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Designing a Flying Humanoid Robot (FHR): Effects of Flight on Interactive Communication*

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***Abstract*— This research constitutes an initial investigation into key issues which arise in designing a flying humanoid robot (FHR), with a focus on human-robot interaction (HRI). The humanoid form offers an interface for natural communication; flight offers excellent mobility. Combining both will yield companion robots capable of approaching, accompanying, and communicating naturally with humans in difficult environments. Problematic is how such a robot should best fly around humans, and what effect a robot's flight will have on a person in terms of non-verbal communicative cues. To answer these questions, we propose an extension to existing proxemics theory ("z-proxemics") and predict how typical humanoid flight motions will be perceived ("z-kinesics"). Data obtained from participants watching animated sequences are analyzed to check our predictions. The paper also reports on the building of a flying humanoid robot, which we will use in interactions.**

I. Introduction and Related Work

Something human-like which can fly has been the stuff of dreams, from tales of Icarus' fall and Leonardo's ornithopters, to robots such as Astroboy and Gundam in modern times—such entities capture our imaginations because they are not only human-like (capable of acting as we do) but are more than human (free to move in a way we cannot). Now, lighter, more efficient motors and power sources have begun to make possible one such artifact, a flying humanoid robot (FHR). The goal of this paper is to present an initial investigation of considerations for designing a FHR, with a specific focus on human interaction with a companion robot.

Why would such a design be useful for a companion robot? The defining characteristics of a FHR, human-likeness and flight capability, address two key problems faced by designers of companion robots, of providing communication capability and mobility. Previous work has suggested that the humanoid form can be used to provide a rich, natural interface for interacting with humans (e.g., [3]). A difficulty is that such robots typically have limited mobility; wheeled or legged robots may fall, get stuck, and be unable to pass simple obstacles. Thus, such robots cannot provide companionship in the same way a person or animal could. It would be an advantage if a companion robot were not reliant on a person to initiate and manage interactions, but could approach, retreat, and accompany people in real environments.

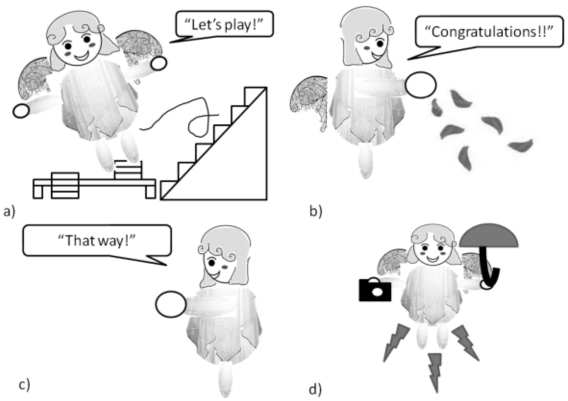

Fig. 1. One possible design for a flying humanoid robot (FHR): "Angel", a soft, safe companion robot intended for playful and affectionate interactions who a) approaches b) entertains, c) accompanies and guides, and d) serves humans

To provide excellent mobility, flight is being increasingly explored. Robots capable of efficient mechanical flight have been created in the shape of a bird, jellyfish, and penguin by a company, Festo. Remote-controlled toys have been developed, one resembling a fish ("Air Swimmers"), and another consisting of a doll attached to a dragonfly base ("Flytech Tinker Bell"). In Human-Robot Interaction (HRI), a quadropter was used to gauge people's opinions toward controlling a flying robot with gestures [16]. A key problem for such robots is that communication is difficult. As a result, in the above study, people reported being frightened of the robot used. Another study sought to provide communication capability in a theater play by pairing flying robots with human actors [14], but this approach may not be convenient for contexts in which a robot's autonomy is desired.

We propose combining humanoid form and flight capability to provide both excellent communication capability and mobility. Previous work has not shown how to design such a FHR, especially one which can fly close to and interact with people. The contribution of this paper is to provide a first investigation into this core question from the perspective of proxemics and kinesics, also reporting on what is, to the authors' knowledge, the first example of a FHR (see Fig. 1). Exploring these topics should help designers to create FHRs for HRI.

The remainder of the paper is organized as follows. Section II identifies challenges for a FHR—building, proxemics and kinesics—which are considered in Sections III, IV and V. Predictions are evaluated in Section VI, leading into discussion in Section VII. Section VIII summarizes contributions.

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II. USAGE SCENARIOS AND REQUIREMENTS

What will be possible for a companion humanoid robot with flight (FHR), and what challenges must be met? Two scenarios are presented for a FHR, “Angel”, regarding approaching and accompanying a human via flight.

A. Approaching

Sandy used to hate coming home after school to the empty, dark house, before her mother got back from work. Now things have changed; every day her companion robot, Angel, flies out to greet her at the door with a big hug and a smile, zipping up the staircase and over furniture, a thick carpet, magazines, and shoes on the floor. Angel is like a baby with wings—small, soft and cute; sometimes she comes over when Sandy is reading or watching TV, wanting to be held. At other times, Angel comes to deliver a message; if Sandy is talking on the phone, Angel drifts into view and looks at Sandy to let her know, then speaks when the call is over. Sandy likes to call Angel over to get her peanut butter from the high shelf in the kitchen, or to play fetch; Angel can bring back a ball even if the room is messy or Sandy throws it out the window! Angel also helps with homework; when Sandy has a question, Angel reads out information from the internet in a way that Sandy can understand. But what Sandy likes most is that Angel seems to care about her: when she got an A+ on a science test, Angel danced over everyone’s heads and threw little glittery pieces of confetti. For Sandy, Angel is a little friend.

