Communicating Directionality in Flying Robots

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ABSTRACT

Small flying robots represent a rapidly emerging family of robotic technologies with aerial capabilities that enable unique forms of assistance in a variety of collaborative tasks. Such tasks will necessitate interaction with humans in close proximity, requiring that designers consider human perceptions regarding robots flying and acting within human environments. We explore the design space regarding explicit robot communication of flight intentions to nearby viewers. We apply design constraints to robot flight behaviors, using biological and airplane flight as inspiration, and develop a set of signaling mechanisms for visually communicating directionality while operating under such constraints. We implement our designs on two commercial flyers, requiring little modification to the base platforms, and evaluate each signaling mechanism, as well as a no-signaling baseline, in a user study in which participants were asked to predict robot intent. We found that three of our designs significantly improved viewer response time and accuracy over the baseline and that the form of the signal offered tradeoffs in precision, generalizability, and perceived robot usability.

Categories and Subject Descriptors

H.1.2 [**Models and Principles**]: User/Machine Systems—*human factors, software psychology*; H.5.2 [**Information Interfaces and Presentation**]: User Interfaces—*evaluation/methodology, user-centered design*

General Terms

Design, Human Factors

Keywords

Robot design; signaling intent; free-flyers; micro air vehicles (MAVs)

1. INTRODUCTION

Recent advances in robotics have enabled a rapid proliferation of small flying robots envisioned to assist humans using aerial abilities that enable free traversal through environments. Such flying assistants are predicted to provide aid in domains including construction [19], power and utilities [36], search and rescue [15], and space exploration [11, 12] by performing sensing, surveillance, inspection, mapping, telepresence, and delivery tasks. These robots currently take a variety of form factors, including multirotors, blimps, small fixed- or flapping-wing aircraft, and floating space-robots. These embodiments all feature a functional, rather than zoomorphic or anthropomorphic, appearance. Lacking cues from robot morphology and established mental models for interacting with free-flying embodiments, while also faced with the prospect of robot movement in any direction at any time, users may experience difficulties predicting robot goals as well as where, when, how far, and how fast the robot will move. Thus, while unconstrained aerial abilities present unique opportunities for assistance, they also pose a challenge in achieving effective human-robot interaction.

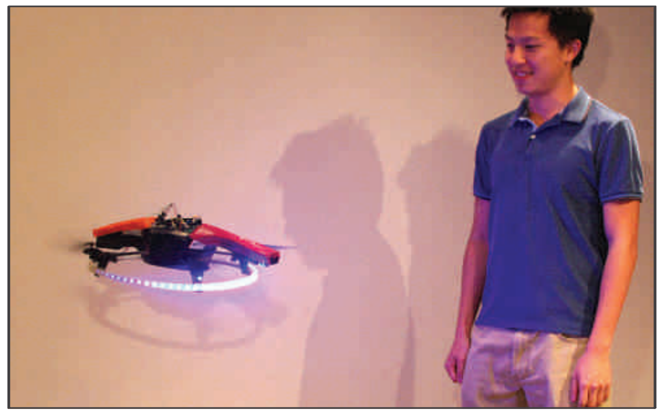

Figure 1: We explore the design of visual signaling mechanisms for flying robots to support the expression of robot intent and increase usability in colocated interactions.

For aerial robots to successfully work and collaborate with proximal users, designers must account for human perceptions of small flying robots traveling within shared environments. Recent research has begun to examine perceptions of aerial robot morphology [2] and proxemics [8]. Additionally, research has explored the *implicit* expression of flight intent [34] and affect [33] by manipulating aerial trajectories, velocities, and accelerations across three spatial dimensions. However, task or environmental factors, such as confined operating spaces, power optimization, or distance from the user, may limit the saliency and clarity of such cues. The goal of this work is to inform the design of flyers that are able to *explicitly* provide intended flight directionality to users at a glance. Such information will support transient proximal interactions, such as when users pass by robots in hallways or indoor environments, and enhance collaborations in which robots act as peers. To this end, we explore the

HRI'15, March 2–5, 2015, Portland, OR, USA.

ACM 978-1-4503-2883-8/15/03 ...$15.00.
http://dx.doi.org/10.1145/2696454.2696475 .

application of flight constraints to leverage users' prior experiences with flying objects and design visual signaling mechanisms that allow robots to express their direction of flight to nearby humans.

In this paper, we outline relevant work that informed our design process and describe our application of flight constraints and the development of visual signals as a solution space for signaling flight directionality (Figure 1). We describe the development of four different reference designs that sample this space, each of which aims to leverage prior user familiarity with light signals as a communicative mechanism. As current platforms lack the capabilities to express our signal designs, we also detail the development of a payload, which can be built or 3D-printed and attached to a flyer, that contains an array of LEDs on which we implement our designs. We present a user study evaluating our designs and conclude with a discussion highlighting the importance of considering robot expression of intent for user interaction, particularly for aerial robots with a high degree of potential mobility.

2. BACKGROUND

Our work draws from an emerging body of research focused on communicating robot intent. Additionally, our designs are informed by the flight movements of familiar artifacts such as planes and flying animals in the natural world. We also draw from human-computer interaction research focusing on the communicative affordances of light signals as communicative mechanisms in product design, which can enable intuitive feedback and features a long history of use across a wide variety of commercial products.

