■ Sorry to Interrupt, But May I Have Your Attention? Preliminary Design and Evaluation of Autonomous Engagement in HRI

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The design and the evaluation of an autonomous interactive robot is a challenging research endeavor because there is as much to learn from the interaction between the integrated technologies as there is from the embodied human-robot interaction, in addition to observing their mutual interdependencies. This paper reports on IRL-0, a prototyping platform that we used to conduct preliminary studies on the influences of combining verbal and nonverbal modalities (facial expressions, head movement, arm gestures, and approach trajectory) for engaging interaction with people in controlled conditions and in real-world settings. IRL-0 is made of a compliant omnidirectional mobile base equipped with an expressive face and a three degrees-of-freedom (DOFs) compliant arm. By assembling this prototype and conducting these preliminary studies, our objective is to acquire insights in terms of design (e.g., technology, control) and experimental procedures that are important to take into consideration for the designing and evaluating autonomous robots engaging interaction with people.

Keywords: Autonomous interaction, Engagement, Facial expression and Head movement, Arm gestures, Mobility, Integrated design and evaluation methodology

1. Introduction

Having a robot autonomously engage interaction with someone involves the integration of multiple modalities such as voice, gesture, and motion. The influences of such integration are commonly seen in human-human interaction. Let us take, for instance, the case of a group of cub scouts selling calendars in a mall during a fundraising activity: it can be observed that the kids who are more expressive and move toward people are more successful in engaging interaction, compared to the ones that remain behind a counter or stand still and seek interest just through vocal requests.

The design and the evaluation of interactive platforms are usually independently conducted research activities, but they also mutually influence each other: the interaction modalities implemented on a platform influence how people respond, and how people interact with an autonomous robot

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may justify specific design requirements for interaction. Recent robots like Rollin' Justin (Borst et al., 2009), PR2 (Wyrobek, Berger, der Loos Van, & Salisbury, 2008), Cody (Chen & Kemp, 2011) and Care-O-bot (Graf, Parlitz, & Hagele, 2009) bring advanced and secure interaction capabilities by providing elasticity in the robots' manipulators and through omnidirectional mobility. However, their design was not specifically influenced by the tight coupling of interaction modalities for engaging people. Our research laboratory is currently leading a five-year research initiative involving the design and the evaluation of the autonomous platform, IRL-1 (Ferland et al., 2012) (formerly known as Johnny-0 (Michaud, Ferland, Létourneau, Legault, & Lauria, 2010)). IRL-1 is a humanoid mobile platform capable of bidirectional interaction with humans in natural ways using motion, language, touch, and affect. It integrates new technologies developed specifically for natural interaction, such as Differential Elastic Actuators (DEAs) (Lauria, Legault, Lavoie, & Michaud, 2008; Lauria, Michaud, et al., 2008) for safe and compliant actuation at the omnidirectional locomotion and manipulation levels, and artificial audition with sound source localization, tracking, and separation (Valin, Michaud, & Rouat, 2007). One situation that we expect IRL-1 to experience is the necessity to engage someone, whether it is for assistance (e.g., for recharging, grabbing an object out of its reach, or acquiring information) or to fulfill a specific task (e.g., for handing objects or directing people to do specific actions). This involves verbal and nonverbal interaction modalities (eye gaze, facial expression, arm gestures, and mobility) tightly coupled with the physical, perceptual, computational, cognitive, energy, and acting capabilities of the robot, allowing it to adapt to the unpredictability of interacting with humans in real-world settings. IRL-1's targeted contributions are in simultaneously exploiting compliance for omnidirectional locomotion and manipulation, grounding reasoning and actions through behavior-producing modules and collectively considering all possible factors experienced 'in the wildness' of the real world (Michaud, Ferland, et al., 2010).

To deal with the complexities of designing an autonomous interactive robot like IRL-1, we adopted an incremental design approach in which we first implemented proof-of-concept prototypes of the robot's subsystems, i.e.: a) an omnidirectional and compliant locomotion platform (Ferland et al., 2010); b) an interactive arm using DEAs (Legault et al., 2008); c) an expressive face (Shayganfar, Rich, & Sidner, 2012); and d) a robot control architecture (Michaud, Ferland, et al., 2010). This allowed us to demonstrate and to characterize the capabilities of each subsystem. We then decided to conduct a preliminary integration using the available proof-of-concept prototypes to create IRL-0 for the following reasons:

- Integration of designed interaction modalities is a key challenge in making an autonomous interactive robot; and
- Human-robot interaction (HRI) brings additional dimensions (e.g., technological capabilities, dynamics of the interaction, environmental constraints, etc.) that can only be observed by having the robot operate in the intended conditions.