B. Accompanying

Going out on walks alone is no fun. On days when Mary’s daughter and grandchildren aren’t visiting, she likes to go for a stroll with her companion robot. Angel is a pleasure to be with—nodding, holding hands, remembering the conversation and asking questions—and has no trouble keeping up: she flies right over bumpy curbs, fence-posts, muddy or snowy puddles, fallen branches, and up and down hills. The other day when Mary lost her way, Angel pointed her in the right direction and led her back home; there’s no need for a map when you’re with Angel: you just say where you want to go or who you want to see, and she’ll guide you! Mary also likes Angel’s soothing voice: she chose it for Angel because it reminded her of an old friend. Today Mary took a walk by the river at sunset; she had Angel fly out over the water to take a photo, then used her display glasses and Angel’s data link to check out two swans from up close. Angel tried to protect her from the hot sun with an umbrella (which also works in rain), but now it is evening and Mary is tired. She gets Angel to light up the ground on the way home; it’s nice not to have to think where she is or worry about tripping. Back at home, Angel bounces up and down to indicate that Mary’s grandchildren are ready for a video chat call. Mary gives each of them a big hug through Angel, which is transmitted on their end.

C. Requirements

These scenarios indicate a number of key challenges. Some have been addressed in previous work, such as recognizing people [12], and talking in a seemingly intelligent way [22]. Challenges constituting the focus of this paper are:

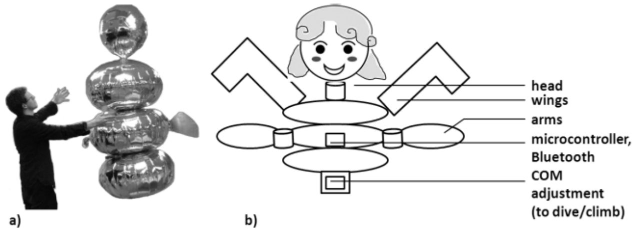

Fig. 2. A prototype flying humanoid robot (FHR), Angel: a) interacting with a person, b) system architecture

- *Embodiment* (Section III): Angel requires a flying humanoid form (minimally a head and arms for simple gestures such as pointing or hugging).
- *Proxemics* (Section IV): Angel must be able to fly toward and alongside of people safely.
- *Kinesics* (Section V): Angel should be able to fly expressively, conveying meanings such as happiness, excitement or playfulness.

These are only first steps for developing the potential for FHRs; future work will address subsequent challenges.

III. BUILDING A FLYING HUMANOID ROBOT (FHR)

A key issue is whether it is possible to build a flying humanoid robot (FHR) such as Angel at low cost. To this end, the creation of a first prototype is described.

Primary requirements were humanoid form (a rotatable head and simple arms), safety and stability—difficult due to the extra control required for flight and the aerodynamic instability of the humanoid form—and light weight. Building on our ongoing work involving playful and affectionate interactions with a humanoid robot [4], we also sought to create an appearance that will invite play and affection.

A. Safety

Previous HRI studies [14], [16] have used remote-controlled aerodynes, which offer impressive maneuverability and speed and can carry sizable payloads, but our eventual goal is to create an autonomous platform, which must be safe. A quadropter was tested, but seemed difficult to operate near a human. Therefore a lighter-than-air approach was selected to achieve flight (as in the popular Air Swimmers toy), which ensures that Angel is soft and slow, and thus safe.

B. Stability

Stability was realized by using three saucer-shaped balloon modules to build the robot’s body. The central module supports most of the actuators and electronics on its sides, and is stabilized by the top and bottom modules. The light top module pulls the robot upward; the lowest module’s weight (including ballast) at the bottom of the balloon pulls the robot downward. The torque exerted by these opposing forces straightens out the robot. This approach also means the robot’s design is scalable (adding modules can accommodate larger payloads) and robust (modules can be swapped out).

C. Light weight

Humanoid robots typically have multiple degrees of freedom (DOFs), requiring many cables and an adequate power supply, which could be heavy. To show that this problem is not prohibitive, commonly available components were used for our prototype: 5 microservos (2.5g each), a gear motor and sliding apparatus from a toy (27g), a microcontroller and Bluetooth board (9g), 26 AWG wire, lithium polymer batteries (3g and 29g each), and nylon balloons heavier than polyester but with better gas retention. What about a robot with more than 6 DOFs? Using the actuators and balloons above (each capable of lifting 80g), a typical number of actuators such as 40 could be lifted by two full balloons. Using light components such as in the 10g flying robot in [24], could realize a much lighter, smaller robot.

D. The Platform

The developed prototype, shown in Fig. 2, can be seen moving in a smooth, "ghostly" manner by flapping two wings on its posterior side, in the accompanying video to this paper. Although of low-cost and minimally-designed, Angel can fly over obstacles difficult for typical humanoid robots, and perform human-like communicative motions (turning her head and pointing) which are not possible for typical flying robots. We hope this will encourage others to try designing FHRs.

