is proposed to describe these features. For instance, by using the keyword "concept," the linguist in charge of the dialogue can list the different words that can be used interchangeably for the same meaning. For example, a greeting can be expressed by "hi," "hello" or "good morning." The human user and the robot can use any of these words for greeting. Then a system of rules describes what should be the reaction of the robot when a certain condition is fulfilled. This condition can be a sentence uttered by the user ("What time is it?") or an event detected by the system (an alarm going off 5 min before a scheduled appointment in the user's agenda). Using the output of the face recognition function (that can detect gender, age, and the name when the robot knows it), the dialogue proposes to adapt the way the robot calls the person in front of it: "Mister," "Madam," "Rodolphe," "Dude," or "Young lady."

As said before, the verbal interaction with robots raises specific problems, mainly with regard to the signal-to-noise ratio. When the speaker is far from the robot, the signal detected by the microphones can be very bad making it necessary to improve the quality of the signal before the robot processes it. In collaboration with Nuance, directional microphones have been implemented on the head of NAO and a beam-forming software to focus the audio attention in front of the robot where the vision sensor has detected a human face, for instance. These two improvements have drastically improved the performances of the speech recognition software so that it can understand a sentence said by a speaker up to 1 m away from the robot and in a fairly noisy environment.

But the verbal interaction with the robot relies on two factors: the speech recognition and the speech synthesis. This last feature seems quite simple considering that synthetic voices are already available in plenty of objects we use every day (cars, subways, elevators, answering machines, etc.). However implementation in a humanoid robot raises specific problems. Firstly, the sound of the voice should be selected with caution. A voice that is "too human" would be strange on a little robot and a "too robotic" voice would reduce the intelligibility and create an emotional distance between the robot and the user. The voice of NAO is, without contest, the voice of a machine but with a fluidity that makes it very comfortable to listen to. In addition to this, the humanoid shape generates the expectation of humanoid behaviors. When human being talks, he does not just simply talk. He moves his hands, his head; he changes the expression and tone of his voice. During human-to-human interactions, it is said that the majority (up to 80%) of the meaning of the messages conveyed comes not from the words but from the gestures, the facial expressions, and the prosody. We will not attempt to reach this ratio yet but the simple pronunciation of words does not allow for natural and seamless communication. Within the GVLEX project [5], Aldebaran and its partners wanted to make NAO able to tell fairytale stories to children without bothering them with a monotonic voice. The semantic analysis of the text should generate modifications in the expression of the voice and gestures that would turn NAO into a real storyteller. The project was very ambitious and did not succeed in all above mentioned objectives but it demonstrated that it was possible to have a simple, real-time analysis of text to generate expressive motions automatically. When NAO says text out loud, it is possible to design a custom-made animation that will be triggered when a dedicated beacon inserted in the text is met. The NAO APIs offers the "animated speech" feature that animates the robot according to the text, with the help of a basic semantic analysis to extract global scheme (affirmation/refutation, etc.). This automatic generation of gestures when the robot is talking is very convincing and life-like.

2.3 A Development Platform

Aldebaran knew, from the very beginning, that it could not develop all the different kinds of applications users would want for their robots. Because Aldebaran's first customers were researchers who wanted to develop their own software on NAO, Aldebaran proposed, with the first version of NAO, NAOqiOS and a set of development tools that allow for easy development of robotic applications. All the functions provided by NAOqiOS are available in C++ and Python. Developers can build applications in one of these languages and benefit from all the services in this framework by using the SDK (Software Development Kit) provided for the robot.