IRL-0 was therefore made to conduct preliminary HRI system studies exploring the influences of nonverbal modalities in making an autonomous robot engage people's attention and interaction. Many useful observations can be made by conducting such preliminary studies with working systems in realistic conditions, as we had noted in our earlier works on child-robot interaction (Michaud et al., 2005; Salter, Michaud, & Larouche, 2010) and homecare teleassistive mobile robot interaction (Labonté et al., 2006; Michaud, Boissy, et al., 2010). Similarly, Satake et al. (2009) implemented an invitation service interaction scenario in which the robot offered shopping information and invited people to visit shops. The specifications of the robot's approach behavior were done by first testing a simpler approach in a mall, during which the velocity limitations of the platform in relation to engaging people were observed. Mutlu and Forlizzi (2008) examined how aspects of workflow, social/emotional, political, and environmental contexts influenced how hospital workers used, perceived, and interacted with a robot, while outlining interruptibility constraints that could not have

been identified without preliminary experimentation on a real platform. Also, the design of the Snackbot (M. K. Lee et al., 2009) first involved the use of the CMAssist robot to conduct an early technology feasibility study.

Consequently, this paper reports on the design and control of IRL-0 and on its use in preliminary studies involving the integration of verbal with nonverbal modalities, e.g., facial expressions, head movement, arm gestures, and general mobility used to autonomously engage interaction with people. Inspired by the cub scout scenario described earlier, we implemented a short, voluntary, neutral (compared with engaging people to sell something, for instance), and simple interaction task, which consisted of having IRL-0 autonomously engage people in a public setting to get them to pick up a baseball cap lying nearby on the floor (3 to 4 m away). Assessments in terms of design (e.g., technology, control) and experimental procedures can then be made from these trials.

The paper is organized as follows: Section 2 situates related work regarding the design and the evaluation of autonomous interactive robots. Section 3 presents IRL-0's hardware and software capabilities along with its behavior-based control architecture for autonomously engaging and interacting with people. Section 4 describes the two studies conducted with IRL-0, followed by Section 5 that discusses insights regarding design and evaluation factors derived from these HRI system studies.

2. Related Work

Most of the work on engagement in HRI involves the influence of combining verbal communication with nonverbal cues, such as head and gaze control (Bruce, Nourbakhsh, & Simmons, 2002; Holroyd, Rich, Sidner, & Ponsler, 2011; Imai, Ono, & Ishiguro, 2003; J. K. Lee & Breazeal, 2010; Yamaoka, Kanda, Ishiguro, & Hagita, 2006; Yamazaki et al., 2007), facial features (Breazeal, Kidd, Thomaz, Hoffman, & Berlin, 2005; Bruce et al., 2002; Faber et al., 2009), deictic gesture (Sidner, Lee, Kidd, Lesh, & Rich, 2005; Holroyd et al., 2011; Yamaoka et al., 2006) and physical expression (Breazeal et al., 2005). Results suggest that such nonverbal cues are beneficial, but these studies usually involve one or two nonverbal modalities with an immobile platform in controlled conditions (except for (Bruce et al., 2002) which conducted trials in real-world settings). Mobility is certainly an important nonverbal modality to convey intention, as demonstrated in Terada, Shamoto, Mei, and Ito (2007) and Yamaji, Miyake, Yoshiike, De Silva, and Okada (2010). It has been used to characterize people's personal spaces in relation to a robot (Takayama & Pantofaru, 2009), the approach and positioning of a robot relative to a seated human subject (Dautenhahn et al., 2006), and to generate a trajectory to initiate interaction with people in a mall (Kanda, Glas, Shiomi, & Hagita, 2009; Satake et al., 2009). Saulnier et al. (Saulnier, 2011; Saulnier, Sharlin, & Greenberg, 2011) examined how a robot can interrupt a human in a socially acceptable manner and observed if humans can interpret the motion and intent of a robot (through mobility and head movement). They used a Wizard of Oz approach and noticed the difficulty of performing the robot's behaviors consistently during experimentation. Autonomous mobility and control is therefore an interesting capability to work on regarding engagement in HRI.

To make the approach autonomous, integrating mobility with verbal and other nonverbal modalities requires the use of a control architecture to allow the robot to determine how, when, and what to do. While there are platforms integrating interaction modalities in a robot control architecture (Asfour et al., 2006; Azad, Asfour, & Dillmann, 2007; Clodic et al., 2006; Michalowski et al., 2007; Michaud et al., 2007; Siegwart et al., 2003; Simmons et al., 2003; J. G. Trafton, Bugajska, Fransen, & Ratwani, 2008; J. Trafton, Fransen, Harrison, & Bugajska, 2009), their interaction capabilities are limited and usually illustrated in demonstrations without HRI evaluations; see Rousseau (2011) for a more detailed review. One exception is Robovie-IV (Mitsunaga et al., 2008; Mitsunaga, Miyashita, Ishiguro, Kogure, & Hagita, 2006), which looked at what makes people accept a robot in a social setting over a six-week study in an office. However, the control architecture used seemed to

simply be event-based for dialogue management and motion control yet had no generation of arm gestures. While this capability could be integrated into the behavior-based architecture presented with Robovie-I (Ishiguro et al., 2001) for autonomous HRI, this has yet to be demonstrated. Our contribution with the work reported in this paper is to present a complete integration of multi-modal interaction capabilities (voice, facial expressions, head movements, arm gestures, mobility by approaching people) in an autonomous robot control architecture and conduct preliminary assessment of this integration in engaging people to interact with the robot.

