# A Proxemic-Based HRI Testbed

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## ABSTRACT

This paper describes a novel, low cost HRI testbed for the evaluation of robot movement, gaze, audio style, and media content as a function of proximity. Numerous human-robot interaction studies have established the importance of proxemics in establishing trust and social consonance, but each has used a robot capable of only some component, for example gaze but not audio style. The Survivor Buddy proxemics testbed is expected to serve as blueprint for duplication or inspire the creation of other robots, enabling researchers to rapidly develop and test new schemes of proxemic based control. It is a small, four-degree of freedom, multi-media "head" costing approximately $2,000 USD to build and can be mounted on other robots or used independently. To enable proxemics support, Survivor Buddy can be coupled with either a dedicated range sensor or distance can be extracted from the embedded camera using computer vision.The paper presents a sample demonstration of proxemic competence for Survivor Buddy mounted on a search and rescue robot following the victim management scenario developed by Bethel and Murphy.

## Categories and Subject Descriptors

I.2.9 [**Artificial Intelligence**]: Robotics

## General Terms

Human Factors

## Keywords

Human-Robot Proxemics, Robot Scaling Functions, Robot Approach Behavior, Social Robots



## 1. INTRODUCTION

A major topic in human-robot interaction (HRI) is how robots can provide socially consistent responses to the humans operating in close proximity, such as a help-desk or receptionist robot or a robot medic. As predicted by Reeves and Nass [19], human-robot proxemics appears to be a direct transfer of human-human proxemics. Hall [6] asserted that humans interact with each other differently based on their proximity to one another and divided interaction space into four zones: Intimate space, Personal space, Social space and Public space. Each zone manifests its own characteristics. For example, an interaction in the Intimate zone usually involves a voice kept to a whisper, while interactions in the Public zone present a loud voice. Argyle [2] later refined each zone into their currently accepted ranges (see Fig. 1), while Bethel et al [3] synthesized the social literature into a comprehensive model of proxemics for robots. Over 22 studies to date have confirmed some aspect of human-human proxemic behavior occurring in human-robot interactions [1, 3, 5, 7–13, 16–18, 20, 21, 23–29], though no study has been able to address proximity in its entirety. Indeed, the literature suggests that researchers have only begun to skim the surface of this important topic.

The lack of a proxemics oriented robotics testbed is a barrier to further research, which is addressed by this paper through the presentation of Survivor Buddy 2.0. The paper first reviews the literature to postulate a super-set of the six known proxemic dependent attributes that should be supported by the testbed: *affective movement, proxemic readings, voice interactions, audio style manipulation, gaze control,* and *media content delivery.* The paper then presents Survivor Buddy 2.0, a low-cost robot "head" which was developed to meet these demands. Survivor Buddy 2.0 also encapsulates the proxemic functionality into a tactical behavior [14], which isolates proxemic adaptation from the nominal behavior, allowing experimentation with different scaling functions (e.g., linear, exponential) or proxemic strategies without changing any other behaviors of the robot. In addition, Survivor Buddy 2.0 can be mounted to another robot for mobile interactions or remain stationary.

## 2. RELATED WORK

There are over 22 human-robot interaction studies that have explored some aspect of proxemics [1, 3, 5, 7–13, 16–18, 20, 21, 23–29]. These studies have used more than eight dif-

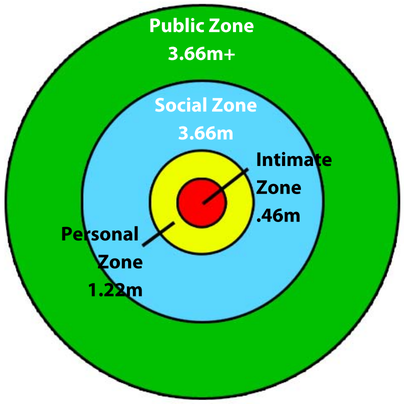



**Figure 1: Argyle's Proxmity Zones.**

ferent robots to examine at least five facets of proxemics (robot-human distance, social gaze, acceptable motions, audio response, and angle of approach), making it difficult to replicate results or extend systems. Thus the literature shows that understanding proxemics is an accepted and critical component of social robots, yet there is very little collaboration, reuse or standardization of the platforms used to evaluate proxemics in social robots. This absence coupled with the criticality of proxemics highlights the need for a proxemic-based HRI testbed that can be either stationary or mobile.

