Architectures and models for humanoid robots in collaborative working environments

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***Abstract*— This paper presents a survey of architectures to integrate humanoid robots in collaborative working environmentse in different real situations. An extensive state of the art is described, and their limitations are addressed. A pattern of architecture is given, and a partial implementation is proposed on a HRP-2 robot. This work is motivated by an European Project called Robot@CWE exploring robot integration inside collaborative working environments.**

***Index Terms*— humanoid robotic, collaborative working environment, pattern architecture,**

I. Introduction

Humanoid robots due to their high redundancy, high number of sensors have a high versatility. For this reason they are considered as a generic robotic platform which can be used in different set-ups. They are already a number of real-life applications demonstrating this versatility: HRP-1S driving a back-hoe [1], HRP-1S performing plant maintenance using a network of RFIDs [2], HRP-2 bringing semi-autonomously a can from a fridge or grasping various objects [3], Asimo acting as a receptionist [4]. On the other hand, nowadays efficient collaborative working environments are a necessity for companies to stay competitive. For some, such as Walmart the know-how related to such applications is the main source of advantages over competitors. Integrating robots into such kind of collaborative environment is therefore a necessity and might also be a way to overcome some of the current limitations.

This paper intends to propose a survey in current humanoid architectures to highlight the current limitations in human/robot collaborative work, and their integration in nowadays Collaborative Working Environments (CWE).

II. Functional architecture

1) The scenario: A user through the Internet asks to a company for a product, or a service to be realized. The client's request is handled by the intra-network. The plan to provide the product or the service is then handled by the appropriate scheduler and send to the production unit. In this case, the production unit is the robot and the operator working together to realize the client request. To achieve this, the robot autonomously perceive the environment, localize itself, recognizes and tracks visually the objects needed for the task. The state of the human collaborator is estimated in order to synchronize with him the realization of the task. This might be achieved through various ways and considering several modalities: local force control, human posture identification through vision, sensor on the human and external sensors (motion capture, network of cameras). This is can be used for a re-synchronization on the mission planning. Once the product or the service is realized, the information is send back to the IT application. The accounting service can then generate the bill and send it to the customer. The same process can be realized when the customer is calling the support service for problems, or modification of his order.

2) The overall architecture: Figure 1 describes an overall functional architecture to achieve collaborative work with a humanoid robot. In order to achieve such scenario, usually such structure possesses 5 functional parts: 1) an autonomous one, 2) an optional remote brain, 3) an intelligence shared with other robots so called *ambient intelligence*, 4) an interaction with the other services of the information system, 5) the Internet.

Such pattern of architecture depicted in figure 1 can be found at different stages with humanoid robots such as Asimo [4][5], and HRP-2 [3][6].

III. Autonomous humanoid robot

This section describes the proposed architecture to achieve minimal autonomy for a humanoid realizing collaborative work with a human.

A. Previous work

There already exists a number of integrative architectures for humanoid robots with impressive capabilities. Namely, Inoue, Inaba, Kagami, Kuffner and Nishiwaki[7] developed such a system on top of the humanoid robot H7. Their system was already able to detect an object using a stereoscopic system [8], plan the trajectory autonomously and walk. The robot was able to knee to grasp the object and walk on stairs. The work of Okada deserves very much interest especially for a complete integration[6] which would aim at having HRP-2 acting as a kitchen maid[9]. His work is also one of the first to consider the problem of planning manipulation tasks [10] in the context of such complex real applications. For their primitive task executions they do use a task formulation approach. Recent work by Bolder et al. [11] demonstrates ASIMO walking and generating reactively full body motion towards objects tracked visually.