IV. SAFE FLIGHT (Z-PROXEMICS)

After an embodiment is available, an essential concern toward eventually realizing autonomy for a flying humanoid robot (FHR) such as Angel is: how can such a robot safely approach and accompany people? This question of how a robot should position itself and keep distance from a human ("proxemics") has until now only been considered in two dimensions. In 3D, this problem becomes even more important, because a human may not be able to adjust the distance to their comfort. Thus, in this section, we introduce considerations for "z-proxemics", which we define as the problem of finding where a robot can move and position itself in 3D space. (Some predictions are evaluated in Section VI.) Two cases are considered here: in the former, a robot approaches a stationary human partner, and in the latter, a robot accompanies a moving human and avoids collisions.

A. Approaching a human (stationary case)

In positioning itself for interaction, a FHR should move close enough to interact and call attention to its presence ("sociopetal" force) but not threaten ("sociofugal" force) or obstruct a person, while minimizing work moving. But, how can this be modeled in 3D?

1) Simple model

First a trivial solution based only on current knowledge is considered. Interaction distance may be modeled by a circle, as in the work of Edward Hall, the founder of proxemics [6]. Around the circle markers can be placed to denote the positional equilibria identified by Adam Kendon for where a person would normally stand during an interaction: "vis-à-vis", "L", or "side-by-side" [8]. Extending this circle to 3D yields a simple sphere model, possibly with stripes to represent good positions for a robot, as shown in Fig. 3a.

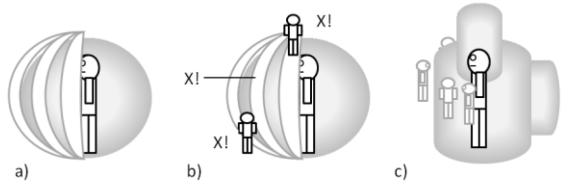

Fig. 3. 3D positioning space for a robot: a) simple sphere model (stripes represent F-formation equilibria), b) problems with the simple model (a FHR can be too close to head or feet and face should be seen) c) proposed model for 3D with equilibria

One indication that this simple model may be insufficient is that robotics researchers are finding that the boundaries of personal space are not isotropic in two dimensions: people may not want a robot behind them [18] and may prefer a robot to approach from the side rather than the front [9]; further anisotropies are likely to exist in the 3D case. Also, it is not clear how to map the two-dimensional equilibria to three dimensions (are "stripes" appropriate?). Additional knowledge is required to find good positions for a FHR.

2) Proposed Model

Fig. 3b shows some short-comings of the simple model leading to, and discussed in, the predictions below.

Prediction 1 (Shape): The top of the proxemic boundary should be higher than in the simple sphere model because the humanoid form is longer along the superior-inferior (z) axis than along the 2D dorsoventral and mediolateral axes (x and y). The legs of a robot positioned over a human with its center of mass on the surface of a ~1 meter radius sphere could "intersect" the human, which is obviously undesirable. Furthermore, people will not want a robot to come too close to their heads, as the head is the center for sensing and of great importance. People will also not want a robot above their heads, regardless of how far away it is, as the robot could fall or drop something; the humanoid form may furthermore convey a rude impression if the robot's feet seem dirty or poised to kick the person. A FHR should also not draw too near to a person's feet as this introduces the possibility of tripping or colliding if the person walks: it is also bothersome for people to have to check to avoid such a happening. Thus, a FHR should not fly too close to or above a person's head, or next to a person's feet.

Prediction 2 (Equilibria): A humanoid robot should typically position itself so that its face and gestures are visible (but not distracting). People sometimes look at each others' faces when talking and observe gestures, which provide non-verbal cues facilitating communication. If a humanoid robot's face and body cannot ever be seen, these channels of information become useless and communication is restricted. Craning one's neck and prolonged/excessive neck flexion are also known to cause pain [20]. Therefore, a FHR should typically position itself such that $z_R/z_H = 1 - c$, where z_R is the height of the center of the robot's face, z_H is the height of the center of the person's face, and c is some small quantity.

These predictions, along with the findings in [18] and [9], lead to the proposed model, shown in Fig. 3c.

B. Accompanying a human (collision avoidance)

We briefly consider the case of a flying humanoid robot (FHR) accompanying a human. Evaluating a detailed model is outside of the scope of this paper; therefore we apply the predictions of the previous subsection to adapt an existing, proved model for collision avoidance. If the predictions (tested in Section VI) are valid, the usefulness of the model should follow. Key concepts are described below.

In general, a FHR will fly ~1m from a person's side (an azimuthal angle of ~90° between walking direction and a vector from human to FHR), with a velocity $\mathbf{v_R}$ similar to the human's, $\mathbf{v_H}$, (typically ~1m/s). The FHR may look with gaze $\mathbf{G_R}$ and orientation $\mathbf{O_R}$ toward the human, a navigation goal, and objects of interest, to convey its focus of attention and engage in turn-taking. Useful information for the 2D case may be found in [13]. A challenge is that, in the real world, a robot cannot move with fixed velocity and at a fixed distance from a person, but is required to compensate for people's movements and avoid collisions with people, other robots, and objects.

Since the robot is intended to be a social companion for humans, it should be able to move in a way that may be perceived as natural; to this end, it seems appropriate to implement in the robot a collision avoiding scheme which has been originally used to describe human behavior, such as the Social Force Model (SFM) [7]. According to this model a pedestrian (the robot) feels a "dragging force" which results in motion toward a goal with a given velocity, while variations from this preferred velocity are determined by the "social force" felt with respect to other pedestrians and obstacles.