2.1 Communicating Robot Intent

User interactions with existing small aerial robots involve a large "gulf of evaluation" [26] where a gap exists between representations provided by a system and user abilities to asses and interpret the system. This gap arises partly from the lack of abilities such robots currently have in effectively communicating with users. Further, due to technological novelty, the potential for unconstrained movements, and lack of prior knowledge or experience, users may have few or incorrect expectations regarding how these robots will behave.

Designing expressive flight motions appears to be one promising approach to bridge this gulf. Designers seeking to craft expressive motions can draw from an increasingly rich investigation into human understandings of robot motion (e.g., [7, 20, 21, 30]). Human-aware motions have been explored for a variety robots with anthropomorphic and zoomorphic features [3, 14, 16, 24, 35], and recent approaches demonstrate the promise of applying similar methods to communicate flying robot intent [34] and affect [33].

However, such expression often requires simultaneously manipulating motion across three spatial dimensions, which may be impossible, impractical, or costly due to environmental, task, power, computational, or platform considerations. Instead, designers might wish to constrain the motion of flyers to better integrate with human social norms or enable assistance in confined spaces.

2.2 Flight Constraints

Constraints are a powerful design tool that can shape users' conceptual models during interactions [25]. An example use of this tool for designing human-robot interactions is the application of constraints to the design of motion trajectories so that mobile ground robots better follow human conventions [22].

In a similar manner, while small aerial robots can freely move in three dimensions simultaneously, such motion may not be conducive to human experiences, which generally occur only in two dimensions. Instead, the motions of airplanes and birds provides an implicit convention for constraining robot flight. Airplanes generally fly in "lanes" at fixed altitudes, changing height only when taking off, landing, or switching lanes. Likewise, birds glide at various constant altitudes while soaring in thermal updrafts [32].

Applying similar constraints to robot flight (e.g., [13]) by enabling free flight motions only in two-dimensional planes (manipulating pitch, yaw, and roll), while changing such altitudinal planes (manipulating thrust) only while otherwise hovering in place, might better support user conceptual models. Additionally, constraining flight behaviors in this manner might enable robots to work more effectively in some of the confined environments in which flyers are envisioned to provide assistance, such as construction sites, indoor spaces during search and rescue, and space stations.

2.3 Signaling Mechanisms

While flight constraints might leverage users' previous experiences and mental models regarding flight behaviors, thereby supporting movement in confined environments, robots using constrained flight may no longer be able to utilize motion as an implicit form of communication, necessitating the exploration of alternative communicative mediums. Flyers seeking to communicate with users may use visual (e.g., lights, displays) [12], auditory (e.g., synthesized speech, non-linguistic utterances [27]), or even haptic (e.g., perching behaviors [38]) mechanisms. However, the high degree of background noise created by the propellers of many current flyers, the inefficiency of utilizing audio cues in conveying directional information, and the potential for safety or social concerns regarding flying robots invading users' personal space place limitations on the potential for auditory and haptic feedback regarding flight intent. Instead, we explore the rich design space regarding the development of visual communication mechanisms for flying robots.

Prior work in human visual perception has shown that dynamic visual cues convey complex properties even in simple animations [5, 29], including indications of animacy and intent [37]. Similarly, research in abstract luminescent displays [23] and lighting dynamics [18] indicates that light can evoke high-level social and emotional responses. However, to date no work has explored the design of directional signals for flying robots, which requires a consideration of viewing angles, an ability to convey movement in multiple dimensions, the potential for signal occlusion, ambient lighting conditions, and cultural connotations of display properties such as color.

Integrating electronic screens in flying robots (e.g., [12]) presents one option for high-fidelity visual feedback. However, screens suffer from a number of limitations, making them less desirable for communicating flight intent. On terrestrial flyers, screens would have to be small to balance weight considerations, providing little feedback except at short distances. Additionally, screens only support unidirectional viewing from a relatively small angle, creating a high potential for occlusion and missed signals. Powering high-fidelity screens may drastically cut into flight time, which is currently a primary consideration limiting the deployment of flyers. While future systems might combine fixed-wing gliding with agile multirotor movements to conserve battery [31] or make use of exotic power systems such as laser beaming [1], current systems generally have flight times between 10–50 minutes [9].

Alternatively, many commercial platforms, such as the Parrot AR.Drone 2.0[1] and the DJI Phantom 2,[2] include a small number of LEDs (typically 4–12) that may aid pilots in orientation during flight in a similar manner to airplane navigation lights. However, while prior research has demonstrated the effectiveness of even a single LED in communicating system state to users for consumer devices

[1] http://ardrone2.parrot.com/

[2] http://www.dji.com/product/phantom-2

such as cell phones and coffeemakers [17], such setups might not be able to capture and convey the complex space of flight intent. Further, ambient lighting conditions may decrease visual saliency when using only a small number of LEDs, while the positioning of the LEDs favors only a limited viewing angle (directly below the robot). To address the limitations of screens and current LED designs, we sought to develop visual signals that might support communication rich enough to convey flight intent while remaining salient across a wide range of perspectives and lighting conditions.

