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Toward Autonomous, Compliant, Omnidirectional Humanoid Robots for Natural Interaction in Real-Life Settings

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Abstract

The field of robotics has made steady progress in the pursuit of bringing autonomous machines into real-life settings. Over the last 3 years, we have seen omnidirectional humanoid platforms that now bring compliance, robustness and adaptiveness to handle the unconstrained situations of the real world. However, today's contributions mostly address only a portion of the physical, cognitive or evaluative dimensions, which are all interdependent. This paper presents an overview of our attempt to integrate as a whole all three dimensions into a robot named Johnny-0. We present Johnny-0's distinct contributions in simultaneously exploiting compliance at the locomotion level, in grounding reasoning and actions through behaviors, and in considering all possible factors experimenting in the wildness of the real world.

Keywords

omnidirectionality · compliance · architecture · evaluation in the wild

1. Introduction

It is an exciting time to be involved in robotics. The dream of having autonomous machines performing useful tasks in everyday environments, as unstructured and unpredictable as they can be, has motivated many decades of research in the robotics, artificial intelligence and human-robot interaction fields. The challenge in making that dream a reality comes from the intrinsic complexities and interdependencies of the components to integrate on a robot. A mobile robot is a system with structural, locomotive, sensing, actuating, energizing and processing capabilities, which forms a constrained set of resources available to deal with the operating conditions of the environment. Such resources are exploited and coordinated based on decisional processes and higher cognitive functions, according to the intended tasks. From the more traditional robot design paradigm of stiff and rigid structures (either for robotic manipulators or mobile robots), we now see robots that show the compliance, robustness and adaptiveness required to operate in unconstrained real-life settings. Recent robots like Rollin' Justin [1], PR2 [2], MEKA compliant arms on a Segway RMP mobile base (which we will refer to as MEKA-Segway) [3, 4] and Care-O-bot [5] have elasticity and force-control capabilities in their robot manipulators, and have omnidirectional locomotion capabilities. In terms of physical capabilities, this group of robotic platforms show great potential in having what it takes to deal with natural settings. Considering that the intelligence manifested by a machine is influenced by its physical, perceptual and reasoning capabilities, advanced platforms such as the ones in this group enable robots to achieve a higher level of cognition. However, their research incentives lie in developing interesting functionalities in terms of motion (articulated torso, omnidirectional base) and interaction skills (e.g., gestures, expressions, touch, force-controlled actuators, manipulation, vision), and not in improving the cognition or artificial intelligence capabilities of robots. However, in the artificial intelligence community, there is a strong interest in going back to the root of artificial intelligence, making machines intelligent [6] and performing useful tasks in the wild, messy world [7]. And with these more advanced physical and cognitive capabilities come the additional challenges of evaluating their influences in real-life conditions, a topic of great interest to the human-robot interaction community.

Contrary to Rollin' Justin, PR2, MEKA-Segway and Care-O-bot (hereby referred to as Compliant Omnidirectional Humanoid platforms, or COH platforms), our interest initially came from cognitive considerations to gradually move to physical elements of the robot. EMIB (Emotion and Motivation for Intentional selection and configuration of Behavior-producing modules) was our first cognitive architecture used to integrate all necessary decisional capabilities of an autonomous robot [8]. It was implemented on a Pioneer 2 robot entry in the 2000 AAAI Mobile Robot Challenge. A robot had to start at the entrance of the conference site, find the registration desk, register, perform volunteer duties (e.g., guard an area) and give a presentation [9]. Our robot entry used sonars as proximity sensors, navigated in the environment by reading

