Modularity and Integration in the Design of a Socially Interactive Robot

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***Abstract*— Designing robots that are capable of interacting with humans in real life settings is a challenging task. One key issue is the integration of multiple modalities (e.g., mobility, physical structure, navigation, vision, audition, dialogue, reasoning) into a coherent framework. Taking the AAAI Mobile Robot Challenge (making a robot attend the National conference on Artificial Intelligence) as the experimental context, we are currently addressing hardware, software and computation integration issues involved in designing a robot capable of sophisticated interaction with humans. This paper reports on our design solutions and the current status of the work, along with the potential impacts this design will have on human-robot interaction research.**

***Index Terms*— Socially interactive mobile robot, Embodied interaction and communication, Multi-modal communication.**

I. INTRODUCTION

The field of mobile robotics has come a long way since the first implementation made in the late 1940s. Mobile robot design requires the integration of multiple areas of expertise such as mechatronics, energy, sensors, actuators, processing and computing, just to name a few. The design challenge is even harder for mobile robots that must possess the ability to deal with the diversity, dynamics and unpredictability of the real world, compared to robots that operate in environments that are engineered, contained and controlled, such as industrial plants. A great number and variety of autonomous mobile robots have been developed, experimented with, refined and improved over the years, addressing different levels of integration required in designing a robot capable of interacting with people[1].

The AAAI Mobile Robot Challenge (or simply the AAAI Challenge) is a great environment for working toward human-like social interaction of autonomous mobile robots operating in real life settings. Introduced in 1999, the AAAI Challenge consists of having a robot 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 [2]. The long-term objective is to have robots participate just like humans attending the conference.

We became interested in taking on this challenge by adopting a holistic approach, i.e., by addressing all design dimensions for such a robot. In this paper, we describe the mobile robotic platform designed, its software capabilities and the tools we utilized in the design. Also discussed is the computational framework integrating the decision-making processes required for autonomous and open interactions with people in public settings.

II. ROBOTIC PLATFORM FOR SOCIAL INTERACTION

To attract people to the university stand during exhibits, our public relation office wanted a tall, visible mobile robot that would help attract people to the university's stand at various exhibitions. They requested that the robot should be able to interact with people, and get these people to engage in discussions with university representatives about programs at the Université de Sherbrooke. Such robot would have to operate in unknown and crowded environments. Contrary to the Mobots initiative [3] or RoboX [4], [5], autonomous navigation, sophisticated manipulations or information providing aspects were not of prime importance: the focus was placed on ways to get the attention of the public. After conducting a detailed analysis of the requirements and discussing with the public relation office representatives, our engineering team organized collaborations with other students on campus. These collaborations provided ways to showcase varying areas of expertise developed through the university's curricula. As a result, the wheeled robotic platform designed, named U2S, has the following characteristics:

- U2S has a humanoid shape. Its face is capable of basic expression by way of its mouth and eyes, which are made up using LEDs matrix. The initial sketch of the robot was made by an art student. Robot locomotion is achieved using differential steering.
- The robot has the ability to play audio tracks, using an audio amplifier and speakers. Music was composed by a student from the Faculty of Music. Voice-generated messages were composed by a student from the Department of Redaction, Communication and Multimedia.
- Visual messages are possible using a LEDs electronic panel installed on the robot's back.
- A graphical touchscreen interface is on the front of the robot. Originally a PDA was used, but turned out to be too small. The interaction scenarios for the menus shown on the PDA were developed by a student in Marketing.

Fig. 1. U2S, the robot-ambassador of the Université de Sherbrooke, front view (left), back view (center) and Spartacus, the AAAI version (right).

- Since the university representatives usually gave out business cards with the universitys website address, a simple automatic card dispenser was installed on the robot.
- Whilst still being able to function (without mobility), U2S can simply be charged by plugging the robot into an electric outlet.
- For control and communication, U2S has a wireless remote control and a short range radio system which enables an operator to talk to people and control the robot's movements from a remote distance. In consideration of naive users, all functionality needed to be simple and easy to use.