3. DESIGN PROCESS

We undertook an iterative design process aimed at realizing a vision of flying robots that can use dynamic visual cues to effectively communicate with nearby users to increase interaction efficiency, naturalness, and satisfaction. Our design process began with an analysis of design constraints and specifications: minimizing power consumption, supporting a wide range of viewing angles and lighting conditions, requiring minimal modifications to existing flyer designs, and, most importantly, providing affordances for the expression of flight directionality. Through a process of iterative ideation, we devised a ring of LED lights surrounding a flyer as a global metaphor that could support 360° viewing-angles while providing a design space for the development of compelling and evocative flight signals. We developed four such signals as reference designs based on metaphors of common user experiences that sample from the potentially unbounded space of using light as a mechanism for signaling flight intent. Finally, we constructed a modular payload, easily integrated with existing commercial platforms, which enabled physical implementation of our signal designs.

3.1 Designing Light Behaviors

We designed several signal behaviors to indicate various flight motions using the global metaphor of a ring of light surrounding small robotic flyers operating within our constrained flight space. In our design, the entire ring glowed at a high intensity when changing altitude "lanes" due to the importance in communicating this

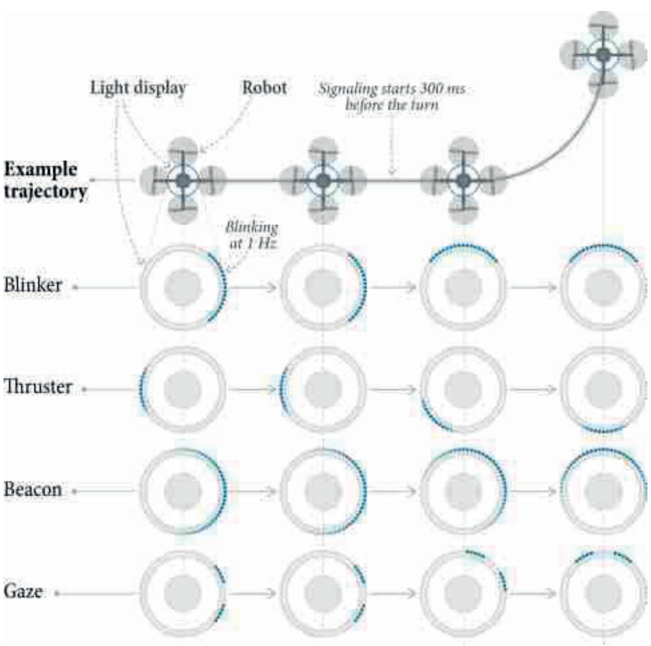

Figure 2: We developed four signal designs drawing from common user experiences with light as a communicative mechanism.

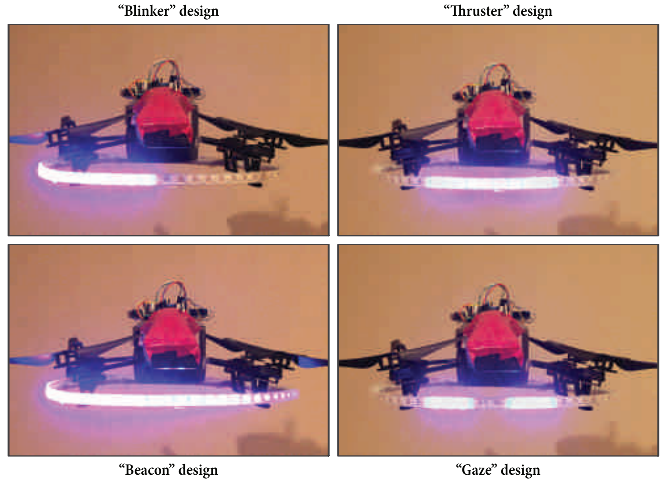

Figure 3: Above, we illustrate physical implementations of the blinker, beacon, thruster, and gaze signals.

ability to users who lack experience with artifacts capable of such movements. To communicate the direction of flight while moving within a plane, as well as transitioning to and from hovering states, we developed four high-level signal metaphors as reference designs, which we refer to as *blinker*, *beacon*, *thruster*, and *gaze* (Figure 2).

Blinker — The blinker design applied the metaphor of automobile turn indicators to a flying robot. Turn indicators using flashing lights serve as an effective mechanism for automobile drivers to convey information regarding future movement in a single dimension (left or right). In our blinker design, a section representing one-quarter of the LED ring, centered on the future direction of movement, blinked at a frequency of 1 Hz prior to changes in movement.