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written letters and symbols using a pan-tilt-zoom (PTZ) camera, interacted with people through a touch-screen interface, displayed a graphical face to express the robot's emotional state, determined what to do next using a finite-state machine (FSM), recharged itself when needed, and generated a HTML report of its experience [10]. We then started to work on a more advanced platform that we first presented in the 2005 AAAI Mobile Robot Competition [11, 12]. Our focus was on integrating perceptual and decisional components for 1) the robust integration of different software packages and intelligent decision-making capabilities [13], 2) natural interaction modalities in open settings, 3) adaptation to environmental changes for localization, and 4) monitoring/reporting decisions made by the robot. Our robot entry, named Spartacus, integrated navigation capabilities, artificial audition and vision, task planning and scheduling, distributed decisional architecture and visualization tools for evaluation in dynamic conditions [13, 14]. Our decisional architecture evolved to become MBA, for Motivated Behavioral Architecture [11, 12]. Trials conducted at the 2005 AAAI event helped establish new requirements for providing meaningful and appropriate modalities for reporting and monitoring the robot's states and experiences. More specifically, when operating in open settings, interactions are rapid, diverse and context-related. An autonomous robot that determines by itself when and what it has to do based on a variety of modalities (time constraints, events occurring in the world, requests from users, etc.) makes it difficult to understand the robot's behavior just from external observations. Therefore, we concentrated our integration effort in 2006 to design a robot that can interact and explain, through speech and graphical displays, its decisions and its experiences as they occur (for on-line and off-line diagnostics) in open settings [15]. Our 2006 implementation showed increased reliability and capabilities of MBA. Our planner is capable of dealing with temporal constraints violation, task cancellation, unknown waypoint that would occur in real-life settings and within a computational architecture using distributed modules (compared to architectures with one centralized module for goal/task generation). Our robot was equipped with a dynamic viewer with voice and graphical interaction, contextualized based on the robot's active tasks.

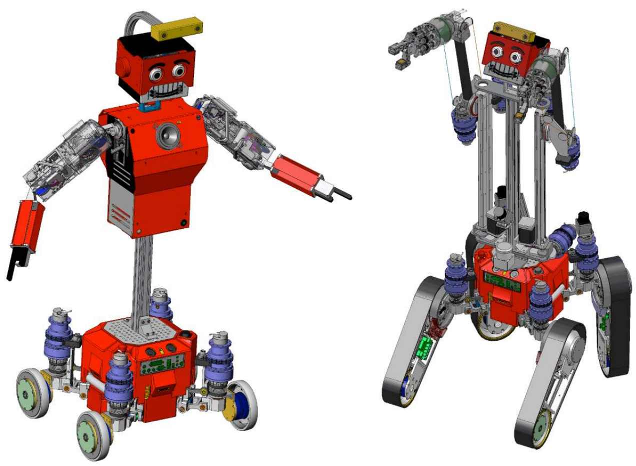

Figure 1. Johnny-0 robot platform concept.

Building from the experience gained with these trials and platforms, our current ongoing project consists of developing a compliant omnidirectional humanoid platform integrating advanced interaction and cognitive capabilities, and evaluating its performances in natural settings. The concept we came up with is illustrated in Figure 1 and is named Johnny-0. Our underlying goal with Johnny-0 is to design a platform capable of natural reciprocal interaction (motion, language, touch, affect) with humans, to address integration issues associated with advanced motion, interaction and cognition capabilities on the same platform, and their use in unconstrained real world conditions. There are many ways to address the challenges of making robots physically and cognitively fit for operating in real-life settings, and our objective with this paper is not to review them all or to debate the best ways to do so. In addition, building a robot like Johnny-0 takes years of interdisciplinary efforts, with multiple milestones. Instead of waiting to have Johnny-0 fully operational, our goal with this paper is to illustrate the distinct contributions we want to make with Johnny-0, to situate them in relation to COH, to present where we are at and where we are going. By doing so, this paper outlines key challenges and orientations for the fields of robotics, artificial intelligence and human-robot interaction. These contributions are presented in the following sections in terms of physical capabilities, cognitive capabilities, and evaluation in real world settings.

2. Physical Capabilities

The most natural way to move in the world is to be able to go in all directions without changing orientation. However, this is not a common capability on mobile robots, and often humans mimic robots by moving in saccade, rigidly and always oriented in the intended direction. Omnidirectionality brings important benefits when moving in tight areas, requiring precise positioning, or responding rapidly to events in the world. However, it also comes with more complex mechanisms and control.

Omnidirectional locomotion can be implemented on a mobile platform by using omnidirectional wheels (e.g., mecanum wheels [16] as the Segway RMP uses), or by using a mechanism to steer standard wheels (as Care-O-bot [17]). Omnidirectional wheels provide true omnidirectional motion but brings limitations in terms of precise odometry, vibration and obstacle crossing. Both Rollin' Justin and PR2 use steerable caster wheels (i.e., wheels aligned with their steer axis), with the difference that Rollin' Justin uses motors for steering the wheels while PR2 uses two-wheel differential steering.