3. IRL-0, an Interactive Omnidirectional Robot Platform

Figure 1 shows IRL-0, our prototyping platform made of a mobile base, an upper body frame, and a compliant arm (total weight approximately 50 kg). The mobile base consists of an omnidirectional non-holonomic platform with eight actuators (Ferland et al., 2010): four for propulsion and four for steering the wheels with each wheel being able to rotate 180° around its steering axis. Propulsion is done using standard DC brushless motors equipped with optical encoders and capable of reaching 1.47 m/s. DEAs (Lauria, Michaud, et al., 2008; Lauria, Legault, et al., 2008) are used for wheel steering, providing compliance, safety, and torque control capabilities to the platform. The hardware architecture consists of distributed modules for sensing and low-level control, communicating with each other through a 1 Mbps CAN bus. A Mini-ITX computer equipped with a 2.0 GHz Core 2 duo processor running in Linux is used on-board for the robot control architecture. A Hokuyo UTM-30LX laser range finder (30 m range, 270° angle and 25 msec/scan) is placed on the base. As a built-in safety feature, the mobile base is programmed to slow down and come to a complete stop when being between 1 m to 0.7 m away from an obstacle. Nickel-metal hydride batteries provide power to the platform for up to three hours of autonomy. A wireless gamepad can be used to remotely control the mobile base if required.

The upper body comes with two loudspeakers, one Kinect motion sensor (providing a 3D point cloud with color for a 640×480 image with an angular field of view of 57° horizontally and 43° vertically, from 0.6 m to 4 m and at 30 frames per second) and a robot head installed on a pan-tilt unit (PTU-D46-17 from Directed Perception, actuated using step motors: pan $\pm 128^\circ$, tilt $[-17, +25]^\circ$). The robot speaks French using text-to-speech software: *lliaphon* (Béchet, 2001) for text-to-phoneme conversion and *mbrola* (Dutoit, Pagel, Pierret, Bataille, & van der Vrecken, 1996) for phoneme-to-sound conversion. Figure 2 illustrates the facial expressions that the robot can make using nine servo-motors (four for the mouth, three for the eyes and two for the eyebrows). This robot face has been used to derive a design methodology for expressing emotions (Shayganfar et al., 2012). Each emotional state can be expressed by two configurations that interchange every five seconds to make facial expressions livelier.

The compliant arm is attached to the upper body and has three serial DOFs (two in the shoulder and one in the elbow), also actuated with DEAs. The arm has a range of about 0.64 m and can handle a payload of about 1 kg at its endpoint. It can sustain impacts with humans or objects and can be controlled from low to high admittance with gravity compensation (Legault et al., 2008). The arm controller receives the desired angle for each joint and generates spline trajectories between waypoints at high admittance (to be safe if it comes in contact with a person) while ensuring that the arm does not collide with the robot. Arm gestures programmed on the robot consist of the following, as shown in Figure 3: Waving, Come Closer, and Pointing. Waving is accomplished with the upper arm almost horizontal, while for the Come Closer gesture, the upper arm is in diagonal with the ground.

Figure 1. IRL-0

3.1 Robot Control Architecture for Autonomously Engage People

IRL-0's control architecture to engage interaction with people is illustrated by Figure 4, consisting of a set of behavior-producing modules (also referred to as behaviors) with priority-based arbitration. The **Interaction Scenario** module is a task-level executive system – implemented using SMACH, a Python library in ROS (Quigley et al., 2009) to build state machines (Bohren et al., 2011) that activate behaviors or inhibit data streams. All modules of the control architecture can access the odometry and joint states of the robot using the ROS `tf` package, which manages and keeps track of every coordinate frames of the robot in the world's coordinate frame. Using data from the Kinect sensor and the ROS `OpenNI` library, the **Body Shape Detection** module extracts the center of a mass of people and only tracks the first person detected until their body leaves the sensor's field of view. However, the Kinect's limited field of view makes the robot only able to try to physically intercept people walking nearby. To provide a wider detection range, the **Leg Detection** module uses laser range finder data to identify potential leg positions (with a reliability estimation derived from perceived leg velocity) over 180° and a 5 m range, based on the approach presented in Arras, Grzonka, Luber, and Burgard (2008). Our implementation requires up to one second to validate the

Figure 2. IRL-0's facial expressions

Figure 3. IRL-0's arm gestures

presence of a person using leg detection. Position and direction of the first pair of legs detected are provided. Combining leg detection with body shape detection allows the robot to first identify potential targets over a large field of view using the laser range finder and then concentrate on the Kinect data, which are more reliable for tracking people.

Seven behaviors are used to control the robot's actions. These behaviors are described below, listed from the lowest to the highest priority:

- **Meet Person.** When the legs of a person are detected, the Waving gesture is initiated with the associated voice message and makes the robot move toward the person. If the legs are detected on

Figure 4. IRL-0's control architecture

either side of the robot, the behavior generates a curved trajectory (4 m radius trajectory at 0.6 m/s for 3 seconds with trapezoidal acceleration/deceleration profiles over 1.2 s – see Figure 6) with the upper body oriented perpendicular to it. Dautenhahn et al. (2006) reports that 0.4 m/s was found to be either too slow or about right for a robot moving toward a seated person. Since IRL-0 has to move faster to intercept moving people, we set the limit to 0.6 m/s for safe and secure approaches. No trajectory is generated if the legs are located in front ($[-45, +45]^\circ$) of the robot.

