Tele-Kinesthetic Teaching of a Humanoid Robot with Haptic Data Acquisition

Pedro Cruz, Vítor Santos and Filipe Silva

***Abstract*— This paper describes a haptic-based data acquisition system implemented and assessed on a proprietary humanoid robot. The system counts on the human teleoperation of the robot and, simultaneously, explores the direct sensorial feedback from it. We propose an approach for kinesthetic teaching in which the user interactively demonstrates a specific motion task, while feeling the dynamics of the system to be controlled via a haptic interface, hence the expression tele-kinesthetic. Besides the obvious visual feedback of the robot apparent behaviour, much more valuable information is received from other sensors, such as force and inertial sensors. The first results show the potential of the proposed interface in both manipulation tasks and for keeping the balance of one single-leg of the robot.**

I. Introduction

The control of full-body humanoid robots is an extremely complex problem, mainly for locomotion tasks. This complexity arises from the many DOFs involved, the lack of precise models, the non-closed form for robot control, the dependency on the environment conditions, the compliance of actuators, the variable stiffness of links, the backlash of transmissions or the noise in internal sensors. Therefore, a walking task, so natural in humans, becomes very difficult in robots with all their mechanical and controlling limitations.

The same problems have been faced by the authors in the development of a custom proprietary humanoid platform [1], [2]. Although conceived with care and with many components previously simulated before effective construction, the platform suffers from many of the limitations mentioned above. Furthermore, its complexity increased with the inclusion of passive actuators in parallel to the servomotors on many of its joints. Compliance of the transmission belts and small amounts of backlash in the gears make the control task even more difficult.

Robot learning by demonstration is a powerful approach in order to automate the tedious manual programming of robots, to learn locomotion without complex dynamical models and to reduce the complexity of high dimensional search spaces [3], [4]. The demonstrations are typically provided by teleoperating the robot or by vision and motion sensors recordings of the user doing the task. Recent progresses aim to provide more user-friendly interfaces, such as kinesthetic teaching [5]-[7].

In this paper, we investigate an approach where the user provides demonstrations by physically interacting with a humanoid robot through a haptic interface. The proposed methodology enables a natural interface for tele-kinesthetic teaching and sensing in which the user provides functional guidance and corrections, while being aware about (*i.e.*, able to "feel") the dynamics of the system, its physical capabilities and/or constraints. In this sense, this approach goes beyond previous research on teaching by demonstration that is unable to raise the level of bidirectional human-robot interaction. Instead, it refers to a deeper relationship between the user and the robot who share control to reach common goals using the same measures of outcome.

Additionally, during the demonstration phase, the sensory information and the commands guiding the execution of a specific task are recorded. All the data logged from the human-robot interaction can be later used for learning purposes. For example, to learn the force-control laws that govern how to perform a given task. Our future intent is to use the recordings of demonstrated behaviors to extract the correlations among sensorimotor events and to acquire the knowledge of how to select and/or combine different behaviors together.

The work reported has an experimental basis since the ideas and strategies have been evaluated on a real robot forming a critical hypothesis-and-test loop. Section II presents the experimental setup with special emphasis on the humanoid platform and the haptic interface. Section III discusses the details of the experiments performed and the qualitative results thereof. Conclusions and perspectives of future work are drawn in the final section.

II. Experimental Setup

A. The humanoid platform

This research on robot learning by demonstration is being conducted on a proprietary whole-body humanoid platform (Fig. 1) with a total of 25 active degrees-of-freedom (DOF): 2×2-DOF ankle, 2×1-DOF knee, 2×3-DOF hip, 3-DOF trunk, 2-DOF neck, 2×3-DOF shoulder and 2×1-DOF elbow). The humanoid robot's height is around 65 cm and the weight 6 kg.