The robot built is shown in Figure 1. To facilitate the design and integration of all the required components, our design follows a distributed approach. Different subsystems communicate with each other to exchange information and coordinate their actions [6]. Each subsystem has its own microcontroller, selected according to the processing requirements for the given subsystem. A Control Area Network (CAN 2.0B) 1 Mbps bus is used for communication between the subsystems. Adopting a modular hardware/software design approach facilitates the design of subsystems by allowing the reuse of microcontroller boards and programs. It also facilitates debugging and subsequent designs and extensions of the platform. The robot has been in operation since October 2002 and is used almost every week from October to May every year in a wide variety of promotional and educational events.

This robotic base demonstrated that it can catch people's attention and serve as a great marketing tool just by being remotely controlled. However, it does require additional sensors and increased on-board processing to conduct the autonomous interactions necessary for the AAAI Challenge. As shown on the right in Figure 1, we have upgraded U2S to a new platform named Spartacus. This robot is equipped with a SICK LMS200 laser range finder (for autonomous navigation), Sony SNC-RZ30N 25X pan-tilt-zoom color camera and an array of eight microphones placed in the robot's body. High level processing is done using an embedded Mini-ITX computer (Pentium M 1.7 GHz). The Mini-ITX computer is connected to the low-level controllers through a CAN bus device, the laser range finder through a serial port, the camera through a 100Mbps Ethernet link and the audio amplifier and speakers using the audio output port. A laptop computer (Pentium M 1.6 GHz) is also installed on the platform and is equipped with a RME Hammerfal DSP Multiface sound card using eight analog inputs to simultaneously sample signals coming from the microphone array. Communication between the two on-board computers is accomplished with a 100Mbps Ethernet link. Communication with external computers can be accomplished using the 802.11g wireless technology, giving the ability to easily add remote processing power or capabilities if required.

III. SOFTWARE CAPABILITIES FOR SOCIAL INTERACTION

Numerous algorithms are required to create a sophisticated socially interactive mobile robot. In the context of the AAAI Challenge, here are some examples that we want to use with Spartacus:

- **Navigation**. When placed at the entrance of the convention center, the robot must find its way autonomously to the registration desk. Therefore, it must be able to avoid obstacles, search for information regarding the location of the registration desk and potentially follow people moving in this direction. Once registered, the robot can use a map of the convention center.
- **Vision Processing**. Being able to extract useful information in real time from images taken by the onboard camera improves interaction with people and the environment. For instance, the robot would benefit from reading various written messages in real life settings, messages that can provide localization information (e.g., room numbers, places) or identity information (e.g., reading name badges). Object recognition and tracking algorithms also makes it possible for the robot to interact with moving objects or people in the environment.
- **Sound Processing**. Auditory capabilities provide important information about the world, such as the localization of sound sources. To do so, simply using one or two omnidirectional microphones on a robot is not enough: it proves too difficult to filter out all of the noise generated in public places. Using a microphone array is a better solution for the localization, tracking and separation of sound sources.
- **Touchscreen Display**. Various information can be communicated through such device, such as: receiving information from people using a menu interface; displaying graphical information such as a PowerPoint presentation; expressing emotional states using a virtual face.

To facilitate sharing of programs, such as those above, without the need to reprogram them or to develop specific software interfaces for different programming environments, we initiated the development of MARIE (Mobile and Autonomous Robot Integrated Environment). MARIE is a middleware programming environment allowing multiple applications, operating on one or multiple machines/OS, to work together in an implementation of mobile robotic nature. This environment provides a software architecture that eliminates the need to choose specific programming tools. It also makes it possible to share code and applications. MARIE currently links Player/Stage/Gazebo [7], CARMEN [8] and RobotFlow/FlowDesigner, a modular data-flow programming environment that facilitates visualization and understanding of what is really happening in the robot's control loops, sensors, actuators [9]. The use of MARIE simplifies the extension of Spartacus' interaction capabilities.