- **Attract Person.** A body shape perceived using the Kinect, allows the robot to maintain a socially acceptable distance (from 1 to 2 m) and keeps the robot facing the person. This distance was set to comply with the upper end of personal distance (0.45 m to 1.2 m) and the lower end of social distance (1.2 m to 3 m) (Hall, 1966). Velocity commands are limited to 0.5 rad/s and 0.3 m/s.

- **Check Person.** This behavior checks whether the person executes the robot's request by going toward the location of the object involved in the interaction scenario. Rotation commands may be sent to the mobile base to keep track of the person (using the **Body Shape Detection** data). Velocity commands are limited to 0.5 rad/s and 0.3 m/s. The behavior sends an indication to the **Interaction Scenario** module when the person is detected in a $1\text{ m} \times 0.8\text{ m}$ range around the baseball cap.

- **Keep Engaged.** Using body shape position provided by the Kinect, this behavior tracks the person by rotating the mobile base (maximum 1 rad/s) and the pan-tilt unit. If the person is located $[-5, +5]^\circ$ in front of the robot, only the pan-tilt unit is used, positioning it to follow the center of

Figure 5. Finite-state machine of the **Interaction Scenario** module

the face (an estimated 1 m above the center of mass of the person). Otherwise, the behavior makes the robot rotate toward the person's position to assist tracking done by the pan-tilt unit.

- **Show Object.** This behavior makes the robot point toward the position of the object used in the interaction scenario (i.e., the baseball cap). It does so by generating voice commands, performing the Pointing gesture, and orienting IRL-0's mobile base (rotated by an angle bisector to the angle between the person and the object) and the head toward the object.

- **Disengage.** While generating vocal messages and making the Waving gesture, this behavior makes the robot base return to the position it was in when engaging interaction. The trajectory is generated using ROS local navigation planner and laser range finder data.

- **Remote Control.** The gamepad allows the experimenter to reposition the mobile base or to stop the robot for security purposes only if necessary. It can also be used to directly demonstrate the robot's capabilities.

The **Interaction Scenario** module activates **Check Person**, **Show Object**, and **Disengage** behaviors by specifying a specific goal to achieve: **Check Person** and **Show Object** get activated when they receive the position of the object to monitor, while **Disengage** is activated when it receives a position to go to.

3.2 Interaction Scenario

Figure 5 illustrates the finite-state machine implemented in the **Interaction Scenario** module to manage how the robot interacts with people in this context, with Table 1 presenting the dialogue generated by the robot for the different states. The right side of Figure 5 indicates which facial expressions the robot adopts according to the states of the interaction scenario. These states are:

- (0) This is an idle state during which only the **Remote Control** behavior is activated. Using the wireless gamepad, the experimenter can position the robot and activate autonomous interaction when everything is set to begin an experiment.
- (1) **Waiting to Detect Legs**. In this state, data is allowed to be processed by the **Leg Detection** module, in search of a potential person for initiating interaction.
- (2) **Move to Intercept**. Once the legs of a person are detected and tracked, the **Meet Person** behavior is used until the **Body Shape Detection** returns a valid detection of a person, which means that the person is close by and in front of the robot. Data from the laser range finder are then inhibited (box I1) to minimize computational load, and body detection data are allowed (box I2) to be transmitted to the **Attract Person** behavior.
- (3) **Interaction Positioning**. The **Attract Person** tries to keep a socially acceptable distance between the robot and the person (as described earlier in this section for this behavior). Figure 6 illustrates the trajectory generated going from state (0) to state (3).
- (4) **Ask for Assistance**. If the person is being located using the Kinect, the **Show Object** (making the robot first try to direct the attention of the person toward the baseball cap) and **Keep Engaged** (triggered using box I3, to turn back toward the person to keep the person engaged in the interaction) behaviors are activated.
- (5) **Assistance Validation**. In this state, the robot validates whether the person is responding to its request for assistance. **Keep Engaged** tries to keep visual contact with the person, and **Check Person** behavior checks whether the person has been detected in a $1\text{ m} \times 0.8\text{ m}$ range around the baseball cap. If so, the **Interaction Scenario** module considers that the person has carried out the robot's request.
- (6) **Convince**. With **Keep Engaged** and **Check Person** activated, if the person is still being detected but does not go take the baseball cap, the robot vocally tries to convince the person to do so through specific vocal requests.
- (7) **Receive Cap**. In this state, the **Keep Engaged** behavior is used to keep the person in the robot's field of view. Note that the robot does not detect that it receives the baseball cap: it considers that the person has given the baseball cap back after a certain time (3 sec., fixed empirically).
- (8) **Goodbye**. Depending on how ends the interaction with the person, vocal messages are generated and the **Disengage** behavior is activated to make the robot go back to its original position.