On the top of this SDK, Aldebaran has developed a graphical tool, called Choregraphe (Fig. 6), which gives access to all these functions in a very intuitive way. A complete description of Choregraphe is given in Pot et al. [6]. Choregraphe graphically represents a specific function with a box; a number of functions are

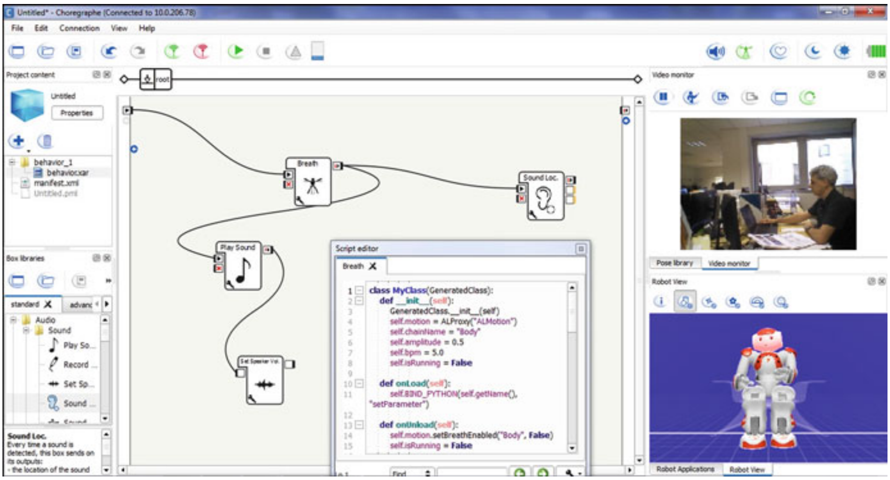


Fig. 6 Choregraphe

available, e.g., walk, speaking text, move joint, stand up, sit down. An arrow can connect two boxes. When this happens and the boxes are "played," the function of the first box is executed and automatically the function of the following box is triggered. Two boxes can be triggered in parallel by having two arrows going out from one box into two different boxes. The connecting arrows carry an event (end of the function represented by the box) but also values that are transmitted, as parameters, from a box to another. The user can create their own box in which the developer can write Python script. By offering special boxes for control of the application (while, for, if, etc.), Choregraphe allows the description of quite complex applications. Some features are very complex to code with classical programming languages (synchronization of the trajectories of the joints, creation of a body position, and so on), the graphical tools proposed by Choregraphe (3D virtual robot, timelines, and more) make them very intuitive to design. Choregraphe is a very powerful tool that can be used by children, to develop their own applications for NAO, but also by expert developers who can rapidly design mock-ups or describe the global architecture of their applications in which they can integrate their own sophisticated Python scripts or call advanced C++ functions.

3 Applications

3.1 What Is an Application for a Humanoid Robot?

The question of "what is an application for a humanoid robot" as well as "what does it do" are constantly asked to robotic engineers. The humanoid shape allows us to answer: "everything a human does." Because the design of a robotic vacuum cleaner constrains it to only the vacuum cleaning function, the shape of a humanoid robot-like NAO opens it up to millions of possibilities for applications. But which applications make the best uses for a humanoid robot? Which applications will make people want to buy one?

By providing a development platform for NAO, Aldebaran expected that researchers and private developers from all around the world will imagine and develop plenty of applications, of which the most promising of which could be selected and industrialized. Aldebaran supports a Developer Program where private developers are invited to develop applications they would like to have on their companion robot at home [7]. The results of this development tend to make nice demonstrations that illustrate the capacities of NAO (and of the developers in the program), a better way to understand the way people want to interact with robots [8] and sometime even a new Choregraphe box. But this is not a real application: it is a behavior that you run and that improves your well-being in some way. Dances and games are applications that entertain you. Entertainment is a very important matter for humanoid robots but would it be enough to make people buy a robot that cost thousands of dollars?

An example of a beautiful feature development on NAO that is not an application is the work made by a private developer, Taylor Veltrop, who was eventually hired and became one of the lead developers at Aldebaran. In this application, NAO is able to cut a banana [9]. Using a Kinect© system as a motion capture system, Veltrop was able to control all the movement and gestures of NAO. Mimicking the appropriate gestures, he controlled NAO to complete the task of cutting a banana. NAO, in a very impressive way, was able to cut a banana with a little knife and a little fork in its hands. Even if this demonstration is very spectacular, it is still far from a real application. Imagine if individuals with severe handicaps would appreciate to have a banana cut by a robot, who would put the knife and fork in NAO's hands? Who would teleoperate the robot for this kind of task? Is this task possible when the controller does not have a direct view of NAO while guiding it? This example is a bit of an exaggeration, and I apologize to Veltrop for that, but it demonstrates quite clearly the difference between the demonstration of a feature (made in laboratories) and a real-life application (provided by a company or developer).