Beacon — The beacon signal followed the metaphor of a beam of light pointing the way, as in flashlights or lighthouses, creating an organic and evocative signal. While hovering, all LEDs were set to a constant low intensity. Prior to movement, light "bunched up" in a gradient by sampling intensity values for LEDs from a Gaussian function centered on the future movement vector, defined as:

$$I(x) = b \times e^{-(x-v)^2 / w\pi^2}$$

where $I(x)$ indicates the intensity $[0,b]$ of LED x; b is a brightness constant determining maximum brightness at the center of the distribution (255 was used in our design); v is the planned motion vector; and w is a variable determining the width of the distribution (10 was used in our design). Increasing b increases beacon intensity, potentially increasing visual saliency. Increasing w "widens" the beacon by reducing fall-off in LED intensity surrounding v, potentially increasing perceptible viewing angles but reducing beacon precision. When changing directions, the beacon smoothly rotated to face the new motion vector, and when slowing to hover, the light diffused back to a uniform low-intensity state.

Thruster — The thruster signal used the metaphor of light and flames produced in jet engines propelling airplanes and spacecraft. In this design, we envisioned light emanating in a focused, high-intensity region along the "back" of the LED ring—in the area opposite to the direction of primary movement. The light representing the thruster rotated along the ring to adjust to changes in movement and "died down" in intensity when slowing and hovering.

Gaze — The gaze signal was inspired by biological motion and the expressive potential of human eye movements. Gaze behaviors can allow observers to divine others' goals, intentions, and potential motions, and imbuing flyers with similar behaviors might increase their social presence in addition to providing mechanisms for con-

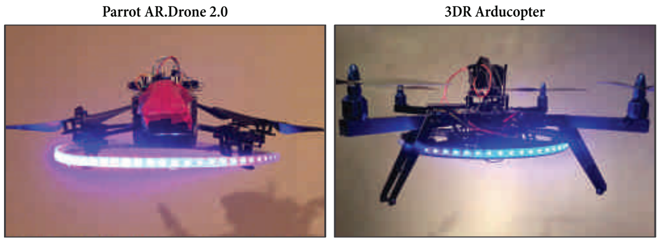

Figure 4: We designed and prototyped a payload to implement our signal designs that easily integrates with two commercial flyers: the Parrot AR.Drone 2.0 (left) and the 3DR Arducopter (right).

veying directionality. In the gaze design, lighting up two regions in close proximity to each other created two small "eyes," which rotated to "look" where the robot intended to fly. We designed eye sizes, distances between the eyes, and rotation speeds using measurements of human eye size [28], inter-pupillary distances [6], and saccade timings [10], and applied scaling factors to account for size differences between the human head and the LED ring.

3.2 Implementing Light Signals

To implement our designs, we designed and prototyped a payload, in the shape of a ring that can be mounted to the legs of existing commercial flyers, containing an Arduino microcontroller[3] and an array of 64 individually-controllable, multi-color LEDs.[4] The payload structure can either be constructed manually using lightweight PVC piping or with 3D printing. The Arduino governs the LEDs, requiring only a future movement vector v from the motion planning software piloting the flyer (or a joystick if the robot is manually piloted), and exposes an interface over both 802.11 and Bluetooth wireless communication protocols. The LED ring, an Adafruit NeoPixel digital RGB LED strip,[5] enables the manipulation of three variables: LED *color* (RGB), *intensity* [0,255], and *position* [0,63]. Intensity and position over time were determined by signal design, as described above. Across all designs, we treated color as a constant variable c, for which we selected blue to avoid potential cultural connotations (e.g., red indicating stop, green go, yellow yield). Figure 3 shows the visual appearance of the designs implemented on our physical LED ring. We have implemented our entire payload design on both the Parrot AR.Drone 2.0 and the 3DR Arducopter (Figure 4), but we used only the former to evaluate our designs as it provided the most stable control in indoor environments.

4. EVALUATION

We conducted a 5×2 within-participants user study to examine how our designs might affect perceptions of a flying robot. Independent variables included signal design (five levels: a baseline no-signaling behavior where all LEDs were off, simulating existing robot behaviors, and each of the four designs detailed above) and user task (two levels: exocentric free flight movements and egocentric flight approaching the user, both at a constant altitude). Dependent variables included participants' predictions of robot intent and ratings regarding aspects of perceived robot usability.

Prior to the study, participants were instructed that they would act as "quality control" by monitoring a robot for errors as it flew to a number of targets, denoted by QR codes, during two tasks. In both tasks, participants observed a Parrot AR.Drone 2.0 carrying our signal payload take off, reach a fixed altitude 75 cm above the floor, and travel from a starting location to several targets (Figure 5).

In the first task, the flyer started in the center of the environment 280 cm from the participant and flew to eight targets located in a circle equidistant from the starting location, where each target was located 45° apart and 190 cm away from the center. In the second task, the robot started across the room 410 cm from the participant and flew to three targets, each separated by approximately 30° and located 85 cm apart. One of the three targets was directly in front of the viewer (160 cm from the starting location), and the others were to the left and right of the participant (240 cm from the starting location). In both tasks, the robot paused for 1 second when reaching a target to simulate taking a measurement before returning to the starting location. Next, the robot either repeated this process by approaching a new target or landed if the task was finished. Task 1 sampled perceptions of general flight motions navigating in an environment from an *exocentric* perspective, while Task 2 captured responses to flight motions approaching users, which are particularly important for usability and safety, from an *egocentric* perspective.