The main obstacle in applying this model to the current problem is that the SFM was designed to describe the inherently 2D motion of human pedestrians, whereas a flying robot should also make use of its 3D motion capabilities to avoid collisions. The original "Circular Specification" (CS) of the SFM, which modeled interaction forces as circles, can be trivially extended to 3D (hereafter referred to as Spherical Specification or SpS), requiring a robot to feel a repulsive force opposite to the center of mass of a human as

$$\boldsymbol{f}_{rh}^{SpS} = Ae^{-d_{rh}/B}\,\frac{\boldsymbol{d}_{rh}}{d_{rh}} \tag{1}$$

where $\mathbf{d_{rh}}$ is the 3D displacement vector from the human's center of mass to the robot's center of mass (d_{rh} is the magnitude of such a vector, or relative distance), A is the "interaction force", and B is the "interaction length" people seek to establish between themselves and others to protect themselves. While the simplicity of this SpS model is appealing, it suffers from the same limitations of its 2D (CS) version, which make it useful only for the panic and evacuation situations it was designed for, but not for normal social interactions. We consider two FHRs approaching in a large 3D channel from opposite directions, as in Fig. 4a. According to the SpS, the forces felt (dashed lines) will mainly be directed opposite to their velocities (solid lines), causing them to slow down. It is clear that such a deceleration is neither optimal nor realistic for a human in this situation, in which stepping aside while keeping the same velocity (i.e., experiencing a force orthogonal to the direction of motion) is sufficient to avoid a collision. [23] introduces a different specification, Collision Prediction (CP), which computes the time t′ at which two pedestrians will find themselves at a minimum relative distance, d′(t′), assuming that they maintain their velocities, and computes the interaction forces by substituting this future minimum relative distance into (1) as

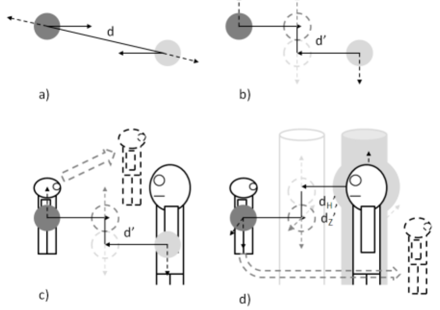

Fig. 4. Modeling 3D collision avoidance with social forces: a) difficult case for Spherical Specification (SpS), b) a solution via Collision Prediction (3CP) c) difficulty of using spherical fields for humans in 3D, d) proposed model

$$\boldsymbol{f}_{rh}^{3CP} = \frac{v}{t'}Ae^{-d'_{rh}/B}\,\frac{\boldsymbol{d'}_{rh}}{d'_{rh}} \tag{2}$$

(The term v/t′, where v is the speed of the robot, is required for a robot to slow down faster when a collision is predicted to occur soon; this term is explained, and further details provided, in [23].) Fig. 4b shows how, for the situation depicted in Fig. 4a, (2) leads to realistic avoidance behavior without the robots slowing down. The CP specification has been proved to better describe the details of human behavior than previous specifications of the SFM. By "3CP" above in (2), we mean the trivial extension of the original equation to 3D by taking in account (future predicted minimum) 3D displacement vectors, i.e., by generating spherical repulsion fields around the centers of mass of pedestrians.

We believe that this specification can well describe robot-robot interactions, as well as interactions with obstacles. Nevertheless some pitfalls arise when it is applied to 3D robot-human interactions. The validity of the circular approach (applying circular fields around the pedestrian center of mass in a 2D plane) is related to the fact that the parts of the body that humans most want to protect from possible collisions (head, heart, lungs, guts, and genitalia, etc.) are located close to an axis in the z direction that passes through the center of mass (the center of the circle). This validity is lost in 3D where the head, one of the parts that humans want to protect most from possible collisions, is peripheral with respect to the center of mass. We consider a FHR and human approaching from opposite directions, as in Fig. 4c. If the force applied from the human's center of mass is insufficient, the robot will collide with the human's head, potentially with disastrous consequences. (Likewise, if the force is large, a robot will make undesirably long detours around a person's sides, which may irritate its waiting companion.)

Positioning the spherical field about the center of a person's head can protect this part, but a robot should also not collide with a person's body or feet; a weaker repulsive field about the z axis can be used for this purpose. Thus, we propose a simplest HBCP (Head-Body CP) specification shown in Fig. 4d in which a robot preferentially tries to avoid the head of a human but also seeks to avoid any collision as follows:

$$\boldsymbol{f}^{HBCP}_{rh} = \frac{v}{t'}\left(A^{H} e^{-d'_{rH}/B^{H}} \frac{\mathbf{d'}_{rH}}{d'_{rH}} + A^{Z} e^{-d'_{rZ}/B^{Z}} \frac{\mathbf{d'}_{rZ}}{d'_{rZ}} \right) \quad (3)$$

In (3) $\mathbf{d'}_{rH}$ and $\mathbf{d'}_{rZ}$ account for (future predicted minimum) displacement vectors in 3D from a human's head center to the robot and in 2D from the z axis along the center of the person to the robot respectively, while A^H, B^H, A^Z and B^Z represent head and body (z axis) specific parameters.

In summary, a FHR accompanying and passing people, as well as other robots, can use (2) and (3) to achieve natural motion and collision avoidance.