## 2.1 Types of Proxemic Research in HRI

There have been five research foci in proxemics, showing the richness of the topic in HRI. One foci seeks to answer what distance from a robot is considered comfortable for the human. Work by Mitsunage et al [11], Oosterhout [16], Syrdal et al [23], Takayama et al [24], and Walters [29] all explore the appropriate distance a robot should maintain while interacting with a human. Results have varied from proposed frameworks which automatically determine the appropriate distance [29], to somewhat confounding results that indicate a complex personality-based nature to the problem [16]. Others conducting these studies have found attributes like pet ownership and gender to be of importance [24]. Some have attempted learning user preference [11] or using feedback as a reward to a learning system to better shape proxemic behavior [10]. Significant technical work has also been completed on maintaining the appropriate distance throughout an interaction including human movement [17].

A second foci is social gaze as a function of proxemics, where the duration and type of gaze depends on proximity. Young-Min et al [9] created a fuzzy logic system to obtain and maintain gaze with a human based on proxemic conditions. Mumm et al [13] recently illustrated that humans increase their distance when a robot they do not like applies an ample amount of gaze behavior toward them.

A third foci is movement of the robot and joints or effectors, with the consensus that motor or actuation speeds should be altered based upon proximity. Mizoguchi et al [12] noted that motor behavior and speed created different responses from users and later it was indicated that motor speeds and timing should be adjusted based on proximity [10]. Bethel et al [3] formalized a scheme which prescribed modifications to movements for each proximity level.

The fourth foci is audio manipulation related to proximity. Partala et al [18] found that altering audio from neutral, sad, and happy levels could successfully manipulate valence. Shiomi et al [21] illustrated that a whispering voice was more effective in convincing users to complete a task, as it encouraged a lower proximity level and a higher bond, while Walters [26] found that humans keep a further distance from a synthetic voice.

A fifth area of investigation is the angle of approach and proxemic behavior. Two studies by Walters et al [27, 28] conclude that humans much prefer the robot to approach from the left or right, rather than the front or back. These studies also indicate regardless of approach angle, humans still expect appropriate proxemic behavior from robots.

## 2.2 Existing Proxemic Testbeds

The review of existing studies and systems highlights the lack of a standardized or even shared proxemics platform among HRI researchers. Such a system would be of general benefit, as it would provide an easy boilerplate to use toward specific experimental needs.

Fifteen of the examined studies utilized mobile robots [1, 3, 8–12, 16, 17, 20, 23, 24, 27–29], while seven others worked with stationary robots which observed the environment from a set location [5, 7, 13, 18, 21, 25, 26]. In studying social gaze as a function of proxemics, Mumm [13] utilized a stationary robot capable of autonomously maintaining gaze. Similarly, studies investigating using a whispering voice robot [21], as well as those evaluating voice styles of a mechanical looking robot [26] also used stationary platforms. One experiment interested in voice manipulation [18] coupled with proxemics created a simulation based method for creating proxemic situations, limiting the need for any robotic platform at all. Most studies interested in a robot's approach to a human [27, 28] or maintaining an appropriate proxemic distance [17] have all operated mobile robots, capable of traversing their environment. Of the studies utilizing mobile robots, most have been of a form factor which requires ample space to move about. Many studies have used systems similar to the PeopleBot configuration [8] [28] [23] [27] [11] [16]. Only Adalgeirsson [1] and Bethel [3] have employed portable or non-anthropomorphic robots. Adalgeirsson's MeBot is an attachment for a mobile phone, while Bethel's work involved search and rescue robots, capable of navigating inside rubble.

Sixteen of the 22 studies [1, 3, 9–13, 16, 17, 20, 24–29] surveyed have performed experiments which rely on actual autonomous systems, with the remainder using Wizard of Oz control of the robot or simulation [5, 7, 8, 18, 21, 23]. Researchers are often interested in a specific attribute and use simulated approaches to other aspects of their experiments. For example, Mumm et al [13] utilized a pre-recorded human voice in order to establish the likeability of their robot in social gaze testing. Walters [26] powered up a robot's fans, servos, and sensors into an idle state in order to give a more "live" feel to experiments focusing on voice. Additionally, most have performed studies in controlled lab environments, while a few have experimented in more everyday situations. For example, Ooserhout et al performed experiments regarding robotic proximity during a three day arts and technology festival [16]. Many rely on the laboratory setting or at least a controlled condition as it allows for more reliable capture of sensory data. Additionally, Wizard of Oz approaches are sometimes used in order to ensure repeatability or to enable a task the robot would otherwise find difficult. For example, Sydral et al used a Wizard of Oz approach in their study of the relationship between individual differences and proxemic behaviors [23]. Huettenrauch et al also used a Wizard of Oz approach to their study of spatial distancing in a co-presence situation [8]. Finally, Partala et al [18] have looked to novel methods like changing image sizes on a screen in order to simulate proximity, rather than using a physical robot at all.