The robot control architecture modules were designed by implementing each interaction modality individually, then by integrating them into behaviors and the **Interaction Scenario** module (see Section 3.2), and finally by successfully testing them (unit and system testing) in controlled laboratory conditions. Timing and parameters were finally adjusted during preliminary trials conducted in real-world settings. Table 2 shows the theoretical minimum and maximum amount of time each state can take. Total interaction length ranges from 27 to 50 sec.

Figure 6. IRL-0's trajectory when approaching a person

Table 1: Dialogues used for the interaction scenario

ID	Dialogue in French (English)
(2)	<i>Bonjour, je voudrais te parler.</i> (Hi! I would like to talk to you.)
(3)	<i>J'ai quelque chose à te demander.</i> (I have something to ask you.)
(4)	<i>Peux-tu me rapporter ma casquette, s'il te plaît?</i> (Can you bring me back my cap, please?)
(6)	<i>Allez, fais un effort!</i> (Come on, make an effort!)
(6)	<i>Tu es sûr que tu ne veux pas m'aider.</i> (Are you sure you don't want to help me?)
(6)	<i>Cela me ferait plaisir!</i> (This would make me so happy!)
(7)	<i>Merci beaucoup.</i> (Thanks a lot.)
(8)	<i>Domage ... au revoir.</i> (Too bad ... goodbye.)
(8)	<i>Bonne journée!</i> (Have a nice day!)

Table 2: State duration of the interaction scenario

States	Min (sec.)	Max (sec.)
(0)	0	0
(1)	5	5
(2)	4	10
(3)	4	10
(4)	3	3
(5)	3	4
(6)	0	10
(7)	3	3
(8)	5	5
Total	27	50

4. HRI Evaluation with IRL-0

IRL-0 has five interaction modalities: one verbal – Voice (V), and four nonverbal – Facial expressions (F), Head movement (H), Arm gestures (A) and Mobility (M). The interaction scenario cannot be accomplished by only using the nonverbal modalities. Because our intent is to conduct preliminary studies by simply using IRL-0 as a prototyping platform, we decided to only test four out of eight possible configurations, each configuration incrementally adding one modality to the set:

- Voice and Facial expression modalities (VF).
- Voice, Facial expression, and Head movement modalities (VFH).
- Voice, Facial expression, Head movement, and Arm gestures modalities (VFHA).
- Voice, Facial expression, Head movement, Arm gestures, and Mobility modalities (VFHAM).

The influences of facial expressions in HRI have already been studied (Breazeal et al., 2005; Bruce et al., 2002; Faber et al., 2009): it is usually what is used by interactive robots with facial expression capability, with voice being the primary modality to provide basic information about the robot’s intent. Therefore, VF can be considered as the baseline configuration and VFHAM is the configuration that integrates all of the interaction capabilities of IRL-0. Each of these configurations, successfully tested and validated, can easily be selected by blocking commands to the actuators not involved in the intended configuration. The underlying objective of our studies is to examine the integration of the interaction modalities and their influences in engaging people to interact with the robot, in order to identify key issues that would influence IRL-1’s design and its evaluation. Therefore, we decided to conduct a study in controlled conditions to validate the implemented interaction scenario with a group of people made aware of the interaction scenario and that IRL-0 would engage interaction with them using different set of modalities. We also conducted trials in real-world settings for uncontrolled conditions where participants passing by the robot were solicited and not made aware prior to interacting with the robot that it would try to engage interaction. In all trials, IRL-0 was positioned according to Figure 6. The studies received ethics approval with no use of video-recording (because some trials were done in public areas).

4.1 Study in Controlled Conditions

The test population consists of 35 able-bodied participants (23 males and 12 females) who completed trials in all four interaction configurations (sequentially and random order, with about a minute pause between trials). The experimenter was located nearby without being too close as to be considered

part of the interaction. This allowed the experimenter to observe what was going on and to intervene for security purposes if necessary. Once the trials were completed, participants were asked to rank the following elements in relation to the configurations and the modalities observed:

Q1.1 Configuration preference, from 1 (most preferred) to 4 (least preferred): providing an overall assessment of the integration of interaction modalities on IRL-0.

Q1.2 Modality usefulness in the interaction scenario: considering it to be useful, useless, or harmful to the interaction.

Participants could also provide general comments about their experience in interacting with IRL-0.

4.1.1 Configuration Preference (Q1.1) The Freidman Test (Siegel, 1988) was used as a nonparametric statistical test for ranks of observations to determine if a significant difference existed between configuration preference. Equations 1 and 2 were used to identify the significant differences between the preference of each configuration for Q1.1. Equation 1 defines the minimum difference $\Delta \bar{R}_{Q1.1}$, with $k = 4$ (the number of compared configurations), $N = 35$ (the total number of participants), and $z_{\alpha/k(k-1)}$ the abscissa value from the unit normal distribution above which $\alpha/k(k-1)$ percent of the distribution lies (set according to $\alpha = 0.05$, the level of the test's significance; refer to Siegel (1988), Appendix A, for more information. Equation 2 expresses that the difference of the averaged rank of preference for two compared conditions ($\bar{R}_i$ and $\bar{R}_j$, i and j being the conditions considered) must exceed the minimum difference $\Delta \bar{R}_c$ to be considered to have significant differences. The average rank for each condition was calculated by adding every rank of the condition and dividing it by the number of participants in the condition. The resulting $\Delta \bar{R}_c$ value for Q1.1 was 0.81.

