A NOVEL CREATIVE DESIGN APPROACH TO SIMPLIFY THE BIPED LOCOMOTION OF HUMANOID ROBOTS

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The paper presents a novel creative design approach in order to simplify the locomotion of humanoid robots in a real environment. The proposed approach is the result of intensive studies to optimize dynamic balance ZMP-based control on full actuated biped platforms. The complex control to move and stabilize a full actuated biped robot in a planar surface is bypassed with a novel creative design approach used to realize a humanoid robot with only two actuated feet and composed by a structure with all passive joints.

Keywords: Humanoid locomotion; Human musculoskeletal locomotion; Low-cost creative engineering design

1. Introduction

Humanoid Robots are quickly becoming an essential part of the changing world today. Robots have left the labs and entered in our offices (e.g., ASIMO by HONDA), helping old people (e.g., LindaBot, Mobiserv and Roboy), and performing on stage (e.g., HRP-4C) etc. However, despite these advances, the most sophisticated humanoid in the market today, still lacks complete. The sad reality is that, even after around 40 years of research in the field of robot locomotion, the robot of today has still a lot to learn before it can meet the agility and deftness of a toddler. However, the research work done in this domain has expanded significantly. Waseda University has a long and rich history in the development of humanoids. In 1973, research groups from Waseda University developed WABOT-I, and in 1984 WABOT-2 as to become a professional musician [1]. In 1999 they developed a humanoid with complete human configuration capable of biped locomotion, WABIAN (WAseda BIpedal humANoid), and in 2012 its Italian version SABIAN [2]. Recently, Google acquired eight advanced robot companies. Boston Dynamics, one of these, is known for its advanced robots including the world's fastest robot, Cheetah [3] (with 29 mph), Big Dog [4], (the all-rough and tough robot that walks, runs, climbs and carries heavy loads), and the latest Atlas, (a biped humanoid

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capable of walking in outdoor rough terrain with the upper limbs capable to doing other tasks while walking). Several versions of Atlas, [5], [6], have been prepared for the DARPA Robotics Challenge program.

With more and more advancement in this sector the demand for faster, energy-efficient and high performance humanoids is ever increasing. These demands are difficult to achieve if we remain limited to the conventional design technologies resulting in more and more complex dynamical systems which may meet the two aforementioned requirements but the cost would be a huge issue in this case. The popular humanoids of today lie in the above category. They have complex mechanical design with rigid links and a huge number of degrees of freedom, thereby, increasing the complexity of architectures, actuation and control requirements. However, some researchers have started exploring unconventional design approaches by using the knowledge acquired by the studies conducted on the biomechanics of human structure and locomotion. The design and development of low cost humanoids is a challenge at various levels by meeting the requirement of human locomotion but, at the same time, limiting the cost and complexity of the design of the humanoid. The Flowers Team of INRIA, (Institut National de Recherche en Informatique et en Automatique) thinks that the challenges faced by the humanoid designers and developers should not only focus on the cognitive intelligence but also to use the intelligent construction of the body to simplify the problem [7]. The result was Poppy, a 3D printed humanoid that took two days to be assembled by a single user. The cost of Poppy, in 2014, was around 7500 euros which included 4700 euros for actuators, 1600 euros for the shell mechanical and electronic components and 1200 euros for the 3D printed mechanical parts [8]. Morphological computation, as it is now called, considers the body of the humanoid to be a form of information processing structure, performing part of the computation to achieve sensorimotor task to simplify the control or to make it more robust to external disturbances. The most immediate result of this is the immediate action or reaction response of the humanoid body without the latency of a controller. In the design and development of Poppy, morphology has a significant role. This concept is also underlined by the Embodied Intelligence concept [9]. The popular work in the area of passive dynamic was Tad McGeer's Passive Dynamics Walkers [10]. His work of 2D biped locomotion was taken forward to 3D walkers, by Collins [11] and Tedrake [12] that had a structure with its own dynamics allowing self-stabilization and maintaining its gait. Many other biped humanoids with compliant body governing the dynamics of walking and running have been developed. Some examples are Athlete Robot [13], BioBiped1 [14], Asimo [15], [16] or HRP-2 [17]. There are fewer still with morphological computation, compliant structure, and physical interaction such as Kenshiro [18], [19]. Acroban is a lightweight humanoid, capable of robust semi-passive dynamic locomotion and physical human robot interaction [20], [21]. The main aim of this project was to experiment with the possibility of using the morphology of the humanoid to simplify the control as well as to explore the variety of human-robot interaction. Roboy was built in nine months at the Unversity of Zurich's Artificial Intelligence Laboratory [22], [23], [24]. The aim behind this was to build it using soft robotics technology and make it a more comfortable part of our daily living [25]. Roboy humanoid is 1.2 meters tall with humanoid musculoskeletal system; it is a tendon driven humanoid. Its musculoskeletal system was build using 3D printing techniques. Roboy's DoF are actuated by 48 motor units with each motor unit consisting of an actuation module, sensing capability and low level electronics. Roboy is one of the most recent development in its own field of research and development with the application of soft mechanism to be a more flexible and human friendly human companion.