# 3. APPROACH

The approach taken to create a proxemic competent HRI testbed is twofold: design and build a *physically competent robot* and create *a software architecture* that allows proxemics to be inserted in a quantifiable, reproducible way avoiding ad hoc implementations.

## 3.1 Necessary Physical Capabilities

Taken together, the HRI literature suggests that a proxemically competent robot should have at least six capabilities:

- **Affective expressiveness**, where the testbed has sufficient degrees of freedom and resolution of joint control to produce a scalable set of motions [1] [3] [7] [10] [12] [20] [25].
- **Audio Control**, where the audio volume has sufficient range to extend across all zones [5] [12] [18] [21] [25] [26].
- **Gaze Control**, where the testbed has the sensors and processing power to support gaze control algorithms such as eye and face tracking [10] [13] [9].
- **Media Content Control**, where the testbed can present and control a variety of media (web, video, voice, videoconferencing, etc.) [1].
- **Approach Control**, where the testbed degrees of freedom allow it change approach angles yet still accomplish the mission, particularly approaching from the side (non-threatening) while maintaining eye contact (showing engagement) [1] [3] [8] [10] [11] [16] [17] [23] [24] [28] [27] [29].
- **Proxemic Awareness**, where the testbed either has proxemic sensing or can access range data from a host robot or external sensor [1] [3] [8] [10] [11] [12] [13] [16] [17] [18] [23] [24] [25] [28] [27] [29] [26] [9].

## 3.2 Software Architecture

The approach to software is to encapsulate proxemics into a tactical behavior following [14], compatible with behavioral and hybrid deliberative/reactive architectures. This architecture is captured in Fig. 2. The nominal behaviors are a mapping of $B(s) = r$, where strategic behaviors (or operator commands) $b$ produce motor and media output or responses, $r$, from sensor input $s$. These outputs are then filtered by the proxemic behavior, which acts to apply a gain or bias function based on sensed distance, $s_{range}$, leading to a new behavioral mapping: $B_{proxemic}(s_{range}, B) = r'$. Note that the range sensor can be either dedicated to the proxemic behavior or shared with the nominal behaviors, as is consistent with behavioral robotics.

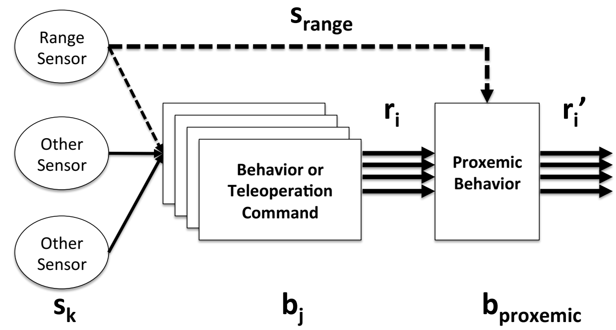



**Figure 2: The proxemic behavior as a tactical behavior, where $B_{proxemic}(s_{range}, B) = r'$.**

The advantage of this approach is that it isolates proxemic adaptation from the nominal behavior. This means an agent (human or computer) can compute $r$ without having to be aware of $s_{range}$ proxemics. The proxemic behavior can apply different scaling functions (e.g., linear, exponential) or proxemic strategies without changing any other behaviors of the robot, thus allowing direct comparison of proxemic interactions.

A proxemic behavior consists of a minimum of five components, each assigned a scaling function: *joint movement range, joint movement speed, approach speed, gaze control,* and *audio control.* More components can be added as warranted by the research. The scaling function is a collection of scaling functions for each zone: Intimate, Personal, Social, and Public.

# 4. IMPLEMENTATION

The implementation of the novel HRI testbed capturing the six capabilities described above is called Survivor Buddy. The implementation consists of two major systems: the *platform itself* and the *proxemic sensing system.* Proxemic sensing is discussed separately because it can be done in a number of ways (through the Survivor Buddy video camera, through a dedicated range finder, or through sharing range data from the base robot). For this version of Survivor Buddy, 2.0, proxemic sensing is done with a dedicated range finder, though in the future it is expected that the testbed will have onboard algorithms for using optical flow with the video camera.