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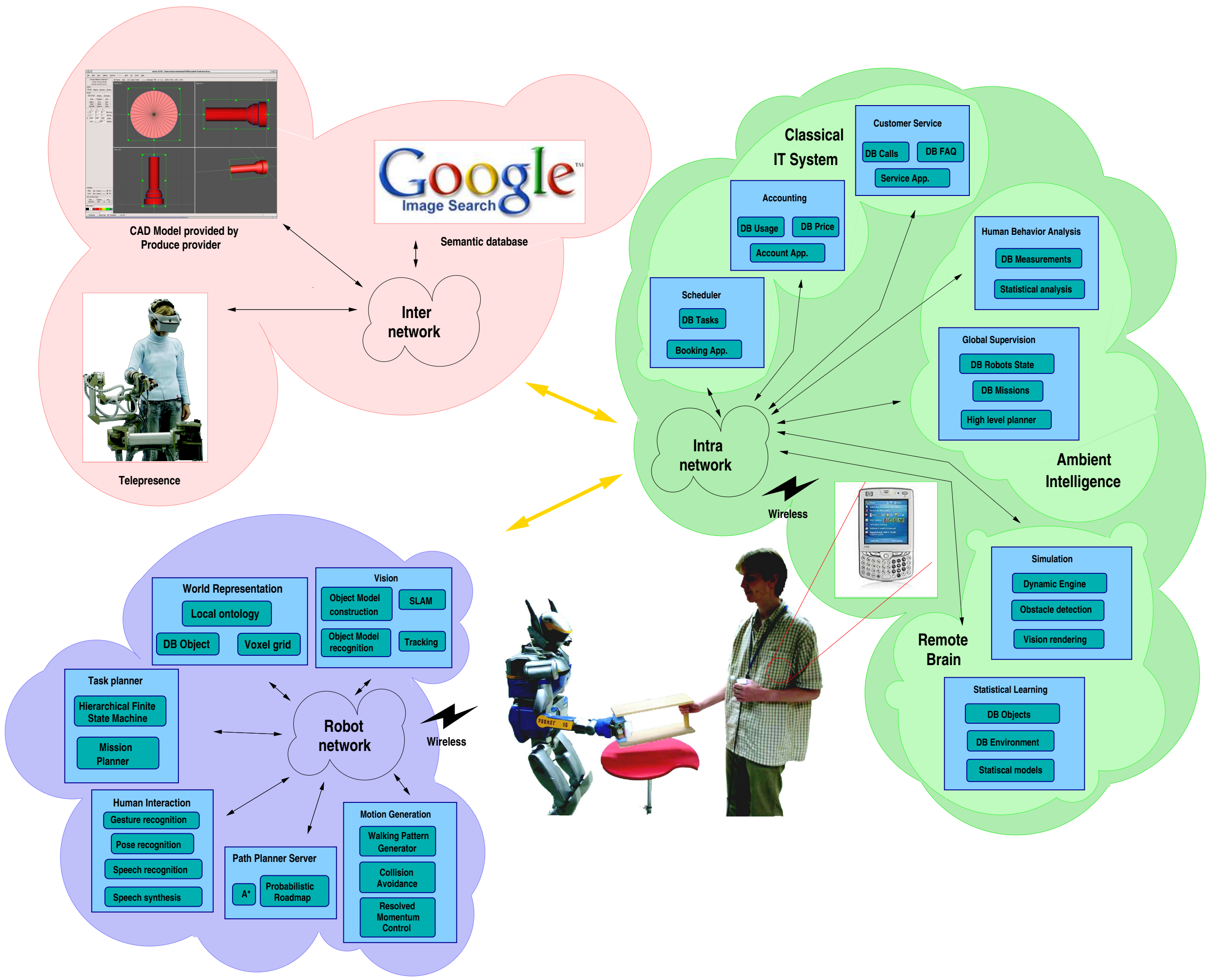

Fig. 1. A general framework to realize a collaborative task in a collaborative environment.

B. Perception

1) Range finder: Although a large number of sensors exist in the market, size constraint limit the range of sensors which can be used inside a humanoid robot. For this reason, only small-size laser can be found inside humanoids robot [12]. One of the current limitation is the fact that this sensor is limited to one scan line. They were also some work realized with the 3D time-of-flight sensor [13]. The limitation with such sensor is the noise and the sensitivity to illumination conditions.