The design specifications for this robot base are to design a leg-track-wheel omnidirectional platform for motion both in outdoor and indoor 3-dimensional spaces [18]. To achieve this specification the mobile articulation cannot be aligned with the steer axis because this limits the vertical motion of tracks. Our first prototype of such a platform, named AZIMUT [18], is symmetrical and has four independent articulated parts attached to the corners of a square chassis. Each articulated part combines a leg, a track and a wheel, and has three degrees of freedom. The leg can rotate 360 degrees vertically around its attachment point, and 180 degrees horizontally for steering. However, this first prototype used stiff transmission mechanisms, with motors and gearboxes placed directly at the attachment points of the articulations, making the platform vulnerable to shocks and surface irregularities when moving over rough terrain.

A robot's mechanical system interacts with its environment when the dynamics of the coupled system (the robot and environment in contact) differ significantly from the dynamics of the robot alone [19, 20]. Not all robots interact with their environment in this manner. For instance, the vast majority of robots used for industrial applications do not mechanically interact with their environment in any significant amount. In many cases, a limited amount of physical interaction can be tolerated without specific modeling or control. However, for complex robotic tasks (e.g., manipulation, locomotion), the lack of knowledge from precise interaction models along with the difficulties of precisely measuring tasks associated with physical quantities (e.g., position of contact points, interaction forces) in real-time, and the difficulties of conducting finite time sampling of digital control loops and also the difficulties associated with non-collocated sensors and transducers, all have negative effects on the performance and stability of robots when using simple force or simple movement controllers. For robots to take a more significant role in human life, they must safely manage intentional and unintentional physical contact with humans, even while performing high-force tasks.

With redundantly actuated robots such as AZIMUT, all articulations must be precisely coordinated to enable motion and guarantee a safe and precise motion without generating high internal forces and slippage. Also, it is necessary to provide some form of protection to the leg articulation due to shock at the tip of an articulation, creating an important force (at the articulation's attachment point. We realized to overcome these problems required the addition of compliance to the platforms locomotion modalities, to provide much needed safety for robots interacting with humans in real-life settings. This is how we got interested in using force controlled actuators, such as series elastic actuators (SEA) [21, 22] as used in MEKA compliant arms. SEA puts a low impedance element (i.e., a mechanical spring) in series with the actuator's gearbox. This provides a backdrivable actuator with intrinsic compliance. However, using SEA for the leg articulation would have made the platform too large to go through doors, because the elastic element is placed in series between the actuator and the articulation. This led us to design a new and compact high-force low-impedance rotary actuator named Differential Elastic Actuator (DEA) [23]. Compared to SEA, DEA uses a differential coupling instead of a serial coupling between a high impedance mechanical speed source and a low impedance mechanical spring. This results in a more compact and simpler solution, with similar performances. DEA are high performance actuators providing higher torque/encumbrance ratio, higher torque/weight ratio, lower rotative inertia, lower rotation velocity of the flexible element, and improved effort transmission through the motor's chassis.

Figure 2 presents the third and current version of AZIMUT, with wheels and with tracks. A passive vertical suspension mechanism (Rosta springs) is used to connect the steerable articulations to AZIMUT-3's chassis, allowing them to keep contact with the ground on uneven surfaces. The steerable wheels are equipped with a propulsion motor (Bayside K064050-3Y) and a wheel encoder (E4 from US Digital allowing a resolution of 60000 pulses per revolution), and is capable of reaching 1.47m/s. They are used directly as wheels or as the track propulsion actuator located at the tip of each leg articulation. DEAs used for steering are made of an electromagnetic brushless motor (Bayside K064050-7Y-2), a custom-designed torsion spring, a one-axis force sensor (TRT-500 load cell from Transducer Techniques) and a angle encoder (Renishaw RM44 wheel encoder with 0.2 deg resolution). DEAs used at the attachment point of leg articulations are made of electromagnetic motors (Bayside K089050-8Y-2), custom-designed torsion springs, one-axis force sensors (MLP-500-C load cell from Transducer Techniques) and a angle encoder (US Digital MAE3-P12-118-220-7 wheel encoder with 0.5 deg resolution). As a result, AZIMUT-3 now comes equipped with both horizontal suspension (passive for the wheel configuration, and active for the leg-track configuration) and an active vertical elastic element that can inherently absorb shocks and perceive the forces coming from the environment. Compared to the other COH, only Rollin' Justin comes with an active horizontal suspension.

