# Examining Distance in UAV Gesture Perception*

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***Abstract*— Unmanned aerial vehicles (UAVs) are becoming more common, presenting the need for effective human-robot communication strategies that address the unique nature of unmanned aerial flight. Visual communication via drone flight paths, also called gestures, may prove to be an ideal method. However, the effectiveness of visual communication techniques is dependent on several factors including an observer's position relative to a UAV. Previous work has studied the maximum line-of-sight at which observers can identify a small UAV [1]. However, this work did not consider how changes in distance may affect an observer's ability to perceive the shape of a UAV's motion. In this study, we conduct a series of online surveys to evaluate how changes in line-of-sight distance and gesture size affect observers' ability to identify and distinguish between UAV gestures. We first examine observers' ability to accurately identify gestures when adjusting a gesture's size relative to the size of a UAV. We then measure how observers' ability to identify gestures changes with respect to varying line-of-sight distances. Lastly, we consider how altering the size of a UAV gesture may improve an observer's ability to identify drone gestures from varying distances. Our results show that increasing the gesture size across varying UAV to gesture ratios did not have a significant effect on participant response accuracy. We found that between 17 m and 75 m from the observer, their ability to accurately identify a drone gesture was inversely proportional to the distance between the observer and the drone. Finally, we found that maintaining a gesture's apparent size improves participant response accuracy over changing line-of-sight distances.**

## I. Introduction

Unmanned Aerial Vehicles (UAVs) have increasingly been deployed in diverse contexts by hobbyists, researchers, and industry professionals. As UAV use continues to expand across broad human interaction domains, the need for effective human-robot communication strategies will grow. Such strategies may be implemented via multiple modalities, including light, sound, or motion; however, clear communication techniques that are both robust and common across domains have yet to be realized. UAVs may present unique constraints when considering the development of a communication system. For example, the effectiveness of audio communication techniques may degrade at long operational distances and in the presence of environmental noise [1]. Light-based mechanisms may have varying effectiveness in different lighting conditions and would require the addition of hardware which increases vehicle weight and reduces overall flight durations. Motion-based communication techniques may be ideal for UAV systems as they are lightweight, software-only solutions and may be perceivable at longer ranges than audio.

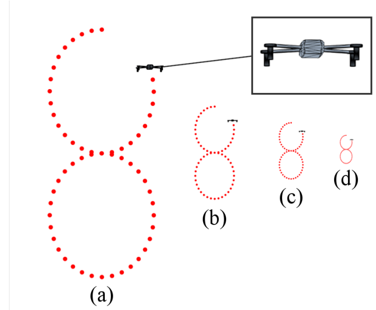


Fig. 1: Perceived Figure-Eight gesture at four line-of-sight distances, (a) 17 m, (b) 46 m, (c) 75 m, and (d) 151 m

In this work, we focus on motion-based UAV communication. Communicative flight paths, which are also referred to as 'gestures,' leverage the motion of a UAV to communicate meaning to an observer. UAV gestures have shown promise in their ability to communicate with observers [2]–[5]; however, variance in an observer's line-of-sight position may affect their ability to accurately perceive a gesture [6]. For example, an observer that is five meters away from a UAV may be able to more easily identify the shape of a gesture's motion than another observer who is fifty meters away. Fig. 1 demonstrates how the perceived shape of a Figure-Eight gesture may change from four observer distances. In this paper, we seek to identify and quantify how changes in line-of-sight distance and gesture size affect an observer's ability to classify and distinguish between a set of UAV gestures. We address the following three research questions:

- R1: Does variance in the ratio of gesture size to UAV size affect an observer's ability to perceive a gesture?
- R2: How do long and short line-of-sight distances affect an observer's ability to perceive a gesture?
- R3: Can gestures be modified to ensure high classification accuracy across varying line-of-sight distances?

Our findings demonstrate that gesture perception accuracy degrades as the distance from an observer increases. We discuss how both the actual and perceived size of a gesture matters for classification outcomes and show how maintenance of a constant visual angle may alleviate distance-based classification degradation. This work contributes a characterization of the relationship between observer distance and gesture classification accuracy alongside a technique for improving gesture perception from long distances.

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## II. Related Work

In recent years, UAVs have been leveraged across diverse contexts including emergency and disaster response [7], [8], environmental data collection and crop surveying [9], [10], and delivery of medicine and disease testing kits [11]. As UAV usage becomes increasingly integrated into human-interaction domains, effective human-robot communications strategies will be even more critical. In this section we give a brief overview of the most relevant work in visual robot communication, viewpoint variance, and depth perception.

### A. Visual Robot Communication

Researchers have highlighted the importance of robots having the ability to communicate and express their intentions for successful human-robot interaction and collaboration [2], [12]–[14]. A study by Dragan et al. found a participant working collaboratively with a robot to complete a task of fulfilling coffee orders was able to achieve the task more quickly when the robot's motion was designed to be legible, expressing the robot's intent to the participant, rather than when the motion was designed to be purely functional. In the same study, participants also had a more positive perception of the collaboration when the robot's motion was designed to be legible [13]. While previous studies on robot communication have largely focused on ground-based and anthropomorphic robots, there is evidence that the ability to express intent may also benefit human-UAV collaboration. Szafir et al. found that participants preferred and felt safer working with drones whose flight paths were manipulated to more quickly communicate their intended target position than drones whose flight paths were purely functional and designed to reach their target position as efficiently as possible [2].