2) Vision: In general vision stays by large a contender to provide information on the surrounding environment [14][15][16]. Visual servoing has also made possible to design robust control law for motion generation [17]. Nowadays chipsets and stereo cameras [8] can be easily integrated inside the head of humanoid robot. The known limitations of classical vision algorithms regarding the robustness under the illumination changes, and condition are slowly overcome by an increasing integration of different approaches. Therefore it is now possible to find real-time SLAM system [18]. working inside humanoid robots. Tracking or recognition of objects can be realized. The main drawback is usually the CPU consumption related to advanced robotic vision system. Even though it is often argued that the CPU speed is increasing at a very rapid pace, it is usually used to address new vision problems which take advantages of this computational power. This is especially true with the very active classification community building huge bag of features databases. However it is clear that those databases are still quite limited to the current capability of a human agent in a collaborative working environment. One way of overcome this limitation is to use cluster of PCs [19][20] usually called the remote brain as depicted at bottom right of figure 1. The very active community of human pose detection also used cameras as input, mostly because of the current cost of such sensor. For all these reasons, it is very likely that vision will still be an important source of information for humanoid robot system in the future.

3) Sound: Another important source of information and exchange with humans is speech recognition and synthesis [21]. With stereo, or an array of, microphones, it is possible to localize in 3D a sound and therefore to drive the attention of the humanoid robot. It can also be used to control the robot over the realization of a complex mission [22][21] and even to teach the robot a sequence of actions [22]. The embed-ability can be overcome by the use of FPGA board. A weak point is sometimes the sensitivity to noise which can be overwhelming in noisy or crowded environments. In such case, multi-modal techniques including vision for instance help to solve the problem [23].

4) Tactile and force sensors: Tactile sensors are very important for humanoid robots because they are the ones allowing a direct interaction with objects and humans. There are several examples of humanoids using tactile sensors specifically for the hands [24][25]. Such sensors are very important to handle properly objects, and to interact safely with humans. Two teams demonstrated humanoids with skin used for whole body motion[26], [27]. They were used to realized lifting of heavy objects [28], and to perform direct interaction with humans [27]. Indeed the use of skin might be one way to implement human-safe behaviors, as the robot will be able to sense any physical interaction with its own body. The main problem of the information of this sensor is the computational power involved by the number of sensors scattered on the body. Finally the current cost of flexible skin might slow down the wide acceptance of such sensor.

Force sensors are also very important for humanoid robots, as a large number of them following Honda's P-1 rely on force sensor to enforce the robot's stability. The main limitation of such sensors is their cost as they need to support the impact, and the weight of the robot when landing on the floor. Force sensor are also used to interact passively with humans. They have been used recently by a humanoid HRP-2 to push a table with a 50 kg load [29].

In the previous example although force is taking into account, the robot is controlled in velocity. A control scheme taking into account force, and generating torque, has been investigated by Sentis and Khatib[30], Ott at DLR [31]. with very promising theoretical and practical results. However current walking humanoid technology is in general based on DC motors and harmonic drive for embedability issues. The uses of such control frameworks involves a precise identification of the dynamical parameters. Such identification is in general very difficult and can be invalid due to the stress imposed to the motors while the robot is walking.

C. Action

1) Control: Proposed initially by Nakamura to control highly redundant robot, the stack of tasks has recently regained some interest for motion generation targeted to humanoid robot. The main interest of this formulation is that it allows to give priority to independent controllers in an elegant fashion while avoiding a complete failure of the system if some tasks are incompatible [32][30][33][34]. Its force based counterpart proposed by Khatib used with current humanoid platform such as Asimo implies to be able to convert a force to a position based controller [35]. This framework has however some defects: it cannot handle per se unilateral constraint. Such constraints are usually handled through a potential function (see [36] for joint limits, and [37] for self-collision avoidance). The problem related to the potential function is that any motion making the robot going away from the limit is projected in the null-space (orthogonal) space, and therefore is not applied. Going away from such limit is therefore usually quite slow. The other problem is the possible discontinuity of the speed when the number of constraints activated vary. The change of dimension might create discontinuities which are not welcome while interacting with humans.