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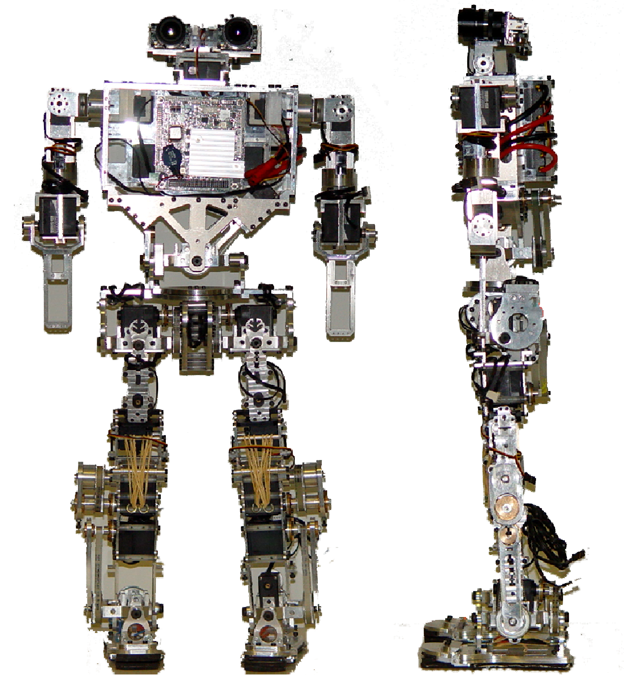

Fig. 1- Front and side views of the whole-body humanoid robot with 25-DOF, 65 cm height and 6 kg weight.

The robot design accounts for a hybrid actuation system that combines motorized actuators with adjustable elastic elements, providing an energy storage/recover mechanism. Anthropometric proportions and ranges served as inspiration towards a platform that permits walking with straight support legs by incorporating a compliant foot with a passive toe joint. Additionally, the robot includes a rich variety of sensors such as joint position sensors embedded in the servomotors, inertial sensors in the structure, force sensors in the feet and a vision system in the head [2].

The force sensors installed on the feet (Fig. 2) allow measuring the centre of pressure and will be latter used to provide force feedback into the haptic tele-kinesthetic interface. The humanoid platform incorporates several physical facilities that will be explored incrementally during the data gathering phase that precedes the learning stage. For example, the feet are articulated with a passive joint (Fig. 3) envisaging some kind of compliancy for walking, but for now that joint is still locked and unused.

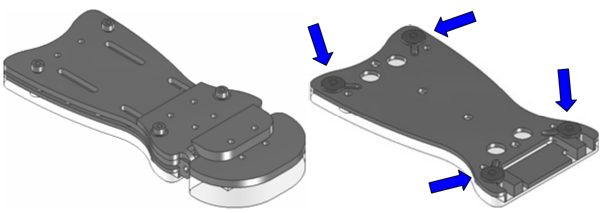

Fig. 2 - Force measurement in the feet: 4 load cells per foot allow obtaining the weight distribution and the estimation of the pressure center.

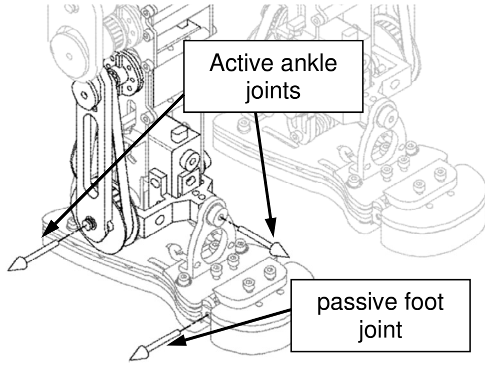

Fig. 3 - Passive and active joints on the foot.

Another example of facility usable in the experiments concerns the hybrid actuation system. Mainly to enhance the system response, and also to lessen the actuators' torque demands, flexible elastic bands were attached between several pair of consecutive links in parallel with the servomotor (Fig. 4). Despite their double usefulness, these passive actuators are very difficult to model, and that is another reason why teaching the robot simple maneuvers by human demonstrations is the option to exploit. For the experiments several sets of elastic bands are to be used in order to experimentally look for an adequate configuration.