Compliance is also a requirement for the manipulation capabilities of COH. Rollin' Justin has its manipulators controlled using force feedback [24, 25], with impressive performances but with robustness still being an issue [26]. PR2 uses a novel gravity compensation system

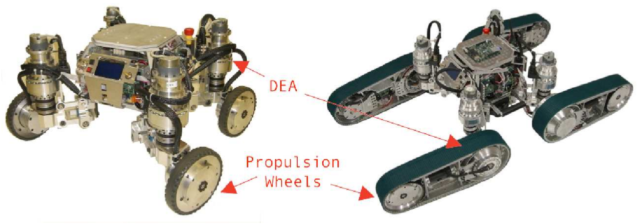

Figure 2. AZIMUT-3 in its wheeled configuration (left) and its tracked configuration (right).

and joint torque actuators [27], while the MEKA torso uses SEAs [3, 4]. Care-O-Bot has force/torque control manipulators [5]. None are capable of facial expressions. Because gesture plays an important role in natural interaction (just like vision, audition and touch), Johnny-0 integrates such capabilities with gestures made using arms, facial expression and the robot's pose (rising itself up using its tracks).

For the upper torso of Johnny-0, we decided to continue to explore the benefit of using DEAs as the actuation scheme. Two torsi are currently being developed, as shown in Figure 1: one mostly aims at simple gesture generation, interaction and manipulation of small objects of 100 g maximum, replacing the servo-motors of a Reddy platform [28, 29] shown in Figure 3 with custom-designed DEAs, while the other is made to handle more complex manipulation tasks using DEAs similar to the ones used to steer AZIMUT-3's articulations. It will have 3 degrees-of-freedom (DOF) DEA arms (left), and a 4 DOF DEA arm with a 2 DOF compliant gripper.

Figure 3. Reddy platform on top of AZIMUT-3 wheeled platform.

3. Cognitive Capabilities

Integrating compliant mechanisms on mobile platforms equipped with multiple sensing modalities (e.g., stereo vision, laser range finder) makes it now possible to demonstrate advanced manipulation (e.g., human-robot physical interaction [26] with Rollin' Justin; navigation over long periods of time with autonomous recharging [30] with PR2; door opening [3, 4] with the MEKA-Segway platform; robot walking aid [31]). The challenge then becomes to integrate these capabilities in an "intelligence" framework, combining functionalities such as goal management [32], natural language interaction [32, 33], social modeling [34], affect [35], anticipation [36], just to name a few.

We can conceptualize such integration challenges into three layers:

Low-Level. The low-level layer is responsible for sensor conditioning (e.g., encoders, torque sensors, microphones, proximity sensors, energy monitoring) and actuation control of the robot platform. These elements are mostly platform-dependent and are engineering issues that change with technological progress. What differs with COH robots is that their compliant actuators are not only controlled in position or velocity, but also in force and torque, a concept known as impedance and interaction control [20]. Interaction control involves specifying a dynamic relationship between motion and force, and implementing a control law that attempts to minimize deviation from this relationship [20]. It can be used for gravity-compensation and emulate the physical behavior of an active damper-spring system. The arm's force and endpoint impedance dynamics can be set to be comparable with the dynamics of human limbs [19]. One difference with Johnny-0 is that the use of DEAs to steer wheels or tracks that are slightly offset from the steering axis makes it possible for the mobile platform to implement impedance and interaction control at the locomotion level. For instance, this allows the robot to respond to forces and torques generated by people guiding it through direct physical interaction [37]. This however makes the platform pseudo-omnidirectional [38], i.e., it cannot instantaneously drive in any direction, and wheels must be precisely coordinated to comply with the system's kinematical nonholonomic constraints. The use of DEAs for steering comes as an advantage for redundantly actuated robots such as AZIMUT-3 because it limits having the wheels force one against each other. In addition, instead of using twist commands (linear and angular velocities) to define the velocity state of the robot's chassis, a more suitable approach is to use its instantaneous centre of rotation (ICR). Such kinematic model provides compliance to the control of the robot's nonholonomic constraints, but brings singularities in the representation framework [39]. This can be considered analogeous to the problem of obstacle avoidance and path planning of mobile robots [38], but with ICR as the representation space. Our approach consists of estimating ICR in the actuators' space instead of in the working space of the robot [40].