Participants were given an ordered list of the targets that the flyer would approach (eight in Task 1, three in Task 2). However, a subset of these targets were randomly changed without participants' knowledge (three in Task 1, one in Task 2). The original target order, the new targets, the targets they were replacing, and the resulting new target order were randomized for every task. Participants were provided a computer interface that timed their recording of either "correct" or "error" for each target and were instructed to respond as soon as they believed they knew where the robot would travel. For each target, participants were only allowed a single response and were unable to respond until their interface was triggered by a notification that the flyer was about to leave the starting location and approach a target. All participants completed both tasks for all five conditions, with randomized target, task, and condition order.

Custom robot control software used measurements from a ceiling-mounted camera and an onboard sonar system to track the flyer, send pitch, roll, yaw, and elevation commands for navigation, and correct disturbances in flight motion. While it constantly sent updated commands to correct the robot's flight path, this system only sent the overall vector representing the direction from the initial starting location to the current target location to the Arduino controlling the lights. This high-level motion vector was sent 300 ms prior to the start of any movement, so the lights telegraphed the overall

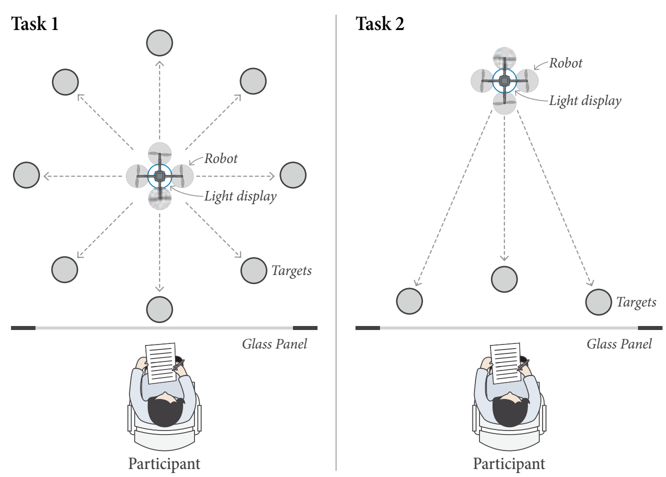

Figure 5: In our study, participants had to predict robot intent as quickly and accurately as possible as it flew to a number of targets across an exocentric task and an egocentric task.

[3] http://www.arduino.cc/

[4] Models for 3D-printing the payload to be attached to the 3DR Arducopter as well as the open-source Arduino code for implementing our designs are available at http://hci.cs.wisc.edu/projects/free-flyer-signaling/.

[5] https://www.adafruit.com/category/168

flight direction slightly before the robot began moving, rather than constantly signaling minute disturbances and corrections that might confuse users. While our system autonomously controlled the robot, an experimenter stood by with a kill-switch that could land the flyer in case of system failure. To ensure participant safety, participants were separated from the flyer by a floor-to-ceiling pane of glass.

4.1 Study Procedure

The study took roughly one hour and consisted of four phases: (1) introduction, (2) observation, (3) evaluation, (4) conclusion.

First, the experimenter obtained informed consent and seated the participant at a table separated from the robot environment by a floor-to-ceiling glass panel, through which they could see the targets and the flyer. Participants were instructed to monitor the robot as described above and were given a tutorial on the software they would use to record either "correct" or "error" while being presented with the robot's "correct" target order and the "correct" current target.

In phases 2 and 3, participants first observed the robot for both tasks in a randomly chosen order for a randomly chosen condition and then completed a questionnaire evaluating their experience and the flyer behaviors that they had just observed. Phases 2 and 3 were then repeated for each of the remaining four conditions.

In phase 4, the experimenter collected demographic information, debriefed the participant, and paid them \$10.00 for their time. Participants were told that they were evaluating five different robot control algorithms, each of which might exhibit different behaviors, but were never informed about the light signals in any way as we wanted to observe whether participants naturally and spontaneously found them intuitive and useful in predicting flyer intent.

4.2 Participants

We recruited a total of 16 participants (10 males, 6 females) from the University of Wisconsin–Madison campus. The average participant age was 23.31 (SD = 3.92), with a range of 18–31. On a seven-point scale, participants reported a moderate prior familiarity with robots (M = 4.25, SD = 1.84) but a low familiarity with small aerial robots (M = 3.06, SD = 1.69).

4.3 Measures and Analysis

Objective and subjective measurements captured the outcomes of our manipulations. Guttman scores [4] served as a composite objective measure of participant *speed*, the average time between the interface allowing participants to record either "correct" or "error" and participant responses, and *accuracy*, the number of correct responses classifying each target approach as either "correct" (matching the order given to participants) or an "error." This metric, which has been utilized to measure perceived robot intent (e.g., [7, 34]), scores incorrect responses as zero and scores correct answers based on speed, with faster answers leading to higher scores.

We constructed a number of scales using subjective responses to questionnaire items. These scales provided manipulation checks (3 items relating to communication, Cronbach's α = .931, and 4 items relating to predictability, Cronbach's α = .821) and measured how the designs affected robot usability. The designs were rated based on the clarity of robot communication (4 items, Cronbach's α = .953), how intuitive participants found robot communication (5 items, Cronbach's α = .948), and participant confidence deducing the meaning of robot communication (7 items, Cronbach's α = .913). Scales also measured perceptions of the robot as a good work partner (3 items, Cronbach's α = .861) and how difficult participants found their task (2 items, Cronbach's α = .832). Participants also gave open-ended responses regarding their impressions of the robot, its communication, and their ability to interpret intent.