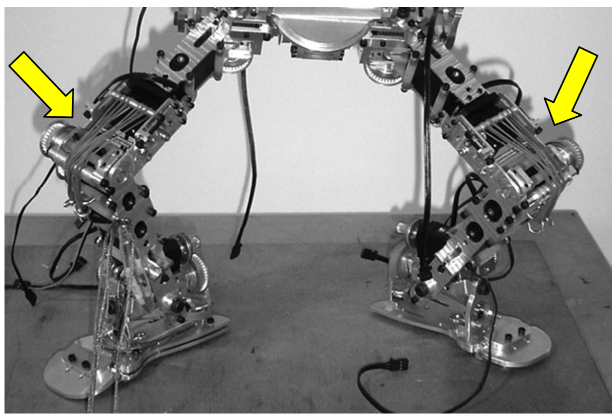

Fig. 4- Elastic bands on the legs installed in parallel with the active joints.

B. *The haptic interface*

The user performs the kinesthetic teaching by tele-operating the robot using a SensAble PHANToM haptic (OMNI model) device with 3-DOF force feedback (Fig. 5). The command of such device is achieved through a dedicated SDK supplied by SensAble™, the OpenHaptics Toolkit, on a PC running Linux. These libraries allowed for the rapid deployment of software solutions for data extraction from the device, such as position, velocity, joint values and transformation matrices. It is also possible to command force vectors to the device or create virtual objects to which the device reacts.

Fig. 5 - The haptic device is an OMNI model with 3-DOF force feedback.

III. Preliminary Results

A set of computational tools has been developed such that an operator can interactively control the arms and legs of the humanoid robot to provide functional guidance and corrections, while recording all the control and sensorial data. Once the setup is settled, the data logging is carried out and before entering complex challenges such as walking, or perhaps hopping and running, simpler tasks needed for those future challenges are tested. The combinations and variations are infinite and hopefully a proper restricted data acquisition and learning will be enough for robot generalization when operating in standalone. This section describes several experiments that have been carried out to validate our approach and the qualitative results thereof.

A. Manipulation tasks

The first set of experiments was performed with the robot's arms. On the one hand, the velocity of the tip of the haptic device is estimated and sent as the reference velocity of the arm's end-effector. The experiment was carried out for a single arm, while the opposite one mirrors the joint angles or speeds. The coordinate mapping was relative to the end-effector position, avoiding calibration issues and allowing a "frame-free" control structure. Since the workspace of the robot arm does not match the haptic device's workspace, the "sensitivity" of the manipulation was determined by a scale factor introduced into the position retrieved from the device.

On the other hand, the control law for the haptic device may incorporate different terms aiming to avoid obstacles, workspace limits or joint limits. For example, the robot system checks the reachability while being teleoperated and renders a small force vector that signals the user when the tooltip approaches the workspace limits. Further, whenever the point is unreachable, a more significant force vector attempts to drive the operator back inside the workspace, and its direction is given by the specific workspace zone it is trying to leave, so that the user is driven back to approximately the same point where control was lost. Due to the lack of pressure sensors in the arms, obstacles in the world must be virtualized in order to allow interaction.

Fig. 6 - Teleoperation of the robot arm with force feedback.

A second experiment was conducted, using the previous control method, where inexperienced operators were asked to test the system by drawing simple lines on a transparent board with a color marker attached to the arm's end-effector (Fig. 6). The board plane location was not known beforehand, therefore, the user was forced to determine it by inputting three points. This plane was then generated in the device's workspace as a planar force field. The setup was mounted facing the front of the robot and looking from down up, removing depth and position perception, so that the operators were not tempted to interact with the board plane visually, but through the haptic interface.