3.2 First Applications

If we consider that a robotic application is software that a user runs on his/her robot and that the final user can also work with, it is possible to say that education is the major application running on NAO. Today 75% of the 10,000 NAOs already being used all over the world are used in the education sector. As soon as NAO is connected to Choregraphe, it becomes a perfect tool for teaching robotics, computer science, physics, and mathematics. At the beginning of the adventure in education, Aldebaran imagined that NAO would only be used at the university level, in Master 2 curricula, but as the time went on, the education market increased to include colleges, high schools, primary schools, and even kindergartens. The imagination of the teachers is without limits so they were able to develop engaging and educational activities for children and even raise money to buy NAO for their classrooms. This evolution in teaching is supported by many institutions (national governments, European Community) because education of robotics and education with robotics are a very good way to teach and attract young people toward scientific and technological careers. Indeed, in most occidental countries, these careers seem less appealing for young people compared to others, such as finance, law, and human sciences, even though they will probably make up a massive percentage of the employment opportunities in the future.

If Education today is the largest market for NAO, it must be said that it is an indirect application or a "meta-application" that does not completely fit with the kind of functions the creators of NAO originally had in mind. If you ask a 15-year-old boy whether education enhances his well-being, his answer will be probably be "Not very much."

The first real robotic application, in the traditional sense, with NAO created by Aldebaran was dedicated to education but not in the traditional sense. This application was focused around the education for children with special needs, particularly children with autism (Fig. 7). In 2011, the University of Notre Dame (Indiana, United States) bought a NAO. Notre Dame was doing research on children

Fig. 7 NAO used for specialized education

with autism and they had the intuition that a small humanoid robot could become a perfect intermediary between the child and the teacher [10]. Children with autism are often very interested in technology so NAO is naturally attractive to them. The researchers programmed educational games on NAO so that the robot could play and learn with the child. And, because it is a robot, NAO is able to play for hours with a child while most other humans would rapidly get bored or annoyed.

After very promising results were obtained by Notre Dame, and the interest of other research institutes in this field were sparked, Aldebaran decided to develop a complete package of applications for special education called “Ask NAO” [11] that can be played on the robot. For this package, NAO is not sold as an open platform but as a complete service made up of a robot, an easy-to-use interface and a specialized application package. This package is not designed only for children but for teachers to easily use as a teaching tool. According to the needs of the child, the teacher will prepare a set of games that the robot will play with the child. When the child gets significantly good results from these games, the robot will either propose other games or increase the difficulty of the applications being played. The individual applications are housed in an online interface that allows the teacher to select the games and to track the progression of each child without needing any sort of development or coding experience.

3.3 Next Applications

Before reaching the ultimate application desired by every man in the world, having a robot fetch a beer in the fridge, some other applications that are more reasonably achievable need to be created. To support the development of this vision of a companion robot, Aldebaran received a strong financial support of the Japanese

Fig. 8 First contact with an elderly person

company SoftBank who invested massively in the French company in 2012. In May 2016, Aldebaran was officially acquired by SoftBank and was rebranded as SoftBank Robotics.