C. Other Notes

In summary, a model was proposed for how a FHR can move and position itself in three dimensions (z-proxemics) during an interaction. To implement the model for approaching, a robot should minimally recognize where it is in 3D, where its human partner is, and which direction the human is facing. For collision avoidance, a robot should also perceive its and others' velocities. An advanced robot can move to prevent obstructing a person from seeing or touching objects of interest (by recognizing gaze focus). In sensing, a robot will detect "blobs" which may not correspond to humans or robots (e.g., bags, umbrellas, waving arms, or balloons); such an obstacle can be modeled by a point source (exerting less repulsive force than a human). As well, a FHR should avoid floors and ceilings; this can be realized via a trivial extension to the 2D CP model's wall avoidance calculation.

V. THE "LANGUAGE" OF HUMANOID FLIGHT (Z-KINESICS)

Angel should be able to fly not only safely but also expressively to suggest that she is happy, excited or playful. Body movements convey meanings [1], and basic knowledge of how people perceive flying motions ("z-kinesics") will be useful for a robot to present a consistent, meaningful impression, while adding a new information channel and richness to interactions. Thus, basic kinds of flying motions were identified, and predictions made for how they would be perceived in a humanoid form (evaluated in Section VI).

A. Previous work

Developmental robotics studies have described how complex motions can be seen as combinations of "primitive motions" [11], but it is unclear what these might be for a flying humanoid robot (FHR) or how they will be perceived. Other research has explored how a robot can communicate emotion, via facial expression, gaze, and babbling [2], and via posture, velocity and largeness of motions [15]. The latter, like this work, focuses on kinesics, but a large difference exists: the current focus is not on how to make a specific motion (pointing or waving in the above work) appear happy or sad, but rather to reveal any fundamental structure which exists in the way people perceive representative flying motions.

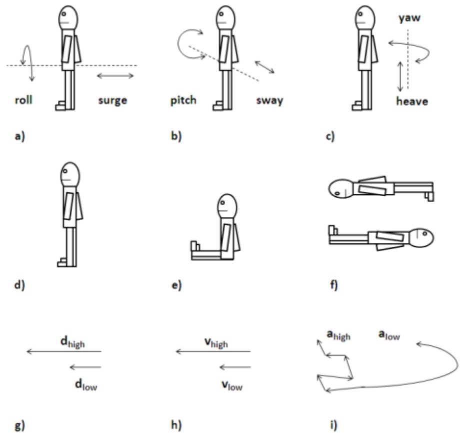

Fig. 5. Kinesics of flight for a humanoid robot: a-c) primitive motions, d-f) postures (standing, sitting, lying) g-i) style of flight: high/low displacement, velocity, acceleration (insect-like or bird-like)

In human science, Ekman and Friesen identified five basic types of human motions, including, but not limited to, emotional displays [5]. These categories can be used to imagine some specific examples of flying motions. E.g., a FHR can trace out a heart in mid-air as an *emblem* to express "love"; but this scheme cannot be used to predict how people will perceive a robot's typical flying motions.

Thus, no previous work describes how people will perceive the motions of a FHR in 3D. The approach proposed here was to consider the effects of primitive motions (as in [11]), as well as key descriptors ([15]), while keeping in mind that motions may have semiotic as well as emotional meanings [5].

B. Proposed Approach

We consider flight dynamics at a general level. Free motion of an entire body in three dimensions may be described in terms of primitive operations (rotations and translations) about the body's center of mass. In this study, the terms "roll", "pitch", and "yaw" are used for rotations about, and "surge", "sway", and "heave" (from nautical parlance) for translations along a humanoid robot's dorsoventral, mediolateral, and superior-inferior axes. Next, we consider that flying bodies exhibit temporally-consistent postural preferences. For an airplane headed toward a goal, this could denote angular equilibria in "wing level", "trim" and "heading". For a humanoid robot, typical human postures such as standing, sitting, and lying down seem appropriate. In addition, flying bodies exhibit changes in position, velocity, and acceleration which collectively describe the overall manner of motion. Large changes in these descriptors result in large, fast, and jerky motions; small changes result in small, slow, and smooth motions. E.g., for the last factor, this could in biological terms mean saccadic, insect-like flight, versus smooth, avian-like flight. Thus, the typical flying patterns in Fig. 5 were chosen, varying in primitive motion, posture, and flight manner.

C. Predictions

The following predictions were made based on the representative motions and descriptors above:

Prediction 1 (Primitive motions): Ascending will show happiness and strong spirit; descending will show sadness and timidity. Sway will indicate playfulness or obstruct. Pitch will show agreement (nodding). Roll will show uncertainty or boredom. Yaw will be seen as disagreement (head-shaking).

Prediction 2 (Postures): Standing will be perceived as normal, while sitting and lying may be seen as playful or strange; lying will also be seen as sleepy (unaroused).

Prediction 3 (Manner of flight): Largeness of motion, velocity, and acceleration will indicate arousal.

Thus, Angel should be able to show happiness, excitement, and playfulness through the identified criteria.

VI. EVALUATION

Data were obtained from participants to check the models for proxemics and kinesics developed in Sections IV and V.

A. Method

The difficulty in checking the predictions was that questionnaires and forced-word choices (e.g., with 6-10 emotions, as used in [2] and [15]) were not a practical option for this study: we were interested in people's unconscious feelings, and it would not be possible to list every meaning participants might see in a robot's motions. Another problem was that our flying humanoid robot (FHR) prototype had a distinctive appearance which could affect people's impressions and could not perform certain motions (e.g., rising or descending in place).