As the humanoids are seen as mimicking human capabilities, there have been attempts to combine the agility and versatility of the biped human anthropology with a creative low-cost engineering design. In the case of humanoid locomotion, considering that the ZMP [26] is the most used theory for stabilization, a continuum contact of the foot of the robot with the ground could be a good approximation respect to the real human swing, in order to reproduce an artificial biped locomotion. In this case, the swiftness of the wheeled locomotion could be considered as a good alternative for the robot feet design. IMR-Type 1 robot uses this approximation. IMR-Type 1 was developed by the researchers in Japan supported by New Energy and Industrial Technology Development Organization (NEDO). It is an unconventional humanoid robot. The motivation behind its development was to provide support to human activities, in a society which has depleting youth and increasing number of aging human population. The aim is to provide a humanoid capable of fast and efficient indoor maneuverability. The interesting design feature of IMR-Type 1, is that it has three legs, instead one two. These three legs have 4 wheels attached to the end of the legs [27]. RollerBlader is another example of legged and wheeled robot. It was developed in the GRASP laboratory, at the University of Pennsylvania, USA. RollerBlader also has unconventional structure of a central platform resting on caster wheels and two 3 DoF legs with wheels. These wheels attached to its legs are passive and also result in nonholonomic constraints [28]. There are some other biped humanoids with wheels, the one developed by Hitachi, EMIEW 2, is a service robot that is required to safely coexist with the humans and provide them with services. It has two wheels instead of feet. It has a height of 80 cm and a weight of 14 kg. As it was built to interact with human its developers maintained human traveling speed of 6km/h for EMIEW 2. The reason for having wheeled-type leg instead of feet was to safely and quickly overcome the floor level differences, including thresholds, mattress, electric cables, etc. An important feature regarding the leg of EMIEW, which deserves some mention, is the active suspension and idling control technology. Active suspension consists of an actuator and a spring. The spring dampens the impact resulting from the uneven surface, or step encounter. The actuator then recovers the robots inclination due to this encounter. Furthermore, the idling control, keeps the excessive idling of the wheel in check when the wheel jumps due to some similar encounter. Once, it lands, it resumes with its steady running [29]. Another example of biped robot with Roller Skates is Zephyr. It has 12 DoFs with legs having the almost the same length as human. Currently, the robot has no arms or head. It has 3 DoFs at the hip joint, one DoF at the knee joint and two DoFs at the ankle joint. The Human type legged robot can be configured with or without the Roller skates [30].

In this paper, the authors propose a novel creative design approach to overcome the limits of the biped locomotion of humanoid robots in the real world. The novel proposed approach is based on a more creative engineering design of humanoid robots reducing the complexity and allowing, in the meanwhile, the same operative functions in the real world. In particular, the authors would like to pose a question and to answer with the presented robotic prototype of biped robot called ROLLO. The question is: it is necessary to use a humanoid robot with many active DOFs on the legs (e.g., 14-16 DOFs) to perform a motion in a real world planar surface? The answer is that it is not necessary to develop a complex robot when the same functions can be performed with simpler solutions. Whit the novel creative design approach here proposed we can have the same motion using only two motors on the feet and passive joints on the body. To perform a human-like motion of the robot on plane grounds is requested only to define a correct design of the whole-body passive joints. In this way, the problem passes from control to design domain.