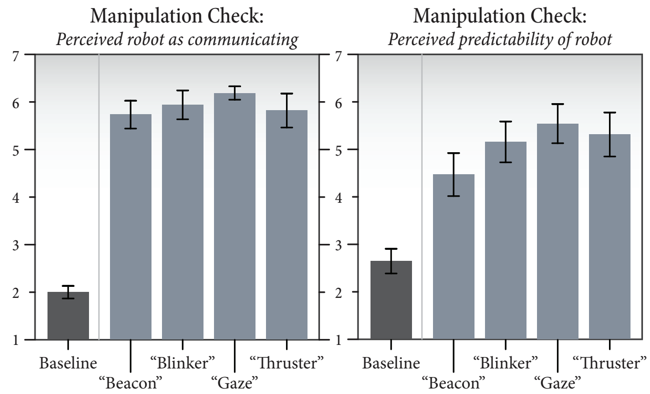

Figure 6: Manipulation checks confirmed that light signals served as communicative mechanisms, increasing robot predictability.

We analyzed data from our objective measures using a two-way repeated-measures Analysis of Covariance (ANCOVA) with type of signal design and task as fixed effects. As participants only filled out subjective responses after completing both tasks in each condition, we analyzed our subjective data using a one-way repeated-measures ANCOVA with condition as a fixed effect. Both models included participant gender, condition order, and task order as covariates to control for potential gender and transfer effects. Post-hoc tests with Bonferroni corrections determined the utility of each design across Tasks 1 and 2, while Tukey's Honestly Significant Difference (HSD) test controlled for Type I errors in all other post-hoc comparisons.

4.4 Results

Figure 6 summarizes our manipulation checks. Figure 7 summarizes our objective and subjective results.

Manipulation Checks — As we did not tell participants that the robot would use lights, or that lights might be in any way connected to flight motions, we first verified that participants noticed our designs and recognized they signaled robot intent. We found a significant effect of signal design on whether participants believed the robot was conveying its intentions, $F(4, 69) = 38.34$, $p < .001$, as well as on participants' self-rated abilities to predict changes in direction and transitions between movement and hovering, $F(4, 69) = 7.56$, $p < .001$. Post-hoc Tukey tests revealed that users differentiated the signal designs from baseline behavior in terms of telegraphing intent (all at $p < .001$) and believed that the use of gaze ($p < .001$), thruster ($p < .001$), blinker ($p < .001$), and beacon ($p = .034$) behaviors improved robot predictability over baseline flight behaviors. We further confirmed that participants were able to intuit the meanings of each design by analyzing open-ended responses describing the robots' use of light. Below we present a subset of responses representative of our data, that overall suggests that participants appeared quite adept at comprehending our designs:

Blinker:

> **P12:** "The robot blinked its lights in the direction it intended to go."
>
> **P13:** "The blue lights. . . would flash towards the direction the robot was moving or about to start moving."

Beacon:

> **P01:** "[The robot] used a gradually decreasing set of lights (brightest in the direction of movement) to signal its direction of movement. It also used a constant ring of lights to denote a stationary or hovering state."

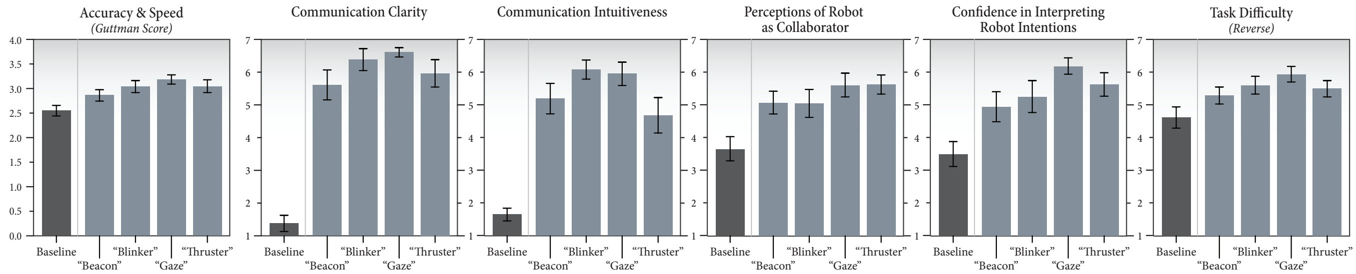

Figure 7: Results show that the gaze, blinker, and thruster designs improved participants' speed and accuracy predicting robot intent. The designs also improved a number of perceptions relating to robot usability by enhancing robot communicative and collaborative abilities.

P07: "A gradient band of blue lights indicated the intended target."

Thruster:

P05: "The lights were the opposite position of the direction it was headed, so if you thought of the lights as jet engines propelling the robot the other way it seemed to work."

P08: "Blue band showing 'back' of robot, this light band would swing around to the other side when the robot changed directions. Light would intensify when robot was moving deliberately."