$$\Delta \bar{R}_c = z_{\alpha/k(k-1)} \sqrt{\frac{k(k+1)}{6N}} \quad (1)$$

$$|\bar{R}_i - \bar{R}_j| \geq \Delta \bar{R}_c \quad (2)$$

Box plots were used to illustrate the results by representing outliers (circle), extremes (star), the smallest observation (lowest horizontal line), the lower quartile (lower end of the box), the median (horizontal line in the box), the upper quartile (upper end of the box), and the highest observation (highest horizontal line). Figure 7 illustrates for the test population that the preferred configuration was VFHAM ($\bar{R}_{VFHAM} = 1.81$), followed by VFHA ($\bar{R}_{VFHA} = 2.01$), VFH ($\bar{R}_{VFH} = 2.64$), and finally by VF ($\bar{R}_{VF} = 3.53$). Significant differences are presented in bold in Table 3. Results suggest that participants preferred interacting with the robot when Head movement (H), Arm gestures (A) and Mobility (M) modalities were added to Voice (V) and Facial expression (F). No significant differences were found between the addition of nonverbal modalities, except for the VFHAM configuration that was preferred to the VFH configuration.

4.1.2 Modality Usefulness (Q1.2) Table 4 summarizes the results obtained for Q1.2 and provides more insights regarding the contributions of the modalities to the interaction. Results suggest that:

- Voice was found to be useful by all (100%). Some participants commented that the robot's voice was clear and comprehensive, suggesting that no improvement is required for this particular modality.
- Arm gestures came in second (77%), with 14% judging that the modality is useless and 9% finding it inappropriate. The interaction was found by some to be more user-friendly when the robot was gesturing and pointing the baseball cap, but for others some arm gestures (i.e., Waving and Come Closer) were difficult to understand.

Figure 7. Q1.1 preferences for the test population

Table 3: Difference ($|\bar{R}_i - \bar{R}_j|$) of average ranks of preferences between each configuration (Q1.1), with $\Delta\bar{R}_c = 0.81$

	$\bar{R}_{VF}$	$\bar{R}_{VFH}$	$\bar{R}_{VFHA}$
$\bar{R}_{VFH}$	0.89	—	—
$\bar{R}_{VFHA}$	1.51	0.63	—
$\bar{R}_{VFHAM}$	1.71	0.83	0.20

- Head movement was considered useless by 31% of the participants but only 3% found it unsuitable. Some participants indicated that when the head was sitting still, they did not feel that they were engaged in a conversation with the robot. One participant indicated that the pan-tilt unit was too slow and noisy.

- Mobility was considered useful by 60% but useless by 17% and unsuitable by 23%. Three participants even felt uncomfortable as the robot moved toward them. This suggests that the trajectory made by the robot when approaching a person should be revised and improved.

- Facial expressions were found useful by about half the participants (indicating that facial expressions are lovely and explicit), while the other half found them useless in relation to the interaction scenario. This observation is consistent with the fact that facial expressions are the least informative of the nonverbal modalities regarding the robot’s intent for the interaction scenario.

4.2 Study in Real-World Settings

The objective of this study was to observe interaction with IRL-0 ‘in the wild’, trying to engage people as they passed by in a corridor. These trials were therefore conducted in the most natural

Table 4: Q1.2 results

	Useful	Useless	Unsuitable
Voice	100%	0%	0%
Arm gestures	77%	14%	9%
Head movement	66%	31%	3%
Mobility	60%	17%	23%
Facial expression	49%	51%	0%

Figure 8. IRL-0 in position to interact with people in real-world settings using the VF configuration (with the robot being connected to its charger).

settings but also in the most difficult conditions for an autonomous robot. With no past experiences on what to expect, this study provides preliminary insights about the robot’s capabilities, people’s response, and the experimental conditions.

This study was conducted over a two-week period in eight similar locations on our university campus, like the one shown in Figure 8. According to Scopelliti, Giuliani, and Fornara (2005), a test population mainly consisting of students is probably more receptive to robots and will react more positively to it in comparison with other populations (e.g., elderly people). Therefore, our results do not represent the perception of a more generalized population; however, our study and trials within were sufficient for the assessments we wanted to make in terms of design, technology, control, and experimental procedures.

To try to minimize the novelty factor that a robot may have when placed in a public space, we demonstrated IRL-0’s capabilities (controlling the robot using the gamepad) at these locations during the first week. We then experimented with the interaction scenario (autonomously carried out by the robot) in the second week. Once at a particular location, IRL-0 was set to interact with people using only one of the four configurations (VF, VFH, VFHA, VFHAM) for two to three hours. Overall, each configuration was used for about nine to ten hours.