Survivor Buddy enables proxemic behavior through allowing the scaling of several attributes, including: joint movement range, joint movement speed, approach speed, gaze control, and audio control. By default, each attribute uses a linear drop-off function for scaling, though it is possible to apply non-linear functions as well. In the base implementation, the maximum value of a feature (joint movement range, joing movement speed, approach speed, gaze control, audio control) is used when the human is at a distance greater than approximately three meters. From approximately three meters to half of a meter the value of each feature is scaled linearly, with its acceptable minimum being placed at the half-meter meter distance. These ranges and functions are configurable to meet other requirements as well. These parameters were chosen as defaults because they provide a simple starting point for exploration.

### 4.1 The Survivor Buddy Platform

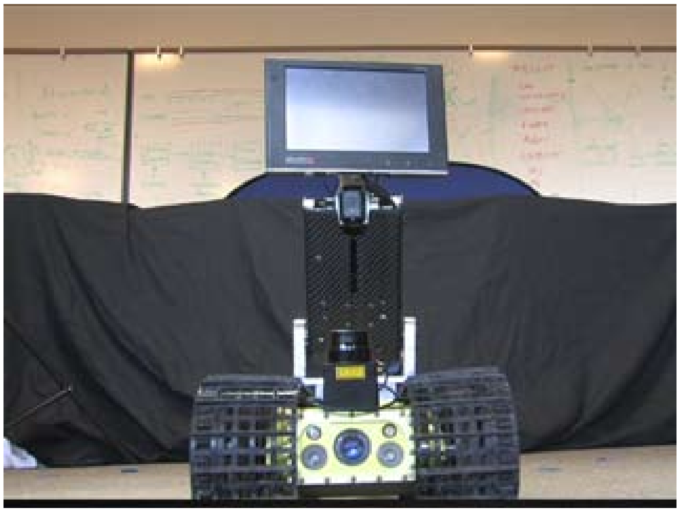


**Figure 3: Survivor Buddy 2.0 with a dedicated Hokuyo proxemics sensor mounted to a ASR/Inuktun Extreme urban search and rescue robot.**

The Survivor Buddy 2.0 platform consists of the effectors and multi-media monitor, control software, and a Voice Toolkit. The Survivor Buddy 2.0 effector design is described in [15] and costs approximately $2,000 USD to build. The robot "head," seen in Fig 3, has four degrees of freedom, a footprint of 14cm X 9.5cm and weighs only 1.72 kg. It is easily attachable to other robot bases, but also has the ability to be mounted in a standalone fashion. Survivor Buddy's "head" is a small, 7-inch MIMO 740 touchscreen monitor, which also contains a webcam and microphone with a speaker system mounted in the "neck". Actuation is through Dynamixel motors, allowing high velocities at each joint in order to enable fluid motion.

Survivor Buddy is controlled through a tether to a netbook and power supply, using a software framework for position control, affective behaviors, shared autonomy, resource control and Windows extended desktop to control media content. The software framework is written in C#, communicates directly with each of the four motors. The software also includes a Voice Toolkit that enables communication through text to speech packages, voice recognition engines, and live streaming of voice. The system can be used by both local and remote users, allowing communication from across the internet.

Survivor Buddy was designed to be mounted to most robot bases, as well as mounted on a stationary object for general HRI interaction studies. A stationary mounting is ideal for allowing humans to approach the robot, as well as interacting with multiple humans within a space; thus it could be used for experiments such as [5, 7, 13, 18, 21, 25, 26].

### 4.2 Six Capabilities

The Survivor Buddy 2.0 design meets the six necessary capabilities, as described below:

- **Affective expressiveness**: Survivor Buddy 2.0 has four degrees of freedom, a head tilt, pan, and roll and a neck that raises and lowers.
- **Audio Control**: Survivor Buddy 2.0 has onboard speakers and microphone.
- **Gaze Control**: Survivor Buddy 2.0 has sufficient degrees of freedom to establish agency, communicate social attention (e.g., maintain eye contact), regulating the interaction process, projecting mental state, and manifesting interaction content [22].
- **Media Content Control**: the Windows extended desktop allows an operator or agent to display any application running on the netbook or through an internet connection on the Survivor Buddy 2.0 monitor.
- **Approach Control**: Survivor Buddy 2.0 has sufficient degrees of freedom to "turn sideways" to "soften" the angle of approach, even if the base robot approaches the human straight on.
- **Proxemic Awareness**: Survivor Buddy 2.0 can accept range readings from an external sensor or use the built-in webcam with a stereo range, optical flow, or other depth algorithm.