The approach selected was to capture participants' implicit thoughts and feelings using the Think Aloud method [19], which has been used commonly in HCI [10], and also in HRI [21]. Animations were used in place of a real robot for generality (to avoid showing hardware specifics), and to ensure any type of flight could be shown.

B. Participants

10 participants (6 females, 4 males; average age 29.4 years, SD=7.8; 6 Japanese and 4 non-Japanese) contributed data.

C. Procedure and Measures

Participants sat before a laptop computer and were told they would watch animated clips of a person and robot interacting while the robot flies in various ways; they were asked to continually describe the robot's motions and their meaning at each moment. Then, participants watched six animated clips in random order, evaluating each freely in their own words. Participants were also free to pause and replay clips and speak for as long as required during and after each clip. The experimenter took notes and prompted participants if they forgot to speak or forgot to comment on the meaning of the robot's actions. Audio was recorded and used afterwards for compiling transcriptions, which were later coded.

D. Animated Clips

The six clips, shown in Fig. 6, consisted of the following:

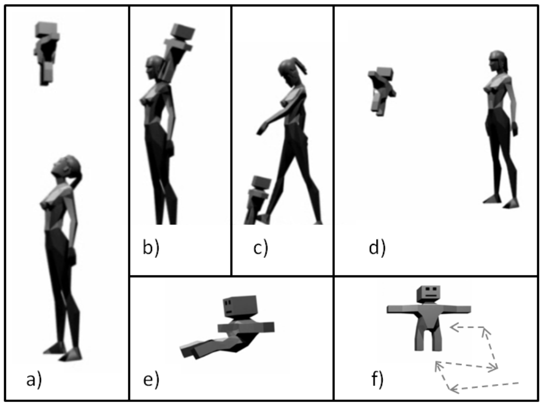

Fig. 6. Some scenes from the animated clips: a) a robot's height makes communication difficult (clip 1i) b) robot near head (clip 2i) c) robot near feet (clip 3i) d) robot rotates around roll axis (clip 4vi) e) robot sitting (clip 5ii) f) insect-like flight (clip 6iii)

Clip 1: a person and robot are conversing; the robot's height makes it (i) difficult or (ii) easy to see the robot's face.

Clip 2: robots fly (i) close to and over a person's head, or (ii) stay away.

Clip 3: robots fly (i) close to a person's feet when walking or (ii) stay away.

Clip 4: a robot interacting with a person performs primitive motions: (i-iii) translations and (iv-vi) rotations.

Clip 5: a robot flies (i) standing, (ii) sitting, or (iii) lying down.

Clip 6: a robot flies with (i) high/low displacement, (ii) velocity, and (iii) acceleration.

E. Hypothesis and Predictions

The key predictions from Section IV and V are summarized here for the reader's convenience.

1) Proxemics

Prediction 1.1 (Clip 1): A FHR should be at around head height during a conversation so the robot's face can be seen.

Prediction 1.2 (Clip 2): A robot should not fly too close to or above a person's head.

Prediction 1.3 (Clip 3): A robot should not fly too close to a person's feet when walking.

2) Kinesics

Prediction 2.1 (Clip 4): Primitive motions (translations and rotations) will show happiness/ sadness, dominance/ timidity, agreement/ disagreement, and playfulness.

Prediction 2.2 (Clip 5): Standing will appear normal.

Prediction 2.3 (Clip 6): Large displacement, velocity, and acceleration will indicate arousal.

F. Coding

After obtaining data, the desired vital information containing participants' subjective impressions was extracted from the transcripts. E.g., for the short fragment of a protocol

TABLE I. TYPICAL IMPRESSIONS ASSOCIATED WITH EACH PREDICTION AND CLIP

Prediction (Clip)	**Typical Impressions (no. of participants)***	**Prediction (Clip)**	**Typical Impressions(no. of participants)***
1.1 (1i)	No communication (6), no eye contact (2)	1.1 (1ii)	Communication occurs (10), eye contact (2), friendly (2)
1.2 (2i)	Scary (6), dangerous (6), disrespectful (2), mischievous (2)	1.2 (2ii)	Safe (3), indifferent (2)
1.3 (3i)	Dangerous (8), child-like (3), abnormal (3), bothersome (2)	1.3 (3ii)	Safe (6)
2.1 (4i)	*Up:* robot was ordered to move (3), going to do a task (2); *Down:* robot was ordered (4), is avoiding (2) , talk ended (2)	2.1 (4ii)	*Close*: robot was ordered (5), wants to talk (4), can't hear (2); *Away:* ordered (4), doesn't want to talk (3), conversation over (2), scared (2), has another task (2)
2.1 (4iii)	*Sway*: robots wants to avoids something (6), was commanded (4), or wishes to look at something (3)	2.1 (4iv)	*Pitch*: robot agrees (4), is greeting (3), playing (3), happy (2)
2.1 (4v)	*Yaw*: robot disagrees (6), circumspection (2), playing (2)	2.1 (4vi)	*Roll*: robot is happy (3), playing (2), wants attention (2)
2.2 (5i)	*Standing:* normal (4), straight (4), walking (3)	2.2 (5ii)	*Sitting:* sliding (5), comfortable (3), funny (2), hyper (2)
2.2 (5iii)	*Lying Supine:* robot is relaxing (5), being pulled (5), dead (2); *Prone:* robot is watching below (3), being pulled (3), lethargic (2), depressed (2), dead (2)	2.3 (6i)	*Displacement High*: robot has not attained its goal (3); *Low:* something happened (3)
2.3 (6ii)	*Velocity High:* robot is scary (6); *Low*: irritating (2)	2.3 (6iii)	*Acceleration High:* hopping (9), happy (6), weird (2), wild (2), has a desire (2); *Low:* happy (3), gentle (3)

*The number in parentheses indicates the number of participants who reported this typical impression

(verbal report from a participant thinking) below, we were most interested in the italicized words and phrases.