Two experimenters were involved in these trials. They remained about 5 to 10 m away from the robot to intervene if needed and to be able to observe without taking part in the interaction. One experimenter manually coded participants' reactions as they interacted with the robot (e.g., started to look at the robot, looked at the object shown, nodded to the robot, spoke, came closer, moved away, stopped, or gave back the baseball cap). The robot also recorded the duration of the interaction, the state at which participants left the interaction (to determine whether the interaction followed the scenario), and if the participant fulfilled the robot's request for assistance. Participants were then stopped by the second experimenter to see whether they would agree to fill out a short questionnaire.

Overall, IRL-0 tried 1,376 times to engage interaction (steps 1 and 2 of Figure 5) with people passing by. During these attempts, 381 trials (or 27.6%) occurred with the robot asking for assistance (state 4 of the Interaction Scenario in Section 3.2), which is similar and slightly higher than the 22% reported in Bruce et al. (2002) for people stopping to interact with a robot in a museum. Many people did not slow down to let the robot process the perceived information fast enough, leaving IRL-0's field of view before it could ask for assistance. This made IRL-0 either go back to its initial position or continue toward a new interaction with another person detected in its field of view.

For these 381 trials:

- 279 failed because of IRL-0's limitations in detecting or recognizing people in real-world and dynamic settings (e.g., one person would engage interaction and was replaced by another one passing in front of the robot; one person would interact with the robot while another grabbed the baseball cap).
- In the remaining 102 trials, IRL-0 was able to complete the interaction scenario with the participants (observing on average 5 reactions made by people while interacting with the robot; interaction lasted on average 29 sec) and 99 participants accepted our request to fill out the following questionnaire:

Q2.1 Is this your first encounter with the robot?

Q2.2 From 1 (low) to 5 (high), how well did you understand what the robot asked you?

Q2.3 From 1 (low) to 5 (high), did you like the robot?

Q2.4 Select the three primary aspects over the following six that made you stop to interact with the robot – Appearance, Attitude (global behavior), Voice, Facial expressions, Head movement, Arm gestures, or Mobility?

We found no significant difference in the data collected and the different configurations for Q2.1 to Q2.3, so no observations could be made between the configurations. Therefore, Table 5 only summarizes the results observed over the four configurations for the 99 trials with participants who filled out the questionnaire. Results for Q2.1 indicate that more than half of the participants had already seen the robot. Participants rated the robot as very understandable (Q2.2) and appreciated the robot (Q2.3).

Table 6 summarizes what made participants stop to interact with IRL-0 (Q2.4). The percentages were calculated using the number of times the modality was chosen by participants and then divided by the number of valid trials for each configuration. In general, most participants were surprised and excited to interact with a robot (which was unusual for about half of them), so they liked whatever the robot did. Some participants indicated that curiosity was the main factor that made them interact with IRL-0. Because participants interacted with IRL-0 using only one set of modalities, we expected that participants interacting with IRL-0 using the VF or VFH configurations would not indicate that Arm gestures made them stop to interact with the robot – unfortunately, some did. The same happened with Mobility while using the VF or VFH configurations (IRL-0 is immobile in these conditions).

Table 5: Results for Q2.1, Q2.2, and Q2.3

	Q2.1	Q2.2	Q2.3	Number of reactions	Interaction time (sec)
Mean	54%	4.6	4.0	5.0	28.8
Std. Err.	5%	0.1	0.1	0.2	0.4

This suggests that clarification to the question is required. Nevertheless, adding Arm gestures and especially Mobility to IRL-0’s interaction modalities seems to play a useful role in engaging people to interact with the robot, and this should be an interesting avenue to explore for future studies with IRL-1.

Table 6: Results for Q2.4

	Voice	Appearance	Facial expressions	Attitude	Arm gestures	Mobility
VF	78%	39%	65%	22%	13%	4%
VFH	63%	60%	50%	40%	13%	10%
VFHA	78%	52%	52%	39%	22%	0%
VFHAM	78%	52%	39%	22%	30%	43%

5. Discussion

By using IRL-0 as a prototyping platform to conduct preliminary trials, our objective was to go beyond system testing in laboratory conditions to seek insights about the design (e.g., technology, control) and the experimental procedures for an autonomous robot engaging people to interact. The trials conducted demonstrate that IRL-0 can autonomously engage people according to the intended interaction scenario. No accident occurred, and the platform revealed to be robust and operating well. Verbal requests were comprehensible, people liked the robot, and the robot was coherent in its actions.

In terms of design, the following considerations can be made from the observations presented in Section 4:

- **Mobility.** On the one hand, motion should be made less threatening as the robot approaches people (see Section 4.1.2). On the other hand, in terms of velocity, the robot may need to move faster to catch up with people moving by. Establishing a similar compromise is reported in Satake et al. (2009), which led to the design of an anticipation model and a path planning strategy to intercept people in a mall. Slowing down and smoothly changing the trajectory using the omnidirectional capability of the platform (as the robot approaches people) should therefore be examined.
- **Perception and tracking.** To improve the robot’s reaction time and minimize inappropriate responses (as in the 279 interrupted interactions in real-world settings) from the robot, people perception and tracking should be improved, both in terms of speed and accuracy. The robot should also be able to track the object involved in the interaction. In addition, participants were frequently observed responding back vocally to IRL-0. Since IRL-0 interacted vocally with people, they expected the robot to be able to understand what they were saying. This justifies the integration of the

sound source localization, tracking, and separation system (Valin et al., 2007) for IRL-1's speech recognition capabilities.