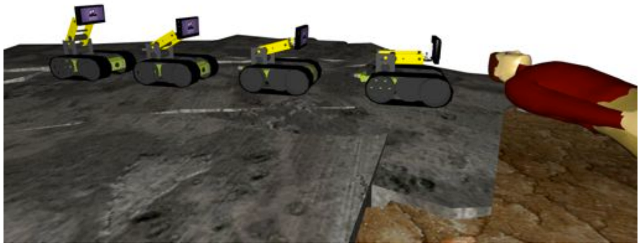
### 4.3 Proxemics Sensing

For the initial demonstration of proxemic competence, the proxemics sensing platform was a dedicated Hokuyo URG-04LX Laser Range Finder mounted on the robot base. It is capable of providing 240 degrees of range data with a resolution of .36 degs/step. Power and communications are through a separate tether using a USB connection.

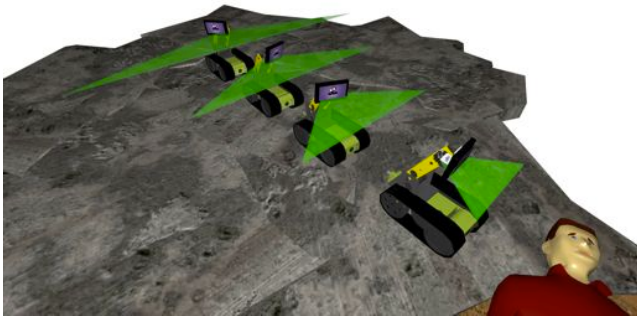
The sensing platform is controlled by a custom C# program developed to provide fast and meaningful proxemics data to active behaviors. The program, layered in style, is first responsible for the management of the laser hardware and the delivery of updated reading information on a continuous basis. The readings are delivered through a subscriber service, where all subscribers are pushed new information as it becomes available. The service provides angle, distance, and timestamp. Additionally, a higher level program, a subscriber to the lower level program, provides tracking data of human objects within the current environment. This program likewise allows subscribers, and delivers information such as human size, location, velocity, and time.

## 5. SEARCH AND RESCUE VICTIM MANAGEMENT EXAMPLE

The scenario from [3, 4] was used to demonstrate the proxemic competence of the Survivor Buddy HRI testbed. In the scenario a robot searches through rubble for survivors, then interacts with the survivor. Bethel [3, 4] showed in 128 human-subject trials that there was strong evidence manifested in difference of respiration rates which indicated stress increased significantly for a robot that did not obey proxemic "rules" compared to one that did. In this demonstration which duplications the path and position of the robot to a victim, the Survivor Buddy head is mounted on an ASR/Inuktun Extreme. Survivor Buddy remains in a folded



(a)



(b)

**Figure 4: Simulation of Survivor Buddy as it moves from the personal space to intimate space of the victim from the side (a) and from above (b).**

up, low-profile position until a survivor is located. At that point, the Survivor Buddy raises up and begins an interaction session with the user, modifying the control based on proxemics.

Fig. 4 shows how Survivor Buddy would visibly change pose and the range of motion of a "no" (manifesting interaction content) as it moves from the victim's *personal space* to their *intimate space*. Fig. 5 provides a filmstrip of the actual robot responding to the decreasing distance by decreasing the volume (shown on the Survivor Buddy monitor using a graphics equalizer type of display), decreasing the range and velocity of motion (shown by the bars marking the change in extent of motion), and change in pose (illustrated by a side view).

# 6. CONCLUSIONS AND FUTURE WORK

Though there are at least 22 studies focused on proxemics-based attributes of HRI, there has yet to be a common or comprehensive proxemics-based testbed. Survivor Buddy 2.0 is a complete proxemics-based HRI testbed. It consists of a physical component capable of proxemic awareness, audio, gaze, media content, and approach control as well as affective expressiveness. The software architecture component treats the proxemic capabilities as an independent tactical behavior, allowing the application of of different scaling functions or proxemic strategies without changing any other behaviors of the robot. As demonstrated with a canonical victim management scenario, Survivor Buddy 2.0 is small enough to be mounted on another robot for mobile interactions where a robot approaches a person as well as used for the more common situations of a person approaching the robot.