Software. The advanced functionalities to integrate on an autonomous intelligent robot come from a broad set of domains. Rapid and specialized progress in these domains makes integration difficult: different development platforms, design practices, communication protocols, programming preferences and methods, operating systems, industrial or field requirements, etc. The appropriate use of heterogeneous software components developed in different contexts is therefore essential for efficient scientific and incremental progress of the autonomous robotics field, avoiding reinventing what is made available by others, and focusing efforts towards new discoveries. The issues surrounding robotic software environments have been the subject of growing interest over the last decade, tackling questions like versatility, maintainability, reusability, standardization, evaluation, etc. [41]. For Johnny-0, we find that the Robot Operating System (ROS) [42] developed by Willow Garage for the PR2 as an open source library, offers very robust, modular and well-supported libraries of code, and is adopted by a large number of users. Integration of ROS to program AZIMUT-3 revealed to be straightforward and very efficient. Therefore, we are currently migrating the code developed with our own robotic software environment MARIE [13, 14, 43] in ROS. Because ROS only provides a structure communication layer on top of host operating systems in a heterogenous computing cluster [42], we are currently interfacing it with Erlang/Open Telecom Platform (OTP) [44], an open-source language and runtime environment from Ericsson. Erlang is a functional, concurrent language, and the OTP environment provides many useful features commonly associated with an operating system (concurrent processes, scheduling, memory management, distribution, networking, etc.) for highly distributed applications with many independent processes. This makes it a nice complement to ROS to implement high-level functions, and useful to orchestrate distributed computing resources with multiple independent threads.

High-Level. There are infinite number of ways to implement high-level decision-making architectures for a robot, which can be classified in four categories: deliberative ('Think, then act'), reactive ('Don't think, (re)act'), hybrid ('Think and act concurrently'), and behavior-based ('Think the way you act') [45]. All are based on important properties associated with intelligence, and finding the best way to include them all is still an open issue.

Currently, hybrid architectures and behavior-based architectures seem to offer the best potential for high-level decision-making of robots operating in unconstrained and open settings. Often referred to as three-layer architectures, a hybrid architecture consists of a reactive (execution) layer, intermediate (coordination) layer, and deliberative (organization) layer. It is organized according to the principle of increasing precision of control in the lower layers while decreasing intelligence [46]. It aims to harness the best of reactive control in the form of dynamic, concurrent and time-responsive control, and the best of deliberative control in the form of globally efficient actions over a long time-scale. However, there are complex issues involved in interfacing these fundamentally differing components and the manner in which their functionality should be partitioned is not yet well understood [47]. The construction of this coordination component is typically the greatest challenge of hybrid system design.

On the other hand, behavior-based architectures employs a set of distributed, interacting modules, called *behaviors*, that collectively achieve the desired system-level behavior. A behavior is a control module that clusters a set of constraints in order to achieve and maintain a goal [47, 48]. A behavior-based architecture is a structured network of interacting behaviors, with no centralized world representation or focus of control. Instead, individual behaviors and networks of behaviors serve as internal state representation and models. Well-designed behavior-based systems take advantage of the dynamics of interaction among the behaviors themselves, and between the behaviors and the environment. The functionality of behavior-based systems can be said to emerge from those interactions and is thus neither a property of the robot or the environment in isolation, but rather a result of the interplay between them [47]. Unlike reactive control, which utilizes collections of reactive rules with little if any state and no representation, behavior-based control uses collections of behaviors, which have no such constraints; behaviors do have state and can be used to encode time-extended processes, to construct representations and to ground reasoning, planning and learning with the operating resources of the robot. The interaction and integration of temporal and spatial effects is of key importance in behavior-based systems. Merely having only one process controlling an actuator for predetermined intervals of time, or using as many processes as there are effectors to control them, does not suffice as the basis for behavior-based control. It is the combined effect of concurrent processes over time and driven by perception and internal states that creates the relevant behavior-based dynamics in a control system [45].