Assistance to people with loss of autonomy is a domain that robotics could be used in, without doubt, and goes hand-in-hand with human assistance. Considering the growing age of its population, Japan decided 30 years ago to invest in humanoid and nonhumanoid robotics for assistance. The goal was to have robots be a solution to help the elderly live longer and more autonomous lives at home. Even though many tests have been conducted successfully, the fact is that, with the exception of Paro [12], a robotic baby seal that reacts to physical contact, there is no product available for this application. Going from prototype to product is a very difficult step and most of the robots designed for assistance are quite big and do not fit with the constraints of the classical Japanese flats. NAO is a very good compromise between the baby seal (cute but without functional features for assistance) and the tall humanoid robot (very functional but bulky). Within the Romeo2 project [13], SoftBank Robotics and its partners have investigated the reaction of French elderly people to the concept of robotic companions. The first reaction to this concept was very negative with responses saying: “a robot is dangerous,” “it is complicated to use,” “if it fails I will be in trouble,” “it is not for me but for my grand-children,” and “I don’t need it.” But as soon as NAO was presented to them as the solution, their attitude changed completely (Fig. 8): “it is cute,” “what could it do?” “can I get one?” “it is nicer than a wheelchair”. This last comment could seem strange but it points out a very important issue. Users often see their technological assistive devices as a stigmatization of their handicap. They are handicapped so they have to deal with ugly devices. It is important to know that one of the major improvements that people using a wheelchair ask for is to have a nicer looking wheelchair. Having NAO as an assistant, the elderly person does not generate pity but envy. One of the major qualities of NAO is that it changes the vision people have about robotics. This research is the foundation to show that people are beginning to consider having a humanoid robot at home.

Among the applications that could be proposed to elderly people, the following ones can be mentioned: reminders about medicines and appointments, recognizing medicine boxes or reading labels, maintaining connection with relatives (by email, chat, etc.), cognitive stimulation with games, and even physical stimulation with coaching applications. Furthermore, SoftBank Robotics is deeply convinced that humanoid robots can become the ultimate interface to the digital world for everyone. Thanks to its verbal interface with people and Wi-Fi connection with the environment, NAO can easily give access to the Internet, emails, voice on IP, and control of the connected house through IoT devices; and as humanoid robots are mobile, they are always available and close to the person.

It is easy to think that if all these types of applications are available for elderly people, having them could be interesting for anyone. If an elderly person is able to pay several thousand dollars for them, because he/she does not have another way of getting access to the applications, any person should be able and willing to pay several hundred dollars to get the comfort of having these functions gathered together on a unique device.

When the size of the market reduces the cost of NAO to a more reasonable price, a huge market for applications will emerge and it will be probably the beginning of a brand-new industry. Like what happened for computers and later for mobile phones, as long as they are limited to professional or very functional applications, they stay in a B2B model. As soon as games appeared on the devices, they became B2C products and new industrial giants rose.

3.4 Business Model

With this new industry of domestic robots, a new business model should be created. A humanoid robot costs a lot of money. How can people pay for it? The mass production, which aligns with the mass market of B2C, will probably participate in lowering the price of NAO. But will it be enough? Considering the comparison with computers and mobile phones, it is probable that an ecosystem will grow around robots. Companies will develop applications for NAO or will sell services using NAO. SoftBank Robotics has been contacted by insurance companies that would be ready to fund a part of the cost of NAO if it could be used to keep an eye on people who are living alone and assist them in staying autonomous at home longer.

As with mobile phones, it is possible to imagine that buying a robot will be cheaper if it is bought with a contract that would provide services like new applications, connection with entertainment or education channels. SoftBank Robotics proposes today an online Application Store [14] on which developers can share their applications with other developers and users which eventually they will be able to monetize.

There are plenty of existing and to-be-invented business models that could be applied to this new market. As soon as the robot is reliable enough and able to interact naturally with people, the cost of the robot will stop being the main issue.

4 Future Directions and Open Problems

In the previous sections of this chapter, NAO was presented as it is today with functions that it can already do but also as it could, and should, be in the future. To be able to create the described applications certain subjects which need to be addressed and tackled can raise numerous problems. Some of them have already been addressed by the research team at SoftBank Robotics but have not yet been industrialized. Some others are today available in the best laboratories all over the world so the industry has to improve the collaboration with these labs in order to take advantage of their research. Finally, some are still hidden somewhere in fundamental research or in ethical domain. A few of them are listed below but there are still others.