Future work includes adding support for additional sensing hardware, offering more software frameworks for behavior design and scaling complex behaviors as a function of proximity as well using Survivor Buddy 2.0 for human-subject tests of autonomous gaze control. Survivor Buddy 2.0 design drawings and software are available upon request.

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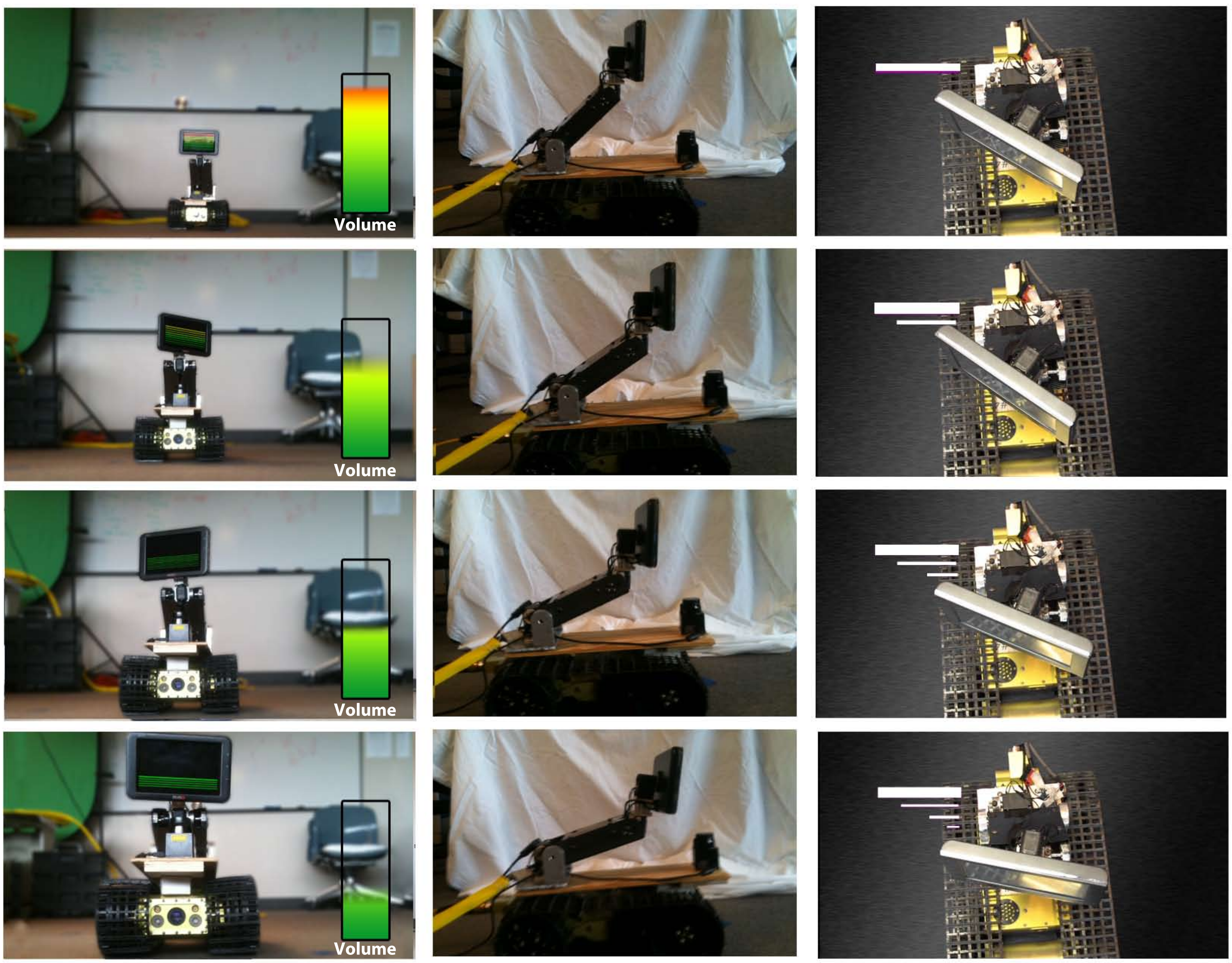


**Figure 5: Views Survivor Buddy as it moves from the personal space to intimate space of the victim. Audio volume is shown on the screen in the left set of images, lowering on approach in center, and decreasing magnitude of the range of head motion of "no" is indicated by bars in the third set of images.**

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