The paper is structured as follows: section 2 shows the ROLLO robot, digital mock-up, electronics, software and realized prototype; section 3 presents an experimental tests on robot; section 4 presents conclusions and future works.

2. ROLLO humanoid robot

2.1. *Functional design of the humanoid robot*

ROLLO robot was conceived with a simple approach to allow balance and to reduce cost for realization. The novel concept of balance implemented in ROLLO is obtained after some intensive works performed by the authors on dynamic balance of very advanced biped robots and presented in [31] and [32]. The main elements of the mechanical structure of the legs of ROLLO are springs, connected in series that allows the robot to perform an alternate biped walking pattern and to allow to remain in a standing position also without alimentation of the motors. The motion is made possible thanks only to the two motors, positioned within the leg structure and directly connected with the wheel rotation. In order to move the robot in a rectilinear direction and with a constant speed, the two gear motors must rotate with the same direction. In this case, two kind of motions are possible: one with the legs moving together, and one with an alternate motion of the legs, in a way that resemble the human walking pattern. The coordination of the motor motion is managed by the on-board electronics. On the contrary, if the speed value of gear motors is the same and the direction of rotation of each motor is opposite the robot will rotate around its center, thanks to the overall structure that keeps together the legs. Arm and hands are not yet active, but they could be controlled in a next future with the same approach used in [33]. The innovative idea proposed in this paper is also the integration of the robot with the BCI technologies which allow to control the robot with the human brain. ROLLO takes inspiration from the T.P.T architecture [34], both from a mechanical and an electronic point of view.

2.2. *Digital mock-up and physical prototype*

The present invention is in a patent pending status [35]. It was born thanks to the Brainhuro project aimed at realizing a humanoid robot controlled by the brain of people affected by amyotrophic lateral sclerosis (ALS) disease. The first robot was conceived with the same characteristics of the SABIAN robot [31], [32], [36], and [37]. However, big dimensions of the SABIAN robot, and the complexity to move the robot in a real environment could limit a simple use of the robot. Another disadvantage is to guaranty a safety for people around the robot. In order to solve these limitations a small and simple robot with the same functionality of the SABIAN has been conceived. ROLLO is the name of the novel avatar robot proposed in this paper and controlled by the human brain using Brain Computer Interface (BCI) systems available in commerce, but the robot can be controlled also by other human machine interfaces (e.g. iphone, tablet, pc, or joystick).

Fig. 1 shows the ROLLO robot used as a classical biped robot controlled by external systems (pc, tablet, iphone) (see Fig. 1a), or as an avatar robot controlled by a brain computer interface system (Fig. 1b). The robot is constituted by a flexible structure in the legs composed by helicoidally springs used in a not conventional way. In particular, helicoidally linear springs can be used for compression/extension phase in the same direction of the axis of the spring. In our robot, the legs are developed with helicoidally linear springs used to develop passive motion generated with a flexional torsion of the spring that oscillates respect to axes coincident to the conventional one. The behavior of a helicoidally linear spring in a conventional way is noted and many formulations are available in literature, but not many formulations are available if the compression or extension of the helicoidally linear spring is generated by a flexional torsion. This is caused because the behavior of the helicoidally linear springs in a flexional torsion is nonlinear and experimental formula can be used only as referent.

Most of the biped robots available in commerce and literature must be colligated to their power supply in order to stay in a standing position before starting motion. Our robot, using helicoidally linear springs can stay in a standing position without activation of the power supply of the robot. This is a very good advantage allowing reducing energy during motion. Fig. 2 shows the digital mock-up of the complete robot (height around 1000 mm, weight around 10 kg) developed by Humanot company [38]. Another characteristic of the robot is to combine the flexibility of the structure with the biped wheeled system allowing many combinations of steps. The robot can move with: an alternated step of each foot respect to the other one moving as a biped wheeled robot; no relative alternated steps of the two feet moving as a wheeled robot; eight velocities which modify the behavior of the flexible structure and the dynamic of the system; etc.. The altitude of the robot can be modified varying the number of the elastic modules in each legs. Fig. 1b shows ROLLO robot with three elastic modules (helicoidally linear springs) in each leg and an IPad used to reproduce the head. In general, the robot is constituted by a flexible structure composed of two springs (1), (2), (or more springs) in each leg which can have different lengths. Other springs or rigid components can be added in order to have different combination of motion (e.g. human-like motion using three springs in proximity of ankle, knee, and hip and rigid elements in proximity of thigh and shin). The springs allow to have a human-like motion varying the velocity of the two motors (3) one in each leg.