4.1 Technical Challenges

One of the first questions that are asked when NAO is presented are about the energetic autonomy. The current batteries in NAO can supply energy for about 1 h of continuous action. If the robot has to be usable all day long, and even all night long, its battery should have an infinite capacity. Such a battery would be heavy to carry, especially for little NAO. Research has to be done on better batteries, but also on reloading facilities. Fast and automatic recharging is a necessary feature for NAO. Automatic recharging seems simple, even vacuum cleaners are able to do it. But their batteries are close to the ground and can present connectors on their lower side to the connectors of the charger. The battery of NAO is located in its back. Bringing the charging current from the feet that would be in contact with a charger on the ground to the battery would require having big power supply cables going through the complex joints of the legs and hips. Ideally the electrical connection should be done directly through the back. Maybe the robot should lie down on its back to recharge the battery. The charger could be seen like a bed for the robot.

A vacuum cleaner can find its charging station thanks to an infrared light mainly because it stays in the same room or general area. The designers imagined that the robot would have a consistent and direct view of it. However, sometimes it does not and the vacuum cleaner robot will turn off in the middle of the room. This is not acceptable for NAO. NAO must find its way back to its charging station, even from another room. It requires both localization and navigation capacities. Considering the navigation sensors embedded on NAO, mainly the two cameras and two simple sonars, it is quite challenging. Of course, the visual SLAM [15] is an efficient solution but it requires a lot of CPU that would not be available on NAO in the foreseeable future. Different approaches have been experimented with, using topological localization [16] or simple artificial beacons [17], but there is still some work to be done in order to make these solutions reliable enough to be used.

While working on navigation algorithms, SoftBank Robotics is also looking for 3D sensors that could be integrated on NAO and that could help to make navigation easier. The integration of sensors based on “Time of Flight” or “Structured Light projection” is currently being examined. However, the constraints of cost and of integration on NAO are so powerful that most of the existing solutions are not acceptable. Stereovision could also be a solution, it is very cheap, but requires a large computation power. The integration of a new generation of CPU using a GPU (Graphical Processor Unit) dedicated to massive parallel computation can be a part of the future.

The other major improvement that could be envisioned with the help of 3D sensing is the grasping. A humanoid robot with arms and hands that is not able to catch anything would be quite a shame. Beyond the sensing problem, the hand of NAO would need to have improved grasping capabilities (better grip, better sensing, wider range of opening, more degrees of freedom), which would tie over to the robot’s interactions. If sign language would be difficult to understand with a hand as small as NAO’s, some naturally expressive gestures (thumb up, pointing or designation with a finger, counting on fingers) could be achieved. Beautiful robotic hands exist [18] but their integration on NAO would be difficult if not impossible: they are too heavy, their motors are not integrated in the hand but in the arm and there is not a lot of free space left in the arm of NAO. Finally, the hands of a walking robot are the most exposed parts of the body when the robot falls. The hands of NAO should be mechanically very resilient in addition to all the features mentioned above.

The little hands of NAO will require small motors that probably do not exist yet. In a general way, the ideal motors for humanoid robots do not yet exist. Robots need small motors which will provide a lot of torque at low speeds when classical motors need gears to change their natural high speed and low torque into low speed and high torque by losing efficiency and backdrivability. The revolution in robotics will probably come from a revolution in actuation. If NAO should some day be able to run and to jump, as well as possess other useful features to compensate for its small size, a new generation of actuators would be necessary.

Plenty of work still needs to be done in artificial intelligence, decision-making, and learning. This very high level of software is necessary to have robots able to evaluate a situation and to trigger the right and relevant behavior for the current situation. Of course, the minimum level of interaction is to ask the robot to fetch something. A real companion should be able to look in the TV guide and see that the user’s favorite soccer team is playing on TV, check the agenda to see if he will be home during the night, order food online because the fridge is empty, and to bring a cold drink when he comes home just in time for the game. With this simple scenario, the roadmap of robotic research can be written for the next 10 years.