IV. MOTIVATED BEHAVIORAL ARCHITECTURE (MBA)

The various processing capabilities required by a sophisticated interactive robot are themselves extremely complex. This is further complicated when they are integrated into an integrated framework for autonomous decision-making. The computational architecture we are currently developing is based on the notion of motivated selection of behavior-producing modules (BPM, or behaviors). The architecture contains different motivational sources derived from perceptual influences, pre-determined scenarios, navigation algorithms, a planning algorithm or other types of reasoning algorithms. One reason for distinguishing these influences through different motivational sources is to simplify programming of the robot's intentions in accomplishing various tasks.

Figure 2 represents the Motivated Behavioral Architecture (MBA). It is composed of three principal elements. BPM are its basic components: they define how particular percepts and conditions influences the control of the robot's actuators. Motivational sources (or Motivations) recommend the use or the inhibition of tasks to be accomplished by the robot. To facilitate addition of new capabilities and independence from the robotic platform, motivations are kept as generic and independent from each other and from the BPM as much as possible, through the use of tasks. This is done by the Dynamic Task Workspace (DTW) and System Know How (SNOW) modules. The DTW organizes tasks in a hierarchy using a tree-like structure, from high-level/abstract tasks (e.g., deliver message), to primitive/BPM-related tasks (e.g., avoid obstacles). Through DTW, motivations share knowledge about how to activate, configure and monitor BPM (which can be typical behavior-based reactive controllers with or without internal states, goal-oriented behaviors or other types of behaviors). Motivations can add and modify tasks (by submitting modification requests *m*), request information about them (*q*) or subscribe to events (*e*) regarding the task's status. The SNOW module defines, communicates tasks parameters (*p*) and behaviors results (*res*) between BPM and DTW.

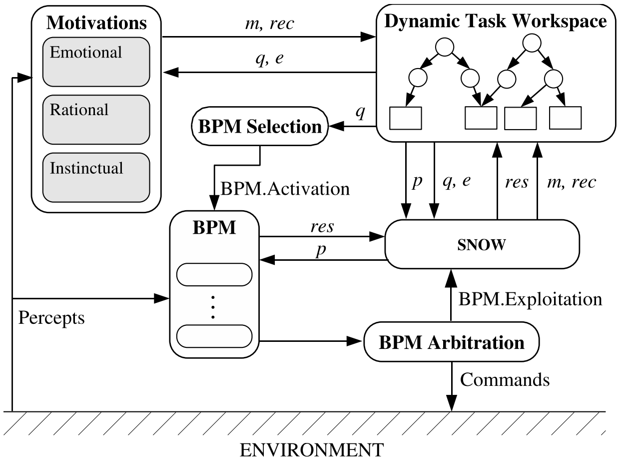

Fig. 2. MBA architectural methodology.

Motivational sources are categorized as either instinctual, rational or emotional. Instinctual motivations provide basic operation of the robot using simple rules. Rational motivations are more related to cognitive processes, such as navigation and planning. Emotional motivations monitor conflictual or transitional situations in the DTW, as for changes in commitments the robot establishes with other agents, humans or robots, in its environment. Motivations can be derived from percepts, from results and states of current goals, and from monitoring tasks. One additional source of information for motivations is the observation of the effective use of the behaviors, represented by the link BPM.Exploitation. Such information can serve as an abstraction of the robot's interactions within the environment. An active behavior may or may not be used to control the robot, depending on to the sensory conditions it monitors and the arbitration mechanism used to coordinate the robot's behaviors. So, an active behavior is exploited only when it provides commands that actually control the robot. All the MBA's modules run concurrently to derive goals and expressing behavior recommendations.

The actual use of a BPM is determined by the arbitration scheme and the BPM's activation conditions, as derived by the BPM Selection module. BPM Arbitration may be priority-based, fusion (e.g., motor-schemas), action selection or defuzzification, depending on the implementation. The BPM Selection module determines which BPM are to be activated according to recommendations (*rec*) made by motivational sources concerning tasks. Recommendation can either be negative, neutral or positive, or take on real values within this range regarding the desirability of the robot to accomplish specific tasks by activating particular BPM. The activation values (BPM.Activation) reflect the robot's intentions derived from interactions between the motivational sources.