While this study does not attempt to associate meaning to the drone gestures used, other studies have demonstrated the feasibility of using drone movements to convey information to observers [5], [15]. A study by Bevins et al. found that novice drone users showed some agreement in attributing meaning (e.g. landing, follow the drone, avoid the area) to certain drone movements [5]. Colley et al. investigated the potential for drones to be used as pedestrian navigation guides and found that most participants intuitively understood certain gestures to communicate "follow me" and "turn a corner" [15].

### B. Observer Viewpoint Variance

Applying the need for intent-expressive communication to UAVs requires considering the unique challenges of UAV communication. Previous studies have shown that observer location affects the effectiveness of gestural communication. Nikolaidis et al. demonstrated how viewpoint can affect observers ability to interpret robot's intention through a study that found that generating motions for an anthropomorphic robot which account for the observer's point of view were more legible to participants than motions that assumed an omniscient observer [16]. Fletcher et al. investigated the ability of observers to identify gestures from different angles using dot animations. This study found that viewpoint rotation significantly affected classification accuracy [6].

### C. Depth Perception

Another important consideration in UAV communication is that the communication may be taking place over large distances. A study by Li et al. tested the ability of observers to detect a drone flying at various distances. The study found that 245 m was the maximum distance at which the majority of the observers could detect a small drone, a Phantom 4, in good weather conditions [1]. A follow-up study identified 307 m as the approximate distance at which 50% or more of observers where able to detect a Mavic Air [17]. This gives an approximate maximum distance at which a similarly-sized drone might be able to communicate with observers through gestures. Li's studies also found that auditory detection of the drone was significantly less reliable than visual detection over large distances. As these findings suggest that people can still see UAVs at distances beyond which sound is inaudible, visual communication methods in place of, or in addition to, auditory communication methods may be especially useful in some contexts.

## III. Background

The goal of this study is to explore how line-of-sight distance affects an observer's ability to accurately perceive a UAV gesture's motion. In particular, we seek to characterize the visual perceptibility for gestures from a range of observer distances and examine how actual and apparent gesture sizes affect observer classification accuracy. To do so, we conducted three online gesture perception surveys and explored the following hypotheses:

H1: Observers' ability to accurately identify gestures will gradually improve, then plateau, as the size of the gesture relative to the UAV increases.

H2: Observers' ability to accurately identify equal-sized gestures will degrade as the distance between the drone and the observer increases.

H3: Observers' ability to identify gestures of the same visual angle will remain constant even as the UAV's distance from the observer increases.

### A. Gesture Set

Fig. 2 outlines the shape of motion for each of the gestures used in this study. This gesture set was used throughout this survey as the set of possible responses given to participants. Survey I tested the participants' ability to identify the loop, clover, b-shape, and diamond animations. Surveys II and III tested the the participants' ability to identify the undulate, figure-eight, x-shape, and u-shape animations. We adopted this gesture set from previous work that explored how untrained observers perceive meaning from UAV gestures [3]–[5] and how observer viewpoint variance affects perceptibility [6]. All of the gestures included in the set were two-dimensional, meaning their motion was limited to the (y,z) plane where the z-axis is perpendicular to the ground and

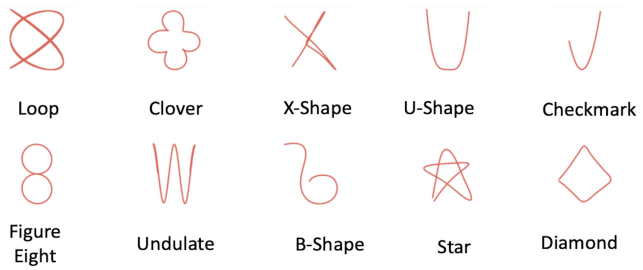


Fig. 2: Set of participant response options

the y-axis is perpendicular to the observer's point of view. Two dimensional motions may be ideal for UAV gestures for a number of reasons. UAVs are often operated at long distances. At great distances, human ability to perceive small changes in depth perception degrades [18]. In this way, motion along the respective x-axis (depth) may not be visible at relatively close distances. Two dimensional gestures can also display their full shape of motion at an ideal viewpoint angle [6], whereas some motions may be occluded from all viewpoints for three-dimensional gestures. The gesture trajectories also formed generally familiar shapes (diamond, star, etc). These types of gestures may be especially useful because observers may be able to recognize and describe them more easily than other complex motions.