- **Arm gestures and Head movement.** Improving these modalities should help make them more distinctive during the interaction (see Section 4.1.2). The use of two 4-DOFs arms with manipulators on IRL-1 will surely help. Reducing the noise generated by the pan-tilt unit for the head and improving the response time of facial expressions should be useful.

In terms of experimental procedures, one general observation from the preliminary studies conducted is the difficulty in getting statistically significant observations. Such situations are not uncommon with platforms that integrate many functionalities and are used in real-world settings, such as those seen in Saulnier (2011) and Yamaji et al. (2010). Nevertheless, these trials reveal important elements that must be taken into consideration for the completion of IRL-1 and upcoming studies.

First, letting people become familiar with the robot is a necessary step for obtaining more consistent results. The test population for the study in controlled conditions (Section 4.1) was made up of people familiar with mobile robots (14 male, 1 female) and people who never interacted with a mobile robot before (9 male, 11 female). Looking more closely at the distinctive results, no significant differences were found between the two groups but overall unfamiliar people had more scattered preferences regarding the configurations and interaction modalities. Whether trials are in controlled or in real-world settings, it may be appropriate to give participants some time to get familiarized with the robot and its capabilities in order to move past the curiosity and novelty factors when people first encounter a robot. In real-world settings, it may be preferable to let the robot interact with people at the experimental location over longer periods of time and only use data from volunteers that are familiar with the robot. Studying how familiarization with the robot impacts engagement could certainly be an interesting topic.

Second, the experimental protocol to put in place to evaluate engagement with IRL-1 should consist of a three-step process:

1. **Distinct usability evaluation of nonverbal modalities in controlled conditions.** The objective would be to evaluate if and by how much each modality (e.g., head movement, arm gestures, approach trajectory) is found suitable and useful. Having no significant differences between many configurations and conditions may suggest that the influences of each modality do not clearly stand out in relation to the interaction scenario. Distinct usability evaluations make it possible to identify what each modality can bring as positive and clear influences to the interaction. Five to six participants may be sufficient for conducting these evaluations (Turner, Lewis, & Nielsen, 2006). To help observe significant differences in the different configurations to be experimented with, these evaluations may lead to changes in the implementation of the interaction scenario, in test configurations and in conditions to evaluate.

2. **Evaluation of integrated nonverbal modalities in controlled conditions.** Combinations of the modalities found suitable and informative in Step 1 should be examined in relation to the interaction scenario. Having participants interact with the robot in all configurations can be used for comparative analyses. Participants could indicate in what ways different sets of nonverbal modalities contribute to the interaction (e.g., making it engaging, informative, lively, and understandable). Timing measurements should also be derived to characterize the interaction dynamics that can result from the different configurations. Changes to the robot control architecture or to the interaction scenario may then be required to adapt to limitations that the robot may have.

3. **Evaluate the interaction scenario in real-world settings.** Two configurations should be used by two distinct groups of participants: one with the minimal set of interaction modalities required to implement the interaction scenario and another that uses the set found to be most appropriate according to findings of Step 2. Evaluation should be oriented toward the interaction scenario through quantitative measures (e.g., success or failure to engage people, reaction time to the request made

by the robot, and task completion), a questionnaire (e.g., evaluate the perceived integrated influences of the modalities on the interaction) and qualitative observations (e.g., verbal comments and observations made as people interact with the robot).

Following this process will make it possible to identify what can lead to more significant observations between the interaction modalities and their integration, guide how and what to experiment with real-world conditions, and describe what to observe.

6. Conclusion and Future Work

The design and the evaluation of interactive autonomous robots involve addressing, at the system level, complex engineering, programming, reasoning, and human factor study issues. Many factors influenced by the robot's hardware, software, capabilities, tasks, and operating conditions must be taken into consideration for determining the experimental methodology. The paper provides a complete description of IRL-0's autonomous control architecture integrating verbal and non-verbal modalities to interact with people in real-world settings. Using IRL-0, we completed a full integrated design and evaluation cycle of interaction modalities in controlled and real-world settings. It demonstrates that IRL-0 can autonomously engage people by using its modalities appropriately and within their limits, pointing out improvements to be made to the approach trajectory, for people perception, tracking and vocal interaction, and for arm gestures and head movements. These preliminary studies also provide important insights on what to focus on and how to proceed with the experimental design and evaluation of an interactive autonomous robot engaging people to interact. In the absence of formal or empirical methods to support the design of interactive autonomous robots, we believe that the approach presented could provide interesting guidelines beneficial for the development of advanced platforms. IRL-0 is now dismantled, and IRL-1 is being prepared for upcoming HRI system studies according to the design and the evaluation considerations outlined in this paper. Data gathered with IRL-0 will be useful for comparative evaluations with IRL-1, allowing further evaluations of the impacts of these considerations.

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