For the user to perceive these force fields as virtual objects, the force rendered by penetrating the field was tested using several behaviour laws, such as the one represented in Fig. 7. The goal of defining such laws is to manage the way how the rendered objects are perceived, avoiding unsafe steep increments in force magnitude that could compromise the control. As the volunteers were unaware of these details, it was possible to collect information on the usability and responsiveness of the overall system when using these laws.

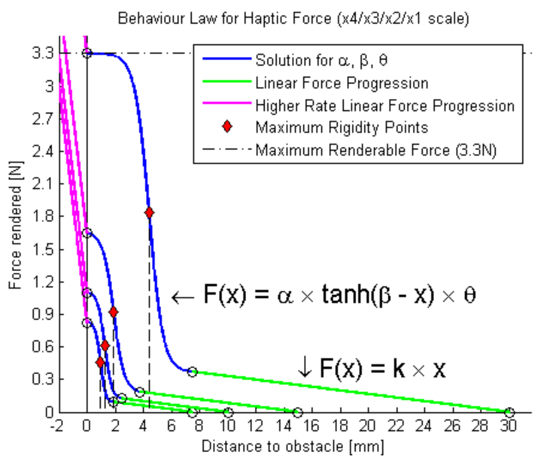

Fig. 7 - Behavior law for haptic force.

B. *Balancing on a single leg*

The next experiments show the potential of the haptic feedback when keeping the balance of a single leg. In this case, the human operator should feel the real "trouble" the robot is itself experiencing and actuate in an appropriated way. The simplest and, perhaps, the most effective way of doing this is by applying force feedback to the human operator based on the centre of pressure (COP). This force drives the operator to react in real time and, depending on his/her skills, succeed to keep the robot balanced.

The proposed challenge is applied to a single robot's leg with 3-DOF (ankle and knee), both on a flat surface and on a surface of variable slope. The COP is estimated from force sensors installed on the robot's foot and distributed by their corners. More concretely, the robot's foot is equipped with four miniature load cells able to measure loads up to 5 lbs and with the most demanding requirements in terms of sensitivity, stiffness, linearity and hysteresis. Fig. 8 depicts the temporal evolution of the force sensing in the foot extremities when the system is subject to different loads.

Several experiments have been carried out to evaluate our approach in two different scenarios (see Fig. 9): (1) the subject performs a given motion by specifying a desired hip trajectory, while experiencing how stable the system is and (2) the subject actuates the haptic device in order to balance the leg, while reacting to unpredictable changes in a slope surface. The later experiment requires a source or external perturbation, such as a manual or automated plane slight tilting and yawing. In both cases, the interaction forces are the key element to provide the reference force feedback to the haptic device.

It is worth noting that the results achieved so far are essentially qualitative. Other expressive examples will be considered, such as balancing in two legs when the ground plane varies or balancing in the one stance leg when other parts of the robot move, such as the trunk, arms of the swing leg. At the same time, quantitative data will be fruitfully combined to elucidate complementary aspects.

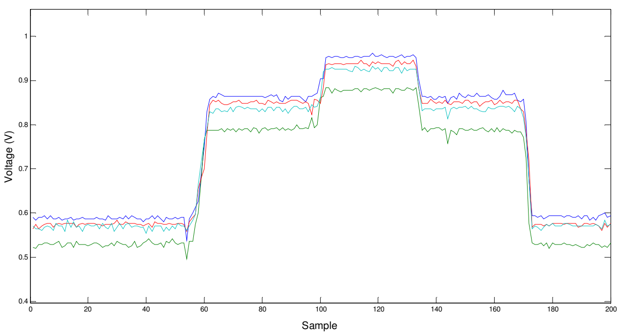

Fig. 8 - An example of the temporal evolution of the four force sensors in the foot extremities.