ROLLO can move using only two gear motors (3). The two legs are the same and constituted by one or more springs (1) or (2), one gear motor (3), two wheels (4) and (5) colligated to the shaft of the gear motor (3). ROLLO can be moved in a rectilinear or curvilinear way. The rotation can be obtained or fixing (4) to the shaft and using a bearing between (5) and the shaft of the (3) or fixing (4) and (5) to the (3) having two driving wheels in each leg; this characteristics is possible only if the robot is constituted by a flexible structure. Wheels (6) and (7) are not fixed and can be moved around the vertical axis perpendicular to the surface where the robot is moving. Elements (8) are used to vary the altitude of wheels (6) and (7) respect to the ground and to the wheels (4) and (5) in order to reproduce a human-like motion (hell-tip). Two elements (9) and (10) are attached to the gear motor (3). A reinforced structure (11) is attached to (12) and (10) in order to fix the battery (13) used as power supply allowing motion of the robot for one hour at maximum speed. In each leg a driver with a switch control the connection between power supply, motors, and electronics (15). The webcam of the iPad (16) is the camera used for the avatar system. iPad (16), electronic (15), arms (18), and hands (17) are fixed to the structure (19). Element (21) is attached to the spring and allows to fix the spring to the wheeled structure or to other springs. The robot can rotate moving the wheels each foot in the opposite direction.

Fig. 3 shows pictures of the robot controlled using a Brain Computer Interface system available in commerce and developed by Liquidweb company. The picture on the left has been done during Ericsson Innovation Day at Genova (Italy) and ROLLO has been used as presenter during the open ceremony.

(a) (b)

Fig. 1 ROLLO: first prototype used as a classical robot (a) or as avatar robot controlled by BCI systems (b)

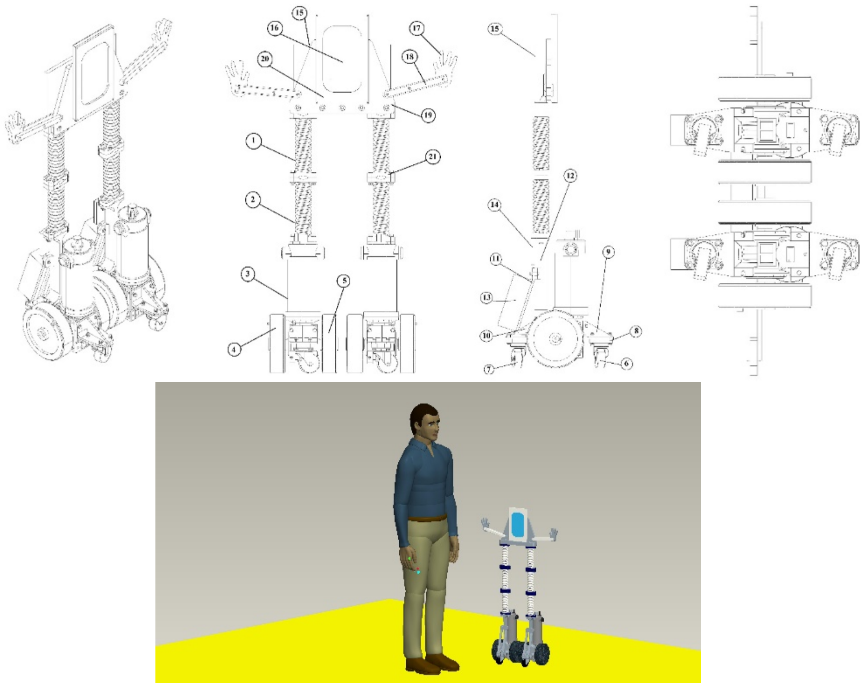

Fig. 2 ROLLO: sketch and digital mock-up

Fig. 3 ROLLO: prototype controlled by the human brain for people affected by amyotrophic lateral sclerosis disease. RICORDARSI DI COPRIRE VOLTI PER PRIVACI

2.3. *Electronic hardware and software*

The whole electronic architecture is schematized in Fig. 4 while Table 1 resumes some of the hardware characteristics of the robot.