COH platforms can be used to implement such architectures with sophisticated sensing modalities, perceptual capabilities, manipulation and navigation skills in a robust and safe fashion, for both the robot and the environment. To our knowledge though, none has yet been used to validate a specific high-level architecture. With Johnny-0 however, the objective is to build from our past experience with our previous high-level architectures (ISB – Intentional Selection of Behaviors [49], EMIB – Emotion, Motivation and Intentional Behaviors [8], MBA – Motivated Behavioral Architecture [11, 12, 15]) and experiment with a novel conceptual framework named HBBA – Hybrid Behavior-Based Architecture. HBBA combines both hybrid and behavior-based paradigms. Figure 4 illustrates the architecture in which behaviors are the basic control components. The Behavior Layer consists of behaviors that are activated and configured according to the intentions of the system (derived by the Motivation Layer), and selects a particular action issued by the behaviors [50]. Motivations are distributed processes, just like behaviors, manifesting desires for the accomplishment or the termination of intentions, which are associated with the activation and configuration of behaviors and with the modulation of perceptual modules. The objective is to have intentions emerge from the interaction of independent motivations, recommending the satisfaction or the inhibition of intentions, inspired from the hedonic axiom which indicates that the organisms direct their behaviors to minimise aversions and maximise desirable outcomes [51]. Desires are communicated to the Intention Workspace, which serves a role similar to a coordination layer in a hybrid architecture. Our design requirements for the Intention Workspace module is to implement generic mechanisms (i.e., mechanisms that are independent of the robot's physical capabilities and intended usage) to generate beliefs (i.e., data structures that represent desires, knowledge about the interaction dynamics of the robot and the environment), and identify conflicts between desires and their satisfaction. The Exploitation link is used to derive information about the effective use of behaviors as influenced by the events occurring in the world and the action selection mechanism. We believe that observing the exploitation of behaviors over time is a very important source of information about the emerging functionality that comes from the behaviors and the motivations, because it combines both a representation of the environment (from the behavioral percepts associated with behaviors) and of the control policy (from the internal decision-making processes).

To illustrate how HBBA will be used with Johnny-0, we plan to implement behaviors for safe navigation, recharge, social interaction (with gestures, voice and vision) and object manipulations. Action selection will be priority-based. Motivations will be implemented to provide the intrinsic modes of operation of the robot (safe navigation while exploring the world and ensuring energetic autonomy), to localize and plan paths to desired locations, to plan and schedule tasks [52], and to interact with people. The Intention Workspace will provide:

A tree representation of desires. Each desire can be associated with a particular configuration and activation of one or more behaviors. The tree representation of desires will provide a general representation of Desires' interdependencies issued by the independent motivations, from high-level/abstract desires (e.g., *Deliver message*) to primitive/behavior-related desires (e.g., *Avoid obstacles*), allowing for behavior configurations to arise in a distributed fashion based on the capabilities available to the robot. This will allow motivations to exchange information asynchronously on how to activate, configure, and monitor behaviors. For instance, one motivation may monitor the robot's energy level to issue a recharging desire, which would be associated with a *Recharge* behavior that would make the robot opportunistically detect and dock to a charging station. Meanwhile, if the robot knows where it is and can determine a path to a nearby charging station, a path