Gaze:

P01: "Instead of a single band of light, there were two smaller bands, almost looking like eyes."

P12: "The lights came up in an 'eyes' pattern indicating which way the robot was 'facing,' i.e., the direction in which it intended to move."

Objective Results — We next confirmed that our designs were useful in allowing participants to more quickly and accurately deduce robot intent. We found an overall main effect of signal design on our objective composite measure, $F(4, 144) = 4.45$, $p = .002$, with Tukey's HSD showing that gaze ($p = .003$), blinker ($p = .016$), and thruster ($p = .046$), but not beacon ($p = .522$), significantly outperformed the baseline. We also found a main effect of task on performance, $F(1, 144) = 14.68$, $p < .001$, with performance significantly higher in Task 1. Comparing the performance of each design across task using five post-hoc comparisons with a Bonferroni-adjusted α level of .01, we found the thruster, $F(1, 144) = 7.08$, $p = .009$, performed significantly worse, while the beacon, $F(1, 144) = 6.04$, $p = .015$, performed marginally worse in Task 2.

Subjective Results — To better understand potential tradeoffs between our designs and how they might each impact user interactions with flying robots, we analyzed responses to a number of scales related to robot usability in terms of perceptions of the robot's communicative abilities and feelings about working with the robot.

Participants rated the robot's communication in terms of clarity, intuitiveness, and their confidence in their own interpretations of the communication. We found a significant effect of signal design on perceived communication clarity, $F(4, 69) = 46.26$, $p < .001$, how intuitive participants rated the robot's communication to be, $F(4, 69) = 22.25$, $p < .001$, and participant confidence understanding the robot and inferring meaning in communication, $F(4, 69) = 6.43$, $p < .001$. We performed post-hoc comparisons using Tukey's HSD for each measure. In terms of clarity, post-hoc tests found all individual designs to be rated significantly higher than the baseline at $p < .001$, but revealed no differences between designs at the $p < .05$ level. However, we found a significant difference between the blinker design, rated as highly intuitive, and the thruster design, which participants found to be less intuitive, $p = .022$. Finally, while gaze ($p < .001$), thruster ($p = .004$), and blinker ($p = .020$) significantly improved participant confidence in understanding robot communication over the baseline, participants felt only marginally more confident when the robot used the beacon signals ($p = .078$).

We also analyzed participant responses to the robot in terms of how they might view it as a collaborative partner in a work environment. We found a significant effect of signal design on participant perceptions of the robot as a good work partner, $F(4, 69) = 5.27$, $p < .001$, and on participant perceptions regarding how the robot helped them with their tasks, $F(4, 69) = 4.62$, $p = .002$. Using Tukey's HSD in post-hoc comparisons between conditions, we found that participants rated gaze ($p = .001$), thruster ($p = .002$), beacon ($p = .029$), and blinker ($p = .044$), as significantly improving perceptions of the robot as a work partner over the baseline. However, participants felt that only the robot demonstrating gaze ($p < .001$) and blinker ($p = .027$) behaviors significantly made their task easier than the baseline, while the thruster design was rated as only marginally helpful ($p = .097$) and the beacon not at all ($p = .216$).

5. DISCUSSION

While participants believed that all signal designs contributed to making the robot a better potential work partner, only the gaze, blinker, and thruster designs enabled participants to more quickly and accurately deduce robot flight intent. We believe the limited utility of the beacon design can be traced to an emphasis on signal *generalizability* at the cost of signal *precision*. Compared with other signal designs, the beacon was developed to provide the widest variety of viewing angles and included the largest number of LEDs lit during movement (our choice of w led to 75% of the ring lit at various intensities during movement). However, gradations of intensity may have been too subtle for participants to perceive, and the increase in viewing angle appears to have hampered the signal's specificity in indicating the robot's future movement:

P07 [Beacon]: "The wide blue band made it less clear exactly which direction the robot intended to travel."

P12 [Beacon]: "…it was difficult to tell which of the light areas was actually brightest because the band was too wide."

P13 [Beacon]: "Since nearly half the ring was illuminated when it was moving, it was a little difficult to tell the precise direction of its intended movement."

P10 [Beacon]: "I preferred the solid LEDs over the gradient ones here, which were harder to see and interpret."

This lack of precision may explain the lower performance of the beacon in task two, which required greater specificity as the targets were closer together. On the other hand, participants appreciated the greater precision offered by the gaze design:

P03 [Gaze]: "I especially like the accuracy offered by the pointer setup the lights had."

While the thruster exhibited equal precision to the gaze design, its poor performance in task two, likely due to occlusion as it approached participants, suggests that it is not an effective design for an egocentric perspective. Additionally, participants rated the blinker as more intuitive than the thruster, possibly resulting from a greater prior familiarity with other vehicles that blink rather than those with jet engines. However, the thruster performed highly under the exocentric demands of task one, and some participants noted that once they had adapted to the increased mental demands of the thruster, they responded positively to the design:

P13 [Thruster]: "The blue lights on the ring light up on the opposite side of the robots intended direction. That part felt did not feel natural or intuitive, but it did light up before the robot changed directions, making its direction predictable."