V. RESULTS

Our first implementation of the MBA architecture, designed to have Spartacus participate in the 2005 AAAI Challenge, is shown in Figure 3. The five BPM used are as follows: Move, generating a constant forward velocity; Rest, stopping the robot; Goto, allowing the robot to move to a specific location; Avoid, making the robot move safely in the environment; Localize, determining the robot position on a given map according to laser and odometry data. This last BPM does not give direct commands to the robot's actuators; it provides information to other BPM or motivational modules through the

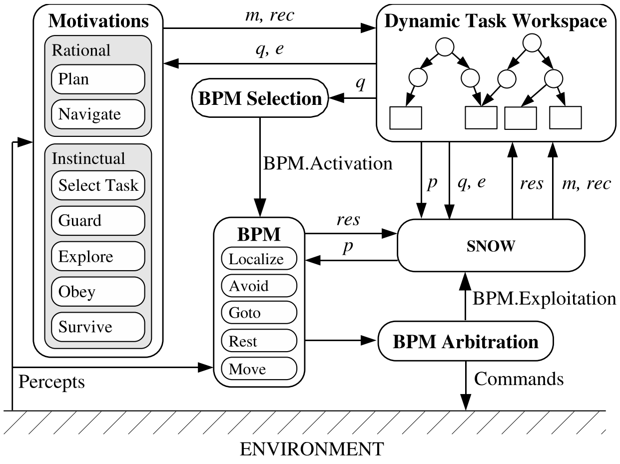

Fig. 3. MBA architectural methodology for our first prototype.

SNOW and DTW, only when a motivational source consider this capability appropriate (e.g., when sufficient processing power is available). Subsumption is used for BPM Arbitration.

In this implementation, only instinctual and rational motivations have been implemented, with rational motivations having a greater priority in case of conflicts with other ones. For instinctual motivations, Survive urges the robot to maintain its physical integrity by recommending to avoid obstacles. Obey is a process allowing the execution of user's requests for tasks. Explore motivates the robot to discover its environment. Guard makes the robot stay in position and guard an area. Select Task selects one high level task when none has yet been prioritized: for instance, between tasks that require the robot to go to a specific location, this motivation selects the task where the location is physically closest to the robot. The other two modules are for rational motivations. Navigate determines the path to go to a specific location, as required for tasks in the DTW. Plan is where a planner can influence the decisions of the robot. In MBA, the role of the planner is to provide the robot with the capability of determining which primitive tasks and which sequence of these tasks are necessary to accomplish high-level tasks under temporal constraints and limited capabilities (as defined by the set of BPM). Since we actually use a planner like a black box, our MBA architecture supports several planners. These planners are SAPA [10], LPG [11] and TLPlan [12]. Our first implementation is a simple reactive planning module that interleaves planning and executing like [13] and [14].

For the first implementation phase, our objective is to validate MBA's working principles in a complete working system. The second phase consists of integrating specific interaction capabilities that we want to demonstrate with our 2005 entry, as listed below:

- **Navigation**. Two navigation tools, CARMEN and pmap, can be used on our robotic platform. CARMEN, the Carnegie Mellon navigation toolkit [8], is a software package for laser-based autonomous navigation using a map previously generated. To generate the map, laser range data must be taken as the robot is exploring an area (whilst being controlled), and this data is then analyzed off-line using a mapping algorithm. Also, manual corrections to the map may sometimes be required to ensure safe navigation of the robot. The pmap package[1] provides a number of libraries and utilities for laser-based mapping (SLAM) in 2D environments, designed to work together to produce high-quality occupancy grid maps. These libraries are now made available through MARIE, allowing for instance production of a map that can be used by CARMEN for autonomous navigation.
- **Vision Processing.** We recently developed an algorithm that can extract symbols and text from a single color image in real world conditions [15]. The algorithm has been trained to recognize Arial fonts with characters having a minimum height of 40 pixels. The zoom capability of the camera allows the camera to 'zoom in' on the regions containing text and to adjust the image resolution so that it can successfully recognize each character. Using a 12X optical zoom camera, the system is able to read printed text on 8.5"x 11" sheet of paper with font size 128 at a maximum distance of 4.5 meters. With the 25X optical zoom camera installed on Spartacus, we expect to read such text at distances as far as 10 meters. For conference name tags using smaller font size (12-18), recognition is possible at a maximum distance of 30 cm with a 12X optical zoom, and at 2.5 meters with the 25X zoom. Since people interacting with Spartacus will likely be at a distance of about 1 meter from the camera, the robot should be able to read their name tag.
  We also plan to use an object recognition algorithm [16] that can identity regions of interest in the image such as human faces and silhouettes. Once identified, these regions can be tracked using color information, as it was achieved in [17]. Combining object recognition and tracking algorithms can reduce the processing required when detecting regions of interest. Also while tracking a region, it is possible to adapt the region models to the current observed conditions in a dynamic environment. Thus, a person can be identified when facing the camera by the recognition algorithm. Once this is achieved, the tracking algorithm would attempt to maintain an appropriate color model of the person. This will enable the algorithm to keep track of the person, even if the face changes direction or the lighting conditions change.
- **Sound Processing.** Spartacus' artificial audition system uses an array of eight microphones. Our approach is capable of simultaneously localizing and tracking as up to four sound sources that are in motion over a 7 m range, in the presence of noise and reverberation [18]. We have also developed a method to separate in real time the sound sources [19] in order to process communicated information from different interlocutors using software

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[1] http://robotics.usc.edu/ ahoward/pmap/

packages such as NUANCE[2]. We tested NUANCE with data generated by our system using speech utterances (i.e., four connected digits) simultaneously made by three separate speakers. Preliminary recognition performance observed with NUANCE is 71%, while human performance in the same condition is around 42%. However, human performance reaches 97% from the sound sources separated by our system. We are continuing to investigate NUANCE's configuration to improve recognition performance.

VI. RELATED WORK

Our first attempt to completing the entire AAAI Challenge was in 2000. Our entry, a Pioneer 2 robot named Lolitta, had the following characteristics: used sonars as proximity sensors; navigated in the environment by reading written letters and symbols, interacted with people through a touch-screen interface, displayed a graphical face to express the emotional state of the robot, determined what to do next using a finite-state machine, recharged itself when needed, and generated a HTML report of the robot's experience [20]. EMIB (Emotion and Motivation for Intentional selection and configuration of Behavior-producing modules) was the architectural methodology used in this implementation [21]. Similarly to MBA, EMIB is based on intentional selection and configuration of BPM according to the robot's intentions. These intentions are influenced by the situation perceived, the need to accomplish specific goals over time, and knowledge innate or acquired about the world. Motivational and emotional variables are used to monitor the goals and the overall states of the system. MBA is a generalization of EMIB in which motivational sources are grouped and exchange information asynchronously through the DTW. The SNOW module, not present in EMIB, separates task representation from BPM. This adds flexibility in allowing a particular robotic implementation to have different methods for accomplishing a task. Motivations can thus use the same task vocabulary for different robotic system. Such an approach shows similarities with a blackboard architecture [22]. This is evident as independent motivational modules cooperate through a shared data structure (i.e., the DTW) to process data and determine BPM activation and configuration. However, in MBA no control shell directing the problem-solving processes is present. Compared to Lolitta, the additions made to Spartacus provide a more flexible environment allowing the expansion and integration of further capabilities over time.