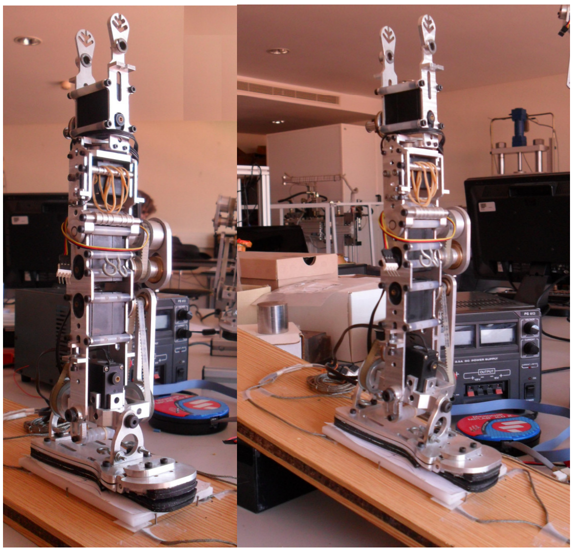

Fig. 9 - Single leg balancing on a flat surface (left) and on a surface of variable slope (right).

C. *Logging data*

During the demonstration phases, the experiment data resulting from the human-robot interaction is logged to be used later for learning purposes. The data logged includes the robot perception and the user actions duly corrected by kinematics chains translators. All this information will allow the robot to extract correlations among sensorimotor events, to learn by itself the force-control laws that govern the execution of a given task, along with the knowledge of how to select, chain and combine behaviors.

In order to support these requirements, the overall control architecture relies on a distributed network of different processor types operating at different levels in the hierarchy, ranging from small microcontrollers for joint-level control to a central processing unit for audio and visual processing (Fig. 10). The slave units, seeded all over the robot's structure, are responsible for actuator direct control, sensor reading (force, inertial, servo status) and immediate processing.

Additionally, a dual CAN bus separates control from high bandwidth sensorial data flow in order to improve the throughput of data and reliability of control. One of these buses is dedicated to high bandwidth flow of sensorial data, namely inertial, force or even others to come in the future. For example, inertial modules are installed in this CAN bus as slave inertial measurement units (IMU). The other CAN bus is dedicated to the real-time control of the system such that all directives circulate on it. This ability is also central in order to exploit the possibility of advanced processing systems such as learned-based, where the global knowledge of data generated and processed locally may serve to supervise and monitor learning procedures.

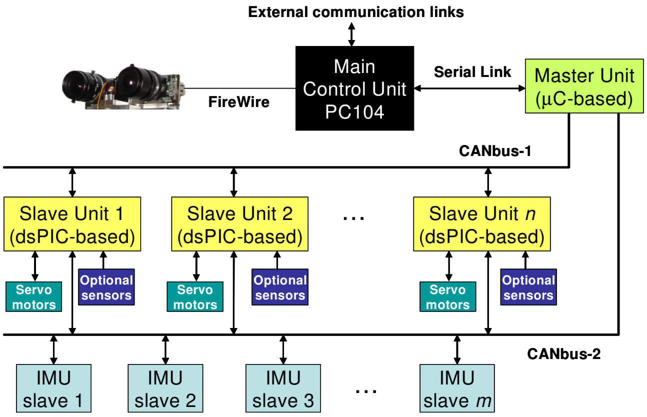

Fig. 10 - Main blocks of the distributed control architecture.

IV. Conclusions and Future Work

The approach proposed for humanoid robot control is model-free and counts on user operation by means of a haptic device. The combination of direct sensory information and implicit kinematic/dynamic limitations allows the operator to “feel” the robot perception and mould the control accordingly to perform some tasks. During the demonstration phase the experiment data is logged, including the robot perception and the user actions duly corrected by kinematics chains translators.

The preliminary results achieved so far are promising and the proposed approach seems to be practically useful for learning from demonstration. The very next future work will include phases of learning and reproduction of motor skills in similar situations. Once several simpler tasks, such as balancing and many more as described, are learned by the robot, the way to walking is open, but possibly several intermediate stages have to be introduced.

Acknowledgment

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