2) Stability: Stability is very important for humanoid robot not to fall down. In order to have humanoid robots working and interacting with humans it is clear they have to comply with this constraint. It is true while transporting an object with a humanoid robot. The main difficulty consist in finding a criterion for which it is possible to have a real-time trajectory generation. In the past few years numerous algorithms based on the popular ZMP criteria have been proposed to solve this problem in real-time [38][39][40]. However the ZMP assumes that both feet are on a horizontal plane. Recently a new criteria has been proposed allowing to go over this limitation by taking into account multiple contacts [41][42]. This might help notably to interact more closely with the environment. But there is no algorithm yet to generate motion in real-time considering this new criteria[43]. One of the challenge regarding humanoid robotics is the recovery from a fall. Kanehiro and al. [44], [45], [46] shown that it was possible to have a full size humanoid robot to get up from the ground while lying down. However the main challenge is still the limitation of the impact when falling. If Fujiwara et al. [47] proposed some controllers in this direction, the technical solution is not totally satisfactory regarding the overall stress put on the mechanic. Either new mechanical design with compliant material should be consider, either the robot should react against disturbances. Some algorithms have been proposed to generate foot-steps maintaining the overall stability of the robot [48] under perturbation. New control scheme against strong perturbations have been investigated by Wieber [49] recently.

3) Natural interaction with user: A constraint important in the case of interaction with humans, is the necessity for the robot to perform motion which are not frightening. This aspect implies for instance to plan motion taking into account psychological constraints. This approach has been investigated in the frame of the Cogniron European Project [50]. When communicating with a human it is also important for a robot to reinforce multimodal communication by proper body motion [51].

D. Decision

In this paragraph decision is seen widely as to solve the problem of finding the sequence of tasks to perform in order to realize a mission. In the context of collaborative working environment, a robot can benefit from information available on the IT system. For instance, instead of trying to solve by itself the overall realization of the mission, a robot can follow the processes described in quality document, and synchronize itself with a human performing such work. The problem then amounts to the analysis of such document and its translation into an appropriate sequence of tasks for the robots. Then the robot has to plan the motion to realize.

1) Decision planning: Decision planning usually considers a set of *skills* which are acquired functionalities such as a controller with a specific set of parameters, the capability to plan a trajectory,... On the other hand a *task* is specified as a set of subgoals which are reached through primitive actions. A recurrent problem with such approach is the creation of the primitive actions from the available controllers on the robot. They are usually created in an *ad hoc* manner depending on the targeted application or the controllers. Although they are several works in trying to build those primitives automatically [52], the question of scalability to real-life applications is still open. Of particular interest in our situation is the work of Drumwright [53] with ASIMO which consider work measurement systems. Such systems are methods developed to measure the time spend into primitive occupational tasks. Drumwright's method then maps such primitives into a system called the *Task Matrix*. More recently, Neo et al. [21] proposed a behavioral system grounded in natural language instructions, allowing on-line whole body motion generation. Gravot et al. [10] proposed to mix symbolic and geometric reasoning for a HRP-2 humanoid to act as a cook. A high level planner decides of the task to realize from a recipe database and a hierarchical task description. The position failing for the environment modelling triggers a partial re-plan of the solution. This work proposes a connection with the problem of motion planning.

2) Motion planning: Motion planning is quite challenging for humanoid robot for several reasons: the high degree of freedom for humanoid robots usually implies a possible combinatorial explosion of the configuration space. Dynamic stability such as ZMP or CoP, implies to expand even more the robot state space, and the constraint to be taken into account. So far, successful approaches decouple the problem of obstacles avoidance in the environment and stability. Kuffner et al [54] proposed to generate a collision free trajectory and to adjust the time parameter to make the trajectory dynamically stable. Bourgeot et al [55] and later Chesnutt et al [56] proposed to discretize the space of feasible steps of the robot and check against collision with a set of feasible steps. Yoshida et al. [57] proposed an iterative method. Each steps starts by planning or reshaping the humanoid upper body motion, it then uses a preview control based pattern generator to obtain a dynamically stable motion. If there is no collision with a sufficient margin the trajectory is accepted, otherwise it iterates. Although not real-time, the latter method was used to plan a trajectory with the robot handling a 2m bar in a complex environment. It was recently extended to plan pivoting of large objects [58].