There has been two other autonomous robotic entries attempting to complete the AAAI Challenge: Lewis and Grace. Lewis [23] is a B21 robot platform equipped with a pan-tilt-zoom color camera and a laser range finder. As with Lolitta, Lewis was able to recognize symbols (arrows) enabling navigation in the world, interacted with people using a touch screen interface, and used a finite-state machine to go through the different steps of the challenge. Its novel feature was its framing algorithm, allowing it to take pictures of people in open settings [24]. Grace [25] is also a B21 robot base equipped with a 15 inches display (showing a virtual face), a laser range finder, a pan-tilt-zoom color camera, a pan-tilt stereo vision head and one wireless microphone. Instead of using symbols, directions to reach the registration desk were provided by an operator using vocal commands. Speech recognition however appeared to be difficult because of background noise. The registration desk was detected by localizing a big pink poster board. Grace used its laser range finder to detect the waiting line for registration. Once at the registration desk, Grace interacted vocally with conference personnel to register. Autonomous navigation was then possible using the laser and a pre-generated map. Grace navigated to the presentation area to conduct its two-minutes presentation. One of the biggest challenges faced by the Grace design team was the integration of the different computational modules, which were manually initiated at the appropriate time during the different steps of the challenge. No global architectural methodology was used.

Finally, one other related work is HERMES [26]. Like Spartacus, it is a directional steered wheeled platform with a humanoid shape. This base has two manipulator arms, features that Spartacus does not have. HERMES combines visual, kinesthetic, tactile and auditory sensing with natural spoken language (input via voice, keyboard or e-mail). Robot control is achieved using a situation-oriented skill- and behavior-based paradigm, with a central situation recognition module. HERMES faces similar integration challenges to those faced in our work. However, HERMES' work concentrates more on situation-dependent natural language communication and kinesthetic sense. Our focus is on enhanced artificial audition, different interaction modalities using vision and graphical displays, all integrated into a common architectural methodology involving autonomous, high-level reasoning (such as planning).

VII. IMPACTS AND CONCLUSION

This paper outlines the integration challenges in designing an autonomous, socially interactive mobile robot. Work is still in progress for completing the design, but already important benefits are observed. For instance, working with an integrated programming environment such as MARIE allows us to focus on the decision-making issues rather than on software programming considerations. Along with the MBA architecture and the Spartacus robotic platform, MARIE provides a common framework to test and to compare different algorithms such as navigation tools and planning algorithms.

Overall, designing a mobile robot that must operate in public environments probably addresses the most complete set of issues related to interactive systems. The process becomes complex and takes time, with system integration playing a fundamental role at all levels. It also opens up the challenge of evaluating visual, auditive and graphical interfaces in creating sophisticated human-robot interaction. Combining a variety of capabilities increases the complexity and diversity of interaction the robot robot can have. This in turn leads to greater complexity and diversity of analyzing and understanding such

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[2] http://www.nuance.com/

increased capabilities which leads us to the rich field of interaction studies. Here are two potential issues that can be addressed by making use of Spartacus integrated capabilities:

- How should we evaluate the impacts of interacting with mobile robots in open environments? People generally interact with a robot like Spartacus with some prior knowledge about robots and devices, but not necessarily from previous encounters with robots. What can be expected from these interactions? Interactions happen in a relatively brief amount of time, in uncontrolled conditions. What are the factors to analyze in order to characterize the interactions?
- What are the necessary components to create appealing and appropriate interactions with people? What makes a robot a credible actor in the world? Must the robot have a face, visual and auditory capabilities, or be capable of explicitly expressing emotions? Is it necessary to have machines that interact in human-like fashion, or should they be made to deliver the intended messages as efficiently as possible?

We believe that these interesting questions will have to be answered through long-term, comparative studies using devices such as Spartacus that can be easily modified according to the research issue addressed. Interaction study is a complex area of research with a great variety of experimental methodologies, both quantitative and qualitative. As roboticists we have begun to have some intuitive answers to these questions. However, they can only be truly answered by having specialists study them with appropriate scientific methodologies, following a framework with incremental levels of sophistication for the robot's interactive capabilities. We believe that the AAAI Challenge could become a nice venue to conduct such studies.

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