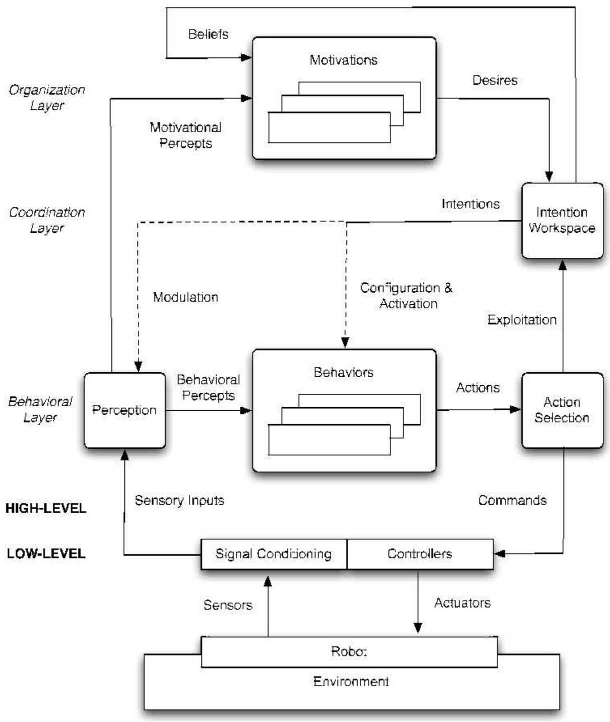

Figure 4. Hybrid Behavior-Based Architecture.

planning motivation could add a sub-desires of navigating to this position, using a *Goto* behavior. If a person is detected, a social motivation may provide an alternative desire by engaging into a conversation to ask for guidance toward the nearest charging station. The robot would then have three alternative solutions to fulfill its desire to recharge. For conflicting desires, a priority-based mechanism based on the motivations will be used, just like action selection at the behavior level.

A representation of the history of behavior exploitations, indexed by intentions. The idea here is to use behaviors as abstract interaction representations of what the robot experiences in the world, and to represent the history [53] (i.e., to explicitly take into consideration the time sequence of their exploitation. By knowing the purpose of each of the behaviors and by observing their history of use, this could provide the robot with the ability to reason and ground its intentions and desires in what it is experiencing in its operating environment. We have demonstrated such a mechanism with a robot that could learn to adapt its behavior strategy when foraging objects in non-stationary, dynamically changing conditions [54, 55]. In such settings, classifying behaviors according to their purpose also provided a way to derive self-observable metrics (as opposed to application-defined metrics), making it possible to learn from the dynamics of the robot in its operating environment. We plan to use this representation to direct or prioritize the desires generated by motivations toward the use of the most appropriate behaviors. For instance, for the recharging desire example, if being guided by people reveals not to be as reliable as using the internal map, a preference could be given to the second option.

An emotion-based mechanism to regulate conflicts between desires and intentions. Robot's adaptability in dynamic, continuous and unpredictable environments ultimately depends on the detection of the situations for which their regular decision-making process is not appropriate. Psychologists have identified that one of the functions of human emotion is to highlight these kinds of situations, allowing other cognitive processes to address them [56–58]. Therefore, we have developed an emotional process that detect such situations from the use of temporal models of intentions [59]. This process does not rely on a priori knowledge of specific environmental conditions nor of the robot's mission objectives, but only on temporal analysis of how behaviors satisfy the robot's intentions. With Johnny-0, we want to extend our emotional mechanism by adding other kind of intentions analysis such as observation of intentions resulting status, oscillations in desires (eliciting confusion) or lack of change in intentions (eliciting boredom) for example. Our long term objective is to provide situated agents with a generic self-analysis mechanism detecting situations requiring adaptation. Such mechanism is required to autonomously trigger relevant learning phases, behavioral strategy switches or modification of decisional processes needed by situations not anticipated by human designers, and therefore necessary to bring robots closer to complete autonomy.

An attention selection mechanism. Attention has been the object of studies for decades, and still remains a major research topic within education, psychology and neuroscience. Early-selection models [60] consider selection to occur before perception, while in late-selection models [61, 62] perception is completed before selection of response is done. Lavie [63, 64] adopts a hybrid view, where attention selection is modulated by the perceptual load. A heavy perceptual load will trigger early selection, which will then require less perceptual ressources. On the other hand, a light perceptual load will trigger selection of the response mechanism. With all the modalities to be integrated on Johnny-0, the robot will not be able to run all modules simultaneously at all times and provide real-time responses. Adding more computers on-board can be possible, but the robot will always be limited by size, weight and energetic capabilities of the platform. Inspired by Lavie, we are exploring the development of an attention selection mechanism that will modulate the perceptual processes based on the intentions of the robot and its available computing resources. Our goal is for these processes to have an adaptive computational load, by percepts selection or output complexity reduction. For instance, artificial audition [65, 66] can be modulated to detect sounds, localize sound sources or separate sound sources depending on the presence of people surrounding the robot and its intentions to interact. A Simultaneous Localization and Mapping (SLAM) algorithm can change resolution depending on available processing load of onboard computers. We believe that such capability is key for providing robots with versatility and flexibility to handle real-life situations.