IV. Ambient intelligence

The aim of ambient intelligence is to provide an environment able to sense people and provide services accordingly [59]. A robot entering such environment establishes a two way relationship by providing and accessing services and information. The previously cited work [21][22] is a first step into interacting with a humanoid robot in a natural manner. A less explored research area is the interaction of humanoid robots with ambient intelligence. To the authors knowledge the first tentative along this line is the work of Sakagushi et al. [60]. It shows, from an architectural viewpoint, that for some specific behaviors such as closing the door of a fridge, it is possible to use indifferently a mobile base or a humanoid robot. From this result, the next phase is to understand how a robot is functionally equivalent to another from the ambient intelligence system viewpoint. When a humanoid robot is inside an environment, the level of ambient intelligence achievable depends upon its communication capabilities (hardware, network protocols) with the surrounding environment. When the level of compatibility is zero, the humanoid robot relies solely on its autonomous capabilities, and the basic set mentioned in section III is necessary. When the hardware and the network protocols are compatible, the interaction with the rest of the environment make necessary to match the robot's ontology and the one of the environment. There is no standard yet corresponding to this in the robotic community, but section VI indicates some solutions. The reason is that the services externalized by the humanoid robot are mostly related with its decision layer capabilities. Thus all the problems induced by the choice of primitives and their composition are present. Moreover the comprehension of the informations provided by the environment for the robot to achieve its task relies again on the agreement of common protocols. Chibani et al. [61] proposed an algorithm to semantically discover context services in order for two agents to interact with each others. Such mechanism completed with activity recognition [62] would allow a humanoid robot to perform high-level actions for a human.

V. Remote Interaction

Remote Interaction in this context embeds communication through the Internet as depicted in the left upper-part of figure 1. One of the interactions is tele-operation, which is already used to maneuver robots in far away situations such as the ISS, or in situations where human-life can be endangered. It is also a mean to overcome the current limitation of robot capabilities regarding autonomous decision making. When the robot is unable to perform a mission because he faces an unknown situation he can call a human for help. This can be especially useful for robots aimed at helping aging people, or persons with low-mobility. Tele-operating a humanoid robot while performing a collaborative work is challenging because several constraints have to be taken into account: safety of the human co-worker, stability of the robot, realization of the task, taking into account the limitation of the robot and the quality of the information involved during decision-making. Mixing autonomous behaviors based on vision and speech recognition with tele-operation, Neo [63][3] demonstrated a humanoid robot able to recognize orders, detected visually the pose of a fridge and a can, and bring back the can to the person. Based on this technology we have demonstrated in collaboration with Technical University of Munich [64] that it is possible to teleoperate the humanoid robot HRP-2 with a telepresence device providing stereoscopic visual feedback and force feedback, while performing a collaborative task with another human on a remote site located in Japan.

The other kind of remote interaction are realized through the access to remote services. Among them it is possible to download CAD models of object locally identified through RFID or bluetooth connection. The robot could also use Google Images to relate words provided by a user to visual representation [65]. This calls for protocols which are described in the new section.

VI. Integration in Collaborative Working Environment

Nowadays IT infrastructure are moving towards Service Oriented Architectures (SOA) [66] because they provide a great flexibility. This flexibility is used in conjunction with Business Process Model to model the overall production inside a company[67]. The most salient feature of this approach is to re-introduce non technical decision maker in the modeling process. Technically the ontology related to the services provided is usually defined by the protocol Web Service Description Language (WSDL). The communication protocol used to perform data-exchange and remote procedure call are XML-RPC or SOAP. Recently new protocols emerged specifically to allow devices to connect seeminglessly to such SOA environment: UPnP and Devices Profile for Web Services (DPWS). They implement a service discovery mechanism, providing standardized service classes, event notification and secure communications (for DPWS). Several EU projects proposes devices and open source implementations of this protocol [68][69]. We do think that following this standard will foster the introduction of robots in CWE, and fix some issues raised recently in the robotic community regarding software development [70].

VII. Conclusion

In this paper we proposed a pattern of architecture depicted in figure 1. For each of the sub-system we described current approaches used in human-size humanoids, and described the current technical locks. We described our current solution in trying to tackle those problems, and the future directions to put humanoid robots in Collaborative Working Environment.

This work is supported from the ROBOT@CWE EU CEC project, Contract No. 34002 under the 6th Research program `www.robot-at-cwe.eu`.

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