The communication is performed by means of two incremental encoding square wave signal outputs, operating at a frequency of 1 kHz. In order to read their values, a hardware description of two Finite State Machines has been implemented within the FPGA VHDL code. An accumulator variable on 32 bits is dedicated to the reading of the encoder value, and it is incremented or decremented in relation of the square wave value of the *A* and *B* encoder signals. Moreover, the signals coming from the encoder are hardware filtered in order to avoid wrong readings. The proximity sensors are infrared Sharp GP2Y0A21YK, operating at 5 Volts and able to give a high output signal when an obstacle is detected in a range between 3 and 15 cm. The output is directly read by the FPGA hardware and used in the control code. This allows the robot to detect dangerous paths and quickly stop its movement. Regarding the control electronics, as with T.P.T. robot [34], the communication is guaranteed by a microcontroller board, with commercials PIC18F976J60 and a transmitter/receiver MRF24WB0MA for Wi-Fi communication. In order to speed up the communication, a custom board has been designed and assembled, eliminating some unused components. Again, UDP sockets have been chosen as communication strategies, with a modification of the TCP/IP libraries of the Microchip stackThe WI-Fi board is interfaced with the FPGA board DE2 Altera, which implements the real control of the robot. In this case, the FPGA is connected to two motor drivers, instead of one, in order to increase the autonomy of the robot and to simplify the wiring of the structure.

The main differences with respect to T.P.T. [34] are related to:

- The handling of the two legs
- Communication with BCI devices

There is also a third improvement that is the interface with a tablet device that will be analyzed in the next section. When a command is received (i.e. forward, backward, turn left, turn right or stop) the Wi-Fi board communicates the command to the FPGA board through serial connection. At the FPGA level, a microcontroller handles the packet and communicates to the I/O pins dedicated to the interface with the motor drivers the direction of rotation and the velocities. In case of forward/backward motion, a bit inside the UDP packet specifies if the walking pattern should be with an alternate motion or not. While in the last case the handling is simple (the two motors are activated with the same direction and velocity until the stop signal arrives), in the first case the microcontroller instantiated within the FPGA is in charge to alternately move the two legs. To achieve this motion, it uses the encoder values in order to move the two legs of the same displacement and in mutual exclusion. If the stop signal comes, the microcontroller allows the legs to finish the complete step, in order to avoid unbalances. The motor drivers are constituted by two VHN5019 devices and the control of direction and velocity is performed with a PWM logic. Regarding the communication with the BCI devices, this is handled by the external software running on a PC. The LabVIEW environment was used to create an additional graphical user interface, able to communicate with the robot and with the external world. The communication with the robot, as usual, is implemented by two threads: one that creates 4-byte UDP packets and sends them to the robot, and one that reads the UDP packets coming from the robot, giving some information to the user. In order to communicate with the external world, an additional thread is added that opens a TCP communication and listens over a specified network port (Fig. 5). The BCI communicator decodes the EEG signals and sends within the same network a TCP packet with the information related to the motion; the Labview interface detects the message and finally communicates to the robot the correct direction.