Probably the most important challenge for humanoid robots is the interaction with the user. When the challenges presented before (autonomy, localization, grasping, and learning) are common to all kinds of robots, the expectations in terms of quality of interaction for humanoid robots is much higher. If the shape of the robot is “human-like,” the way the user communicates with it should be “human-like” as well. The human shape helps for the acceptability of an interactive machine but also emphasizes the need of a high-quality level of the interaction. To improve the performance of this type of interaction, all the modalities have to be used: audition, vision, tactile sensing. If the dialogue system presented before is a first step toward a real discussion between man and robot, a lot of work still has to be done to deal with a real natural language (however this responsibility falls mainly with the Natural Language Processing community). The humanoid robot has to also “know” that the interaction does not only rely on verbal communication but also on nonverbal (prosody, affective burst) and gestural aspects. The meaning of a sentence can change if there is perceived sarcasm in the voice. There are also sentences that generally cannot be understood without an accompanying gesture such as “take this” with the designation of an object by pointing. To have a better awareness of the context, the robot should pay attention to all the details in the behavior of its user. Within the Juliette project, the recognition of gestures and activities was experimented [21], [19] with good results but it was necessary to continue to make evolve this technology to take it even further. If the robot is able to evaluate the mood of the user by detecting his/her facial expression and his/her physical attitude, it could have much better empathy. The next question following this one is how is the robot supposed to react when it detects, for example, I am sad? Should it be sad with me? Or should it be funny to try to change my mood? It will depend on the emotional profile of the user. This profile should be modeled and possibly understood by the robot. Buendia and Devillers [20] show what could be envisioned in such a situation.

4.2 Ethical Challenges

Because NAO could become the first humanoid robot to enter into our homes, it will bring with it new questions about ethics, privacy, safety, and responsibility.

When we propose to provide NAO as companion for elderly people, even if it is cute and could be accepted as a possible assistive technology, we often are asked about the respect to their dignity. Do we respect elderly people when we give them a machine to take care of them, to talk to them, and to become their companion? It would be more respectful to have a human company. Personally, I had this question when a Japanese researcher first presented Paro, the robotic seal, to me for the first time. I said to this researcher that he could not respect the dignity of the person when giving them an advanced Teddy bear. In my mind I was picturing the elderly people as babies. The researcher said “Ok, you might be right but come and see the results: the person is quieter, they talk about the baby seal together. Simply, they are becoming happier. Where is more dignity: in a stressed person watching TV alone or in a quiet person playing with Paro?” Of course, it would be better if our society could provide full-time nurses for each lonely old person, but it is not possible. A robot, in general, and a humanoid robot in particular, is a way to partially compensate for this impossible task and bring some well-being to the person who has a loss of autonomy.

By sharing our lives and living in our homes, NAO could learn a lot about us, and hopefully it will. If the robot knows the user’s habits, the time he wakes up, the kind of music he likes to listen to when he cooks, and his favorite TV show when he drinks a beer, it can adapt its own behavior to the user and provide him with better assistance at the right moment. If computers are already able to learn your preferences when you buy things on the Internet and to recommend relevant products with targeted advertising, it is possible to imagine that a robot witnessing every moment of your life could become a perfect spy for advertising purposes, or even worse. A robot is a walking camera that could record parts of their user's life that they would probably prefer not to see on the Net. This is an ethical commitment that robot manufacturers should respect: the robot does not transfer collected information to anyone without asking explicit permission of the user first. This seems very simple but it means that the robot cannot benefit from the Cloud to store and to process the data it collects. In a connected world, is it really what people need? SoftBank Robotics and other domestic robot manufacturers have to find a solution to respect the privacy of the users without constraining the future use of their robots.