1. Oh my.
2. The robots came close, then one passed to the left and one flew over the top of a person's head.
3. The person didn't get *startled*.
4. *Normally you'd crouch down* a bit.
5. Thinking they were *going to collide*.
6. Oh…!
7. The robots came closer (than before).
8. That *surprised* me.
9. They came very close and avoided at the last moment.

The above example shows that participants used different words, such as "startled" and "surprised", to refer to similar concepts. Other examples are "communicating" and "talking"; or "bother", "hard to walk", and "robot blocked her". Code labels were used to gather such statements which share a similar meaning. As a result, *typical* impressions (code labels shared by more than one person) could be separated from outliers, yielding Table 1.

G. Results

Participants' typical impressions in Table 1 were compared to our predictions.

1) Proxemics

Predictions 1.1, 1.2, and 1.3 were supported by participants' reactions. As per Prediction 1.1, communication did not occur when a robot's face was hard to see (1i) but did when the robot was at head height (1ii); for Predictions 1.2 and 1.3, robots which did not keep away from a person's head and feet were deemed unsafe, scary, and bothersome (2i, 3i), whereas those that did were considered safe (2ii, 3ii).

2) Kinesics

Prediction 2.1, that primitive motions could be used to show valence, dominance, agreement and playfulness, was only partially supported. Translations (4i-iii) were interpreted to be mostly proxemic in function, rather than emotional, although for rotations (4iv-vi), some participants perceived playfulness and commented that the robot was nodding or shaking its head (even though the motions shown were quite different from typical nodding or head-shaking). Prediction 2.2, that standing will be considered normal, was supported by direct comments from approx. half of the participants (5i); other postures were associated with rare circumstances, such as being pulled or sliding (5ii-iii). Prediction 2.3, that flight manner can be used to show arousal, was supported by some comments; flight with high velocity or acceleration was considered scary or wild, whereas low acceleration flight was considered gentle (6i-iii).

In summary, we found the model proposed in Section IV anticipated, and that in Section V partially anticipated, people's impressions of a FHR's flight.

VII. DISCUSSION

A first flying humanoid robot (FHR), Angel, was built; although a work in progress, Angel can communicate in a human-like fashion by turning its head and pointing which has not been possible for past flying robots, and fly over obstacles which could not be traversed by a conventional wheeled or walking humanoid robot. Additionally, predictions were made regarding z-proxemics and perceived flight kinesics, and feedback obtained for better understanding. Yet this study represents only an initial investigation into some topics of interest for a FHR; much work remains to be done, both on unaddressed topics and those covered.

A. Other important topics

A FHR design will also impact verbal and haptic communication; and dexterous manipulation will enlarge the possibilities for FHRs. For verbal communication, a FHR should take into account effects of wind and altitude on sound

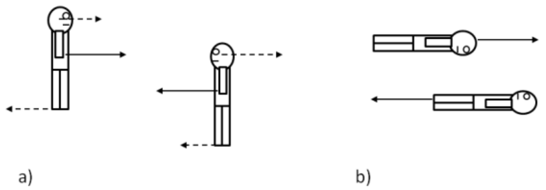

Fig. 7. Torque exerted on non-point-source FHRs spins them into natural, efficient orientations for passing

propagation to predict audibility; when loud speech or gesturing are undesirable, a cell phone connection or wristband communicator could be useful. For haptic communication with balloon-like FHRs, tensed plastic may not feel as pleasant as, e.g., urethane, but lack of friction with the ground for FHRs will result in immediate and sensitive reactions to touch, which may provide a pleasurable feeling of control. Dexterous manipulation will allow FHRs to help humans when there is trouble; advanced FHRs may provide basic life support and CPR, and use tools designed for humans, such as doorknobs and fire extinguishers.

B. *Future work on topics covered in this study*

In terms of constructing FHRs, control and energy are key issues. Egomotion recognition such as in [17], and anenometers, may help with drift due to wind and air currents. Trapping heat (Montgolfiere balloons), using “reversible liquids”, and hybrid aerodynes could avoid limitations of helium-afforded buoyancy for aerostats. Very small FHRs may borrow energy from vortex patterns like insects.

Regarding the evaluation, more participants of various cultures and ages should be used, and an actual robot in place of simulations to confirm our results. For proxemics, one fascinating topic is how to model interactions with a non-point source FHR (e.g., a robot represented by two points at its top and bottom). Forces acting on such a FHR will induce torque on each point, affecting the robot’s 3D orientation and rendering possible scenarios such as the one shown in Fig. 7. Another topic is how people will avoid collisions with a FHR (ducking, dodging, etc.). For kinesics, accurate communication of intentions and emotions through flight will be useful. In the future, we intend on the HRI side to use the developed FHR platform to engage in interactions involving play and communication of affection.