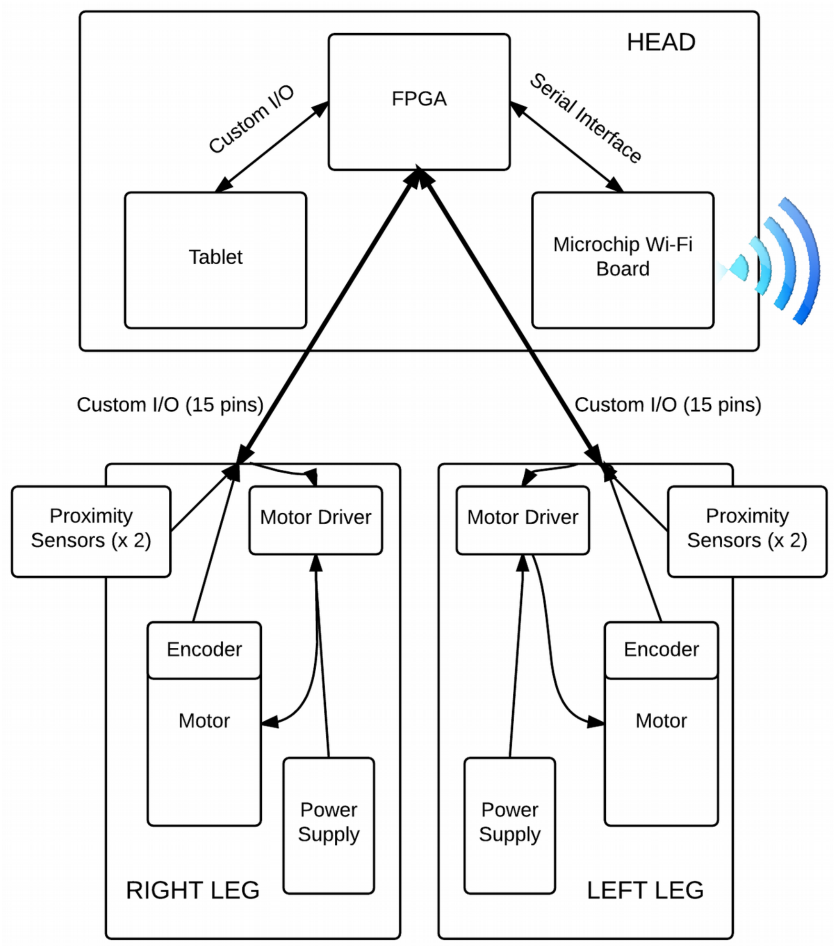

Fig. 4. Electronic hardware architecture of ROLLO

Table 1. Hardware characteristics of ROLLO.

Characteristics	**Value**
Power Supply	2x24 V – 500 watts
Sensors	Proximity sensors, cameras and accelerometers (tablet), motor encoders
Actuators	2 servomotors (250 watts for each motor)

Control	Joystick / BCI
Communication	WiFi – UDP sockets

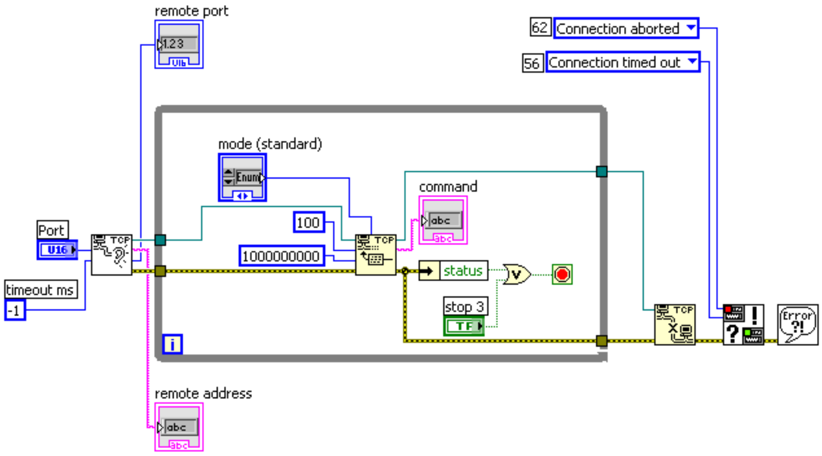

Fig. 5. LabVIEW thread for the TCP listening. FORSE ANDREBBE RIFATTA IN MODO PIU' SCHEMATICO E SENZA NUMERI, ma parametrizzata. VA INOLTRE SPIEGATA CON RIFERIMENTO ALLA FIGURA

Moreover, with this kind of architecture it is possible to control the robot also if the BCI communicator (or another application sending TCP packets) is inside another LAN, i.e., it is possible to remotely control the robot. At this aim, the LabVIEW interface can instantiate a TCP socket over a public ip, therefore accessible from the outside. The GUI can be seen in Fig. 6. The upper part is related to the communication with the world, i.e. BCI headset or a TCP application; in the bottom right side the user can monitor the communication between the interface and the robot, checking if the packet sent is correct; in the bottom left side, some local commands (i.e. velocity, emergency stop) are available for the user. Obviously, the robot can be controlled also by means of a joystick/joypad or with the keyboard. A first test has been performed on February 2015: the remote controls of the robot were sent by means of the BCI headset from Siena (Italy), while the robot was in Genova (Italy). The tests gave encouraging results, confirming the full interfacing between the robot and BCI technologies.