At last, science fiction movies demonstrate that the real danger with humanoid robots is that they will some day turn against humans and will destroy them because ... they have a good reason for that. So the question becomes who is responsible if someone's robot hurts or kills somebody? Is it the robot manufacturer? Is it the owner of the robot? Is it the developer of the software that was controlling the robot when it happened? Considering the size of NAO, we have some time to think about it before it is even possible to assume it could kill anyone. Nevertheless, it is important to start thinking about it now. It is important to remember that, whatever it looks like and whatever it is capable of, a robot is a machine. It does not have its own free will. The robot will only execute tasks that have been asked of it. If the execution of the task leads to a problem, experts will have to determine if it is because the task has been improperly done (the manufacturer is probably responsible) or because the ordered task was the origin of the problem (the user is probably responsible). Like for other advanced devices (autopilot in planes), when an accident occurs, the inquiry determines if the fault comes from the pilot or from the airplane's manufacturer. But no inquiry ever concluded with the notion that the party responsible for the crash of a plane was the plane itself. There is, and there will always be, a man behind the machine. The responsibility of the robot manufacturer is to give people a way to make that a reality.

5 Conclusion

Designing NAO, the first mass produced humanoid robot was a wonderful adventure. In this paper, we presented its hardware design, the basic functions, and tools that are implemented on it to make it a useful platform. We think that this platform can become a wonderful companion robot for children, adults, and the elderly, at home, at school, and even at work. To conclude this presentation of NAO, we want to share some lessons we learned from more than 10 years with this little robotic fellow.

We had the idea that a programmable humanoid robot could address any kind of use case. Because it is humanoid, it could, potentially, do everything that a human can do. But, of course, NAO is far from being a "human-like" robot: it is smaller, its hands are not dexterous enough, it cannot carry things… Some design choices forbid certain types of use cases from being implemented. With the robot we had designed, we could define relevant use cases (research, education, cognitive support, …) which are today have been pretty successful. After this first experience of "techno-push" development, we considered that our next humanoid robot should be designed based on a real-use case definition, in a more "design thinking" approach.

The choice of the humanoid appearance is definitely a good one. The appearance of NAO plays a major role in its acceptability by the general public. As mentioned, the risk of having a human-like robot is to create a disappointment when the behavior of the robot is not as human-like as its appearance. When the robot looks like a human, the public expects it reacts like they would to a human. Today the technology cannot provide this level of seamless interaction. That is the main reason why we think that robots should continue to resemble machines. It is a cute and entertaining machine but still just a machine.

Last but not least, we discovered that the development of robotic applications requires very special skills. An application for a humanoid robot is not a video game or an application for a smartphone. Even if there is a kind of game that plays in one of NAO's applications, or if applications should be downloaded on the robot to bring new skills or usages to it, there are two main specificities which separate these groups: First, the man-machine interaction relies on complex sensors (audio and vision). The humanoid-robot application should deal with the lack of robustness of the sensor processing in real life conditions. Second, the great power of the humanoid robot brings great responsibility to the application developer: he/she has to value the embodiment of the robot. If the customer paid to have a robot rather than a tablet, he wants to take advantage of the robotic device as a whole: the application should use the mobility and the expressivity provided by the humanoid shape. Whatever the use cases of the humanoid robots will be, these two points will be the main challenges for the success of the applications.

References

1. H. Kitano, M. Asada, Y. Kuniyoshi, I. Noda, E. Osawa, Robocup: the robot world cup initiative, in *Proceedings of the First International Conference on Autonomous Agents* (ACM, New York, 1997), pp. 340–347
2. D. Gouaillier, V. Hugel, P. Blazevic, C. Kilner, J. Monceaux, P. Lafourcade, et al., Mechatronic design of NAO humanoid, in *Robotic and Automation ICRA 09* (IEEE, Kobe, 2009), pp. 769–774
3. Aldebaran, *doc.aldebaran.com* 2014, Récupéré sur http://doc.aldebaran.com/
4. S. Kajita, F. Kanehiro, K. Kanzko, K. Fujiwara, K. Harada, K. Yokoi, et al., Biped walking pattern generation by using preview control of zero-moment point, *Robotics and Automation (ICRA2003)* (IEEE, Taipei, 2003), pp. 1620–1626