P07 [Thruster]: "The reversal of indication of the lights confused me at first but then I figured out the pattern so it was useful, once I learned what the indication on the lights meant."

P09 [Thruster]: "If it were going forward, the back half of the lights would light up. I found that this was easy to understand, but required more effort on my part than the lights indicating the ultimate destination."

P12 [Thruster]: "I thought of the lights as 'engines' (even though I know they weren't). They reminded me of the engine lights of the Millennium Falcon. So it was natural for me to see them light up in the opposite direction from the way the robot was headed."

P14 [Thruster]: "I enjoyed that lights that were lit opposite of the direction, it gave the robot a ship feel (engines on the back)."

Additionally, one participant had a concern with using blinkers in a work environment, and another preferred the additional processing time and specificity offered by the thruster:

P09 [Blinker]: "I found the flashing lights to be a little distracting."

P03 [Thruster]: "I really liked how the lights didn't just flash immediately in the direction because it allowed me time to process that the robot was going to change direction. Also, smaller lights made predicting fine directions much easier, meaning better error detection."

Participants appreciated that the signals indicated the general intent of the robot, rather than showing minute course-corrections:

P09 [Gaze]: "The lights indicated the direction of the ultimate destination of the robot, not the direction it intended to move in. I found this intuitive, and it gave me a broader picture of where the robot intended to go. It was easier to tell when the robot was off course. It never ended up in the wrong location from where it indicated it was going."

P13 [Beacon]: "Even when the robot went to the wrong station, it indicated the direction it was going, which made it at least seem safe."

The communication of high-level flight intent may have resulted in high participant ratings of the robot as a good work partner across all designs; even when the robot made "errors" according to the target list participants had been given, it at least communicated with them regarding its intentions. In the end, participants universally noted the necessity of signaling behaviors for the robot, even if it made errors:

P08 [Baseline]: "No blue signal lights were used to indicate which target the robot intended to visit. This left me to guess... which was not easy. Sometimes it would take off in one direction and unpredictably change directions."

P16 [Baseline]: "There were no lights it was hard to understand the robot. It kinda did what it wanted to on its own."

P07 [Baseline]: "I thought I could learn it's behavior and pattern set to help me identify which target it will approach but I didn't. It was harder without the lights to help indicate where it was going. This one flew very dangerously."

P08 [Baseline]: "Signal lights, to signal the robot's inentions (*sic*), and facilitate interaction with humans, are a necessity"

5.1 Limitations and Future Work

While our constraints appear useful in leveraging mental models of flying objects and our designs significantly improved observer abilities to decipher robot intent, open questions remain regarding our approach. We currently lack an understanding of how flight constraints affect user perceptions of small flying robots. Future work is needed to examine tradeoffs between fully three-dimensional flight and two-dimensional flight at various altitude lanes. Additionally, each signaling behavior we developed and evaluated served as a reference design sampling the potentially infinite space of utilizing visual cues to convey directionality. Alternative designs are possible, for example using a single LED to indicate direction (corresponding to a beacon design with minimized w). Our designs are based on parameters we thought provided optimal choices of viewing angles, occlusion potential, and discernibility from a distance. Future work might explore additional parameter values, designs, or design combinations (e.g., integrating gaze and thruster). Finally, while the implementation of our light-ring affords full access to the RGB gamut for each LED, we constrained our designs to a single color to avoid potential confounding effects of cultural connotations of color. Future work may expand our design exploration to signals that use color to communicate other aspects of motion, such as acceleration (as in brake lights), or convey information related to high-level robot state, such as affect, interruptibility, or task importance.

6. CONCLUSION

In this work, we explored the design of *explicit* communication mechanisms that convey robot flight intentions at a glance. We first analyzed the "gulf of evaluation" between robot flight abilities, robot signaling abilities, and user expectations and understandings. Next, we applied constraints limiting robot flight to align with human understandings of flight motion and provide utility in enclosed environments. To design mechanisms for robots to better express directionality while operating under such constraints, we conceived of a ring of light surrounding a flyer as a global metaphor and developed four reference designs to sample this solution space. We conducted a user study evaluating our designs and found that three reference designs objectively improved observer speed and accuracy when predicting robot intent while offering tradeoffs in perceptions of robot usability across several aspects.

Our work has important implications for researchers and designers seeking to bring flying robots into human environments. Our results demonstrate the promise of developing explicit communicative mechanisms to enhance user interactions and improve the potential of robots to act as work partners. In particular, the results illustrate tradeoffs in design decisions involving occlusion, precision, and generalizability. Users preferred signal specificity at the cost of generalizability and overall found gaze behaviors to be highly useful in improving flyer abilities to communicate and collaborate effectively. Additionally, user responses support the notion that visual cues should convey high level aspects of flight intentions rather than low level corrections to flight paths. Finally, our research may inform future explorations by providing a model for scenarios evaluating user understandings of flight intent and demonstrating practical design improvements that improve interactions with free-flying robots.

7. ACKNOWLEDGMENTS

This research was supported by a NASA Space Technology Research Fellowship under award NNX12AN14H. We thank Catherine Steffel for her help preparing this manuscript.

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