4. Evaluation in the Wild

Nature is filled with examples of autonomous creatures capable of dealing with the diversity, unpredictability, and rapidly changing conditions of the real world. Such creatures must make decisions and take actions based on incomplete perception and knowledge about the world, with limited reasoning and physical capabilities, under time constraints, in uncontrolled conditions and with abstract cues about the intent of others. The basic challenge is to determine how to evaluate the creature's ability to make the most of what it has available to handle the complexities of the wild world.

Because of their safe, robust and more natural capabilities, COH offers great potential by putting robots out there to discover what works, what does not, and to identify what we should focus on. However, COH are mostly used in skill demonstration trials done in controlled conditions (e.g., object manipulation with Justin [25], PR2 operating in an office environment [30, 67], MEKA-Segway opening doors [4], navigation and object detection with Care-O-bot [5]). Guidelines for experimental research are gradually being put together, with ideas for benchmarking, shared data sets, shared performance metrics, standard testing grounds, and shared software and hardware platforms [68]. But this is a research topic still at its infancy, with issues regarding the experimental methodology (e.g., quantitative, qualitative, or mixed [69]) and what measure to use [70] based on the research questions addressed (e.g., feasibility, characterization, means, generalization, discrimination [71]). In addition, with the high number of capabilities integrated on COH and used in open conditions, it is difficult to assess what is going on simply by looking at the robot's behavior, or by analyzing log files off-line. Dynamic and interactive tools are required for development and evaluation of advanced robots in the real world [13, 14].

With Johnny-0, our objective is to build from these ideas and extend them from three perspectives:

- Control level of the experimental conditions. The wildness factor of experimental trials with robots can come from their autonomy (ranging from controlled or teleoperated to fixed or fully autonomous), the participants in the trials (ranging from people familiar with the robot to actor/actress playing a specific role [72] and to uninformed people) and the operating environment (ranging from lab settings and adapted spaces to natural and unconstrained settings) in which they come together [73]. All three elements influence each other and must be clearly identified to understand the context and outcome of experimental research with COH.

- Cognitive capabilities of the robot. By using ROS as a common software platform, we want to be able to evaluate various cognitive capabilities, from skills implemented on a different hardware platform to decisional architectures. This will provide a common ground to conduct comparative studies and eliminate bias that could affect such evaluations.

- Evolution of the robot over time. Following an incremental design methodology, our objective is to be able to evaluate the robot's autonomy and situate the influence of added components (whether it is from physical or cognitive improvements). Using the RoboCup@Home benchmark tests, we will evaluate Johnny-0's sustainability in realistic non-standardized home environment setting.

5. Conclusion

As said in the introduction, it is an exciting time to be involved in robotics, the reason being that there are now robotic platforms that can aspire to be fully autonomous and operate in real-life settings.

It is also an exciting time because while many pieces of the puzzle are now available, we still need to conceive ways in which to combine them together. Many ways can be imagined to solve this puzzle, and none can be considered invalid at this point. The design of advanced COH robots is still in a basic research phase [71] of investigating ideas and concepts, putting initial structure on problems and framing critical research questions. Progress is accomplished through multiple iterations of increasing complexity, identifying new challenges and research issues as we move through these iterations. Inspiration can come from many disciplines or be derived from nature, from the physical to the cognitive capabilities and from the evaluation of robots in natural settings.

By describing our approach in building Johnny-0 and situating its contributions in relation to other COH platforms, the main objective of this paper is to illustrate the importance of addressing as a whole the physical, cognitive and evaluative dimensions when designing an autonomous mobile robot for real world settings. Even though a lot still remains to be done for Johnny-0 to be fully operational and running, we believe that there is value from knowing what is currently being integrated and how this integration is addressed. COH probably covers the most complete set of issues related to autonomous and interactive mobile robots, with system integration playing a fundamental role at all levels. Solving all of the issues outlined in this paper requires interdisciplinary and collaborative work in our attempts, as a community, to significantly accelerate scientific progress of the field.

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