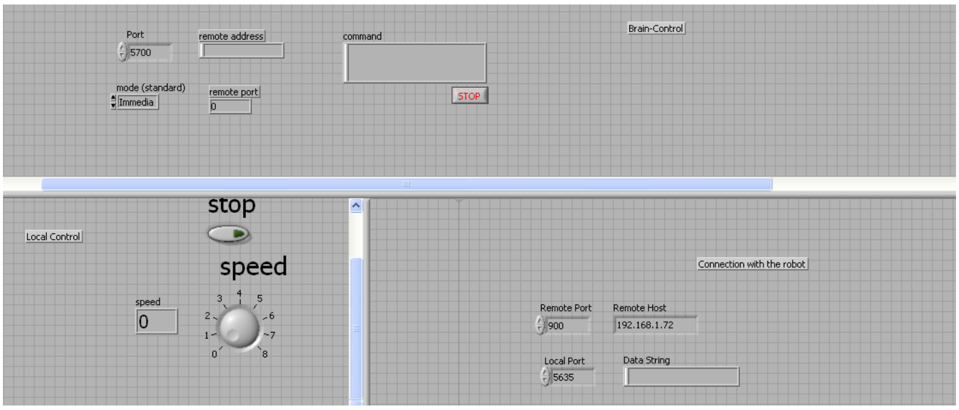

Fig. 6 Graphical User Interface of ROLLO.

2.4. ***Tablet interface and overall architecture***

Finally, a further added value of Rollo is the possibility to interface the hardware architecture with a tablet device that constitutes also the face of the robot. A mandatory feature for the project was that the robot was endowed with cameras in order to record images of the surrounding environment, and send them to the user. The feature can be extremely important for people suffering from ALS, or any other disease that prevents them from freely moving. Indeed it can be a way to explore an environment, to stay closer with beloved people and to try novel ways of communication.This aspect has been implemented with an Android Tablet (Samsung Galaxy Tab S), chosen for its thinness and for the quality of the embedded cameras. A custom built android application has been written in order to:

1. visualize a happy face on the full screen
2. stream the camera images on board of the control PC

While the first point was easily achieved by modifying the layout of the application, for the second point a more interesting work has been performed. Two protocols dedicated to real time streaming have been used:

- *RTSP Protocol*. Real Time Streaming Protocol is a networking protocol mainly used to stream real time media data like audio or video. It establishes a streaming session between client and server and it is used to send video stream from the android tablet to a streaming server.
- *RTMP Protocol*. Real Time Messaging Protocol was developed by Adobe for Flash Player to transmit the real-time media (audio, video) between server and flash player. This protocol is used to receive video stream from the server to the flash player on the control PC.

The*libstreaming*library for RTSP was used in order to stream images from the Android tablet to the streaming server. As streaming server, the Wowza Media Engine was used, that is a very popular streaming engine which can stream high quality video and audio. In the implementation, it acts as server side streaming framework, which receives video from the android device and as a streaming service, which will be consumed by a webpage to display the video. On the control PC side, the *jwplayer* software which supports RTMP protocol was used and integrated with a Web application in order to visualize the video. However, the code is still under development and some integration in progress are related to:

- Visualization of the user face on the tablet screen
- Utilization of the tablet for interactive applications
- Integration of the tablet with the FPGA