VIII. CONCLUSION

This paper reports on considerations when designing a flying humanoid robot (FHR) for human-robot interaction (HRI). A model for “z-proxemics” was proposed to show where such a robot can fly and position itself, comprising a Head-Body Collision Prediction (HBCP) specification to avoid collisions with a person. The kinesic significance of a FHR’s manner of flight was investigated. Simulations were used to confirm the validity of the models. Results suggested that a FHR should fly near head height when communicating, but not too close to or above a person’s head or near a person’s feet; that rotations can show agreement and playfulness; that a standing posture is associated with neutral impressions; and that velocity and acceleration can show arousal. The paper also described a first FHR, Angel, built to engage in playful and affectionate interactions.

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REFERENCES

[1] R. Birdwhistell, “Kinesics and Context,” University of Pennsylvania Press, Philadelphia, 1970.

[2] C. Breazeal, “Emotion and sociable humanoid robots,” *International Journal of Human-Computer Studies*, 59, 119-155, 2003.

[3] A. G. Brooks and R. C. Arkin, “Behavioral overlays for non-verbal communication expression on a humanoid robot,” Auton. Robots 22(1): 55-74, 2007.

[4] M. D. Cooney, T. Kanda, A. Alissandrakis, and H. Ishiguro, “Interaction Design for an Enjoyable Play Interaction with a Small Humanoid Robot,” *Humanoids 2011*, 2011.

[5] P. Ekman, and W. V. Friesen, “The repertoire of nonverbal behavior: Categories, origins, usage, and coding,” *Semiotica*, 1, 49-98, 1969.

[6] E. T. Hall, “The Hidden Dimension,” New York: Doubleday, 1966.

[7] D. Helbing, and A. Johansson, “Pedestrian, Crowd and Evacuation Dynamics,” *Encyclopedia of Complexity and Systems Science* 16, 6476-6495, 2010.

[8] A. Kendon, “Conducting Interaction: Patterns of Behavior in Focused Encounters,” Cambridge: Cambridge University Press, 1990.

[9] K. L. Koay, D. S. Syrdal, M. L. Walters, and K. Dautenhahn, “Living with Robots: Investigating the Habituation Effect in Participants’ Preferences During a Longitudinal Human-Robot Interaction Study,” *RO-MAN*, 2007.

[10] C. Lewis, and J. Rieman, "Task-Centered User Interface Design: A Practical Introduction," Technical Document, 1993.

[11] M. Lopes, and J. Santos-Victor, “A Developmental Roadmap for Learning by Imitation in Robots,” *SMC* - B, 37(2): 308–321, 2007.

[12] M. Mazloom, S. Kasaei, N. Alemi, “Construction and Application of SVM model and Wavelet-PCA for Face Recognition,” *ICCEE*, 2009.

[13] Y. Morales, S. Satake, R. Huq, D. Glas, T. Kanda, and N. Hagita, “How Do People Walk Side-By-Side?- Using A Computational Model of Human Behavior For A Social Robot,” *HRI 2012*, 2012.

[14] R. Murphy et al., “A Midsummer Night’s Dream (with flying robots),” *Autonomous Robots*, 30(2), 143-156, 2011.

[15] K. Nakagawa, K. Shinozawa, H. Ishiguro, T. Akimoto, and N. Hagita, “Motion modification method to control affective nuances for robots,” *IROS*, pp. 5003–5008, 2009.

[16] W.S. Ng, and E. Sharlin, “Collocated Interaction with Flying Robots”, *RO-MAN 2011*, 2011.

[17] R. Roberts, C. Potthast, and F. Dellaert, “Learning General Optical Flow Subspaces for Egomotion Estimation and Detection of Motion Anomalies,” *CVPR 2009*: 57-64, 2009.

[18] E. A. Sisbot, L. F. Marin-Urias, R. Alami, and T. Simeon, “A Human Aware Mobile Robot Motion Planner,” IEEE Transactions on Robotics, Volume: 23, Issue: 5, pp: 874-883, 2007.

[19] M. W. van Someren, Y. F. Barnard, and J.A. C. Sandberg, “The Think Aloud Method: A Practical Guide to Modelling Cognitive Processes,” San Diego: Academic Press, 1994.

[20] L. Straker, C. Pollock, R. Burgess-Limerick, R. Skoss, and J. Coleman, “The impact of computer display height and desk design on muscle activity during information technology work by young adults,” *Journal of Electromyography and Kinesiology* 18(4): 606-617, 2008.

[21] A. Weiss, R. Bernhaupt, M. Tscheligi, and I. Yoshida, “Addressing User Experience and Societal Impact in a User Study with a Humanoid Robot,” Workshop at *AISB 2009*, 2009.

[22] J. Weizenbaum, "ELIZA — A Computer Program For the Study of Natural Language Communication Between Man And Machine," *Communications of the ACM* 9 (1): 36–45, 1966.

[23] F. Zanlungo, T. Ikeda, and T. Kanda, “Social force model with explicit collision prediction,” *Europhysics Letters Journal* 93-68005, 2011.

[24] J.-C. Zufferey, A. Klaptocz, A. Beyeler, J.-D. Nicoud, and D. Floreano. “A 10-gram Vision-based Flying Robot,” *Advanced Robotics*, 21(14) pp. 1671-1684, 2007.