5. R. Gelin, O. d'Alessandro, Q.A. Le, O. Deroo, J.C. Martin, S. Rosset, Towards a storytelling humanoid robot, in *AAAI Fall Symposium : Dialogue with Robots*, Arlington, 2010
6. E. Pot, J. Monceaux, R. Gelin, B. Maisonnier, Choregraphe: a graphical tool for humanoid robot programming, in *Robot and Human Interactive Communication, RO-MAN 2009* (IEEE, Toyama, 2009), pp. 46–51
7. Aldebaran, *Developer Community* (2015), Récupéré sur https://community.aldebaran.com/
8. R. Baddoura, G. Venture, Social vs. useful HRI: experiencing the familiar, perceiving the robot as a sociable partner and responding to its actions. Int. J. Soc. Robot. **5**(4), 529–547 (2013)
9. Teleoperation, (s.d.). https://www.youtube.com/watch?v=_7nGBi3a9YA
10. M. Villano, C. Crowel, K. Wier, K. Tang, B. Thomas, N. Shea, et al., DOMER: a wizard of oz interface for using interactive robots to scaffold social skills for children with autism spectrum disorders, in *Proceedings of the 6th International Conference on Human-robot Interaction* (ACM, 2011), pp. 279–280
11. O. Joubert, L'enfant autiste, le robot, et l'enseignant : une rencontre sociétale. Enfance **2015**(1), 127–140 (2015)
12. C. Kidd, W. Taggart, S. Turkle, A sociale robot to encourage social interaction among elderly, in *International Conference on Robotics and Automation (ICRA 2006)* (IEEE, Orlando, 2006), pp. 3972–3976
13. A. Pandey, R. Gelin, R. Alami, R. Viry, A. Buendia, R. Meertens, et al., Romeo2 project: humanoid robot assistant and companion for everyday life: I. Situation assessment for social intelligence, in *International Workshop on Artificial Intelligence and Cognition* (CEUR, Torino, 2014), pp. 140–147
14. Aldebaran. *Store* 2015, Récupéré sur https://store.aldebaran-robotics.com/
15. M. Dissanayake, P. Newman, S. Clark, H. Durrant-WWhyte, M. Csorba, A solution to the simultaneous localization and map building (SLAM) problem, in *Robotic and Automation (ICRA 2001)* (IEEE, Seoul, 2001), pp. 229–241
16. E. Wirbel, B. Steux, S. Bonnabel, A. de la Fortelle, Humanoid robot navigation: from a visual SLAM to a visual compass, in *Networking, Sensing and Control (ICNSC)* (IEEE, Evry, 2013), pp. 678–683
17. L. George, A. Mazel, Humanoid robot indoor navigation based on 2D bar codes: application to the NAO robot, in *Himanoid Robots (Humanoids)* (IEEE, Atlanta, 2013), pp. 329–335
18. J. Martell, G. Gini, Robotic hands: design review and proposal of new design process. World Acad. Sci. Eng. Technol. **20**, 85–90 (2007)
19. D.A.G. Jauregui, P. Horain, Real-time 3D motion capture by monocular vision and virtual rendering, in *Computer Vision (ECCV2012)* (Springer, Firenze, 2012), pp. 663–666
20. A. Buendia, L. Devillers, From informative cooperative dialogues to long-term social relation with a robot, in*Natural Interaction with Robots, Knowbots and Smartphones*, ed. by J. Dans Mariani, S. Rosset, M. Garnier-Rizet, L.. Devillers (Springer, New York, 2014), pp. 135–151.
21. D. Gouaillier, C. Collette, C. Kilner, Omni-directional closed loop walk for NAO, in *Humanoid Robots (Humanoids 2010)* (IEEE, Nashville, 2010), pp. 448–454
22. M. Khedher, M. El Yacoubi, B. Dorizzi, Human action recognition using continuous HMMs and HOG/HOF silhouette representation, in *International Conference on Pattern Recognition and Methods (ICPRAM 12)* (SciTePress, Algarve, 2012), pp. 503–508