The first aspect has been considered while testing the platform with ALS patients: it emerged that it could be psychologically positive and pleasant to move the robot having their own face, as if the robot was an *avatar* of the locked-in patient. This has been quickly implemented by using common video conferencing tools such as Skype or Google hangouts. Regarding the second point, many functionalities can be implemented on an Android tablet making use of the embedded sensors of the tablet. e.g. accelerometers, and of the OpenCv [--] libraries. The first element can help to understand if the motion of the robot is stable or if it is in danger of falling. Indeed, since the presence of the springs, the upper section of the robot can tilt when the motion of the robot is too fast or not uniform. A simple code was written by the author in order to monitor the inclination of the tablet. The code uses the the *SensorEventListener* interface in order to evaluate the accelerometer output.The OpenCv libraries can be used in order to implement some features such as marker recognition or face detection. The API for face detection contained in the Android SDK *android.media.FaceDetector class* has been used. This class detects faces on an image or video by calling the *findFaces* method. The method returns the following information:

- Confidence that it is actually a face - a float value between 0 and 1.
- Distance between the eyes - in pixels.
- Position (x,y) of the mid-point between the eyes.
- Pose rotations (X,Y,Z)

For the marker detection, the ArUco libraries [--] used for the preliminary tests with T.P.T. robot [34] has been integrated. Both accelerometers and artificial vision libraries gives information that can be extremely useful for the robot control. It has been already mentioned that the accelerometer output can be used in order to avoid unbalances of the robot; face or marker recognition, and in particular the information about the position of the face (or marker) can be extremely useful to make the robot follow a moving person, or target, or for the interaction between the robot or the patient (e.g., the robot could recognize the patient and ask him questions).On these basis, the process of integration between the tablet and the FPGA hardware has started. The USB-host mode supported by the android devices is being used in order to interact with some I/O pins of the FPGA hardware, configured for the USB protocol. The overall control architecture is therefore constituted as in Fig. 7.

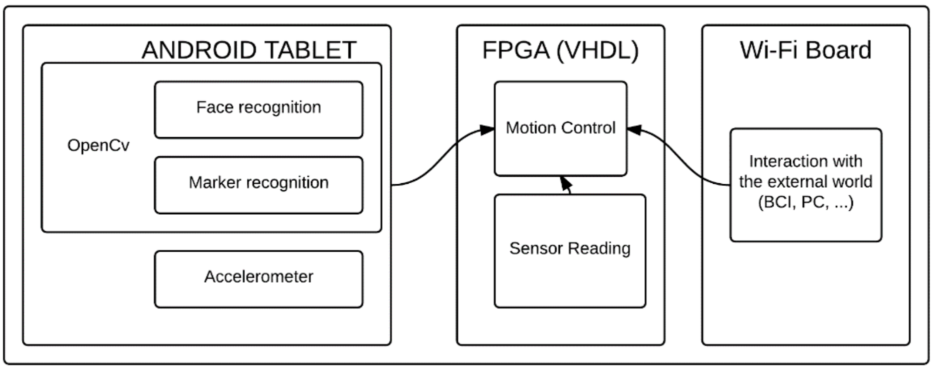

Fig.7 Overall Software architecture

A humanoid platform so constituted is able to achieve important tasks, such as integration with BCI technologies, face and marker detection, video streaming, target following, adopting a biped alternate motion and being extremely low-cost (the price for the whole hardware was no more than 3500 euro). It is belief of the author that a similar product marks the right track to bring humanoid robotics really in the house of common people, giving also a psychological and practical help to people with physical disability.

3. Experimental tests: results and discussion

In the following some experiments on the ROLLO robot are shown.

4. Conclusions and Future works

The paper presented a novel approach to simplify the biped locomotion of humanoid robots. The authors, after intensive studies on classical full actuated humanoid platforms with a ZMP-based control, worked to bypass the ZMP-based control approach using a novel creative design approach. In this paper, the novel approach is based on the reduction of the actuated joints using more passive than actuated joints on a humanoid platform. In particular, in this work a bipedal wheeled robotic platform is presented and discussed. The results confirm that the approximation using only two active motors on a biped wheeled robot proposed with the novel creative design approach, has more advantage in movement in a real planar ground environment than a full actuated humanoid robot with a ZMP-based control approach. The authors suggest using the same approach to design novel generation of creative low-cost humanoid robots. The future works will be based on the implementation of the same approach in real novel platforms that Humanot Company is developing.

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