### *B. Gesture Animations*

We created UAV gesture animations to visually represent gesture motions in our online perception surveys. We chose to use gesture animations rather than video of UAVs for a number of reasons. Visual perception of a UAV can be influenced by a number of factors including visual noise. Variance in the light environment or visual background can impact an observer's ability to perceive a UAV. Using animation techniques also allow for highly precise and reproducible motions that may not have been possible in a field video context. In this way, we use gesture animation to reduced the potential for confounding influence and leave studies of perception in field contexts to future work. All of the UAV animations were generated using MATLAB. Each of the animations were defined by 128-130 waypoints and were 13 seconds long. The animations showed a UAV performing a gesture once, then repeating the gesture in reverse.

### *C. Visual Angle Calculations*

To compare the size and distance of gestures viewed on participants' screen to gestures performed by a small UAV, the visual angle of the animated drone was computed using the visual angle calculation (1) [19]. This visual angle was then used to calculate the approximate distance at which the UAV would form the same apparent size,

$$V = 2 * arctan(S/2D) \tag{1}$$

where,
V = visual angle;
S = size of the object; and
D = distance of the object from the observer.

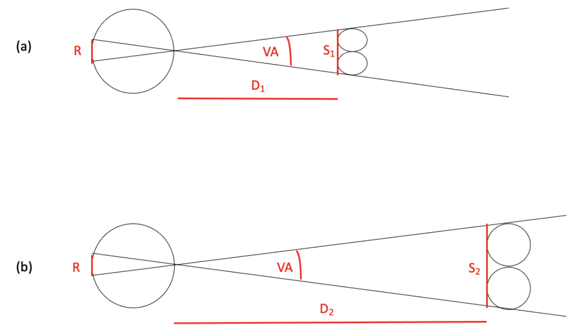


Fig. 3: Equal visual angles of different-sized gestures with $S_1$ and $S_2$ representing different gesture sizes, $D_1$ and $D_2$ representing different distances, VA representing some visual angle, and R representing some retinal image size

For our visual angle calculations we used 63.5 cm as the average distance between a participant and their computer screen [20] and 26.67 cm as the width of the real drone (a DJI Flame Wheel F330).

The relationship between visual angle, distance, and size is illustrated in Figure 3. Although the gestures are different sizes, they subtend the same visual angle, meaning that rays extending from the boundaries of the gestures will enter the eye at the same angle VA and project the same retinal image size R onto the retina. The retinal image size determines the apparent size of an image [19].

Fig 4 illustrates the difference between the actual and apparent size of a gesture. The top half of the image shows two gestures that are the same size. However, the image that is farther away subtends a smaller visual angle and will appear smaller to the observer. Meanwhile, the bottom half of the figure shows the farther gesture enlarged to form the same visual angle and thus the two images will have the same apparent size to the observer.

## IV. Survey Approach

Our study was comprised of three parts, each testing one of our three hypotheses. In each, we used surveys to collect data

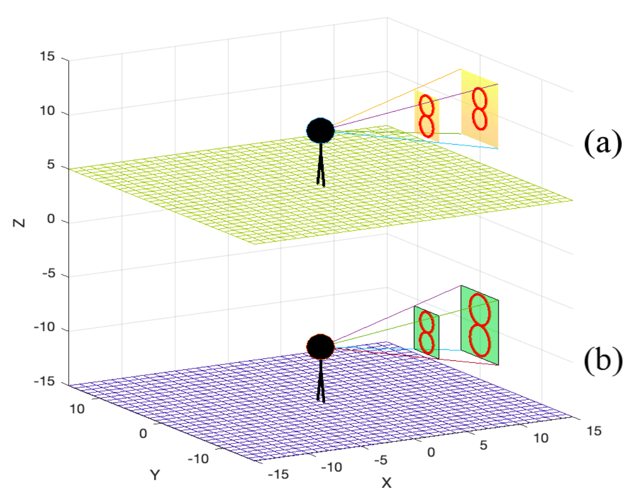


Fig. 4: Actual vs apparent gesture size

on participants' ability to identify the shape of UAV gestures. This section provides details on the implementation and goals of each of the components of our study. The surveys used in this study were created using Qualtrics and participants were recruited using Amazon's Mechanical Turk. Responses from over 350 unique participants were collected for this study. Participants were asked to watch several short animations of a UAV moving along specific flight paths. After watching a gesture animation, they were asked to choose the gesture shape that they thought corresponded to the UAV's motion. Multiple attention tests were incorporated into the studies. Messages were included at the end of both an instruction video and an additional gesture video asking participants to enter a random number on the next page to confirm that they had fully watched the videos. Different surveys were created to display the gesture videos in different orders and the multiple choice options were randomized to account for the possibility of order bias.

### A. Survey I

For part 1 of our study we tested our first hypothesis in order to determine how the size of a UAV gesture trajectory relative to the size of the UAV might affect observers' ability to identify the gesture. To do so we created three surveys with animations of different-sized UAVs performing identical gestures. We recruited 36 participants for each survey and tested them on four different UAV gestures, providing 144 responses per survey. The purpose of this study was to determine how gesture size impacts perception and thus determine how UAV operators could adjust their flight paths to improve gestural communication.

### B. Survey II

The purpose of part 2 of our study was to test our second hypothesis and learn how distance might affect an observer's ability to accurately identify a UAV gesture. To do so we created four different gesture animations in which the apparent size of the UAV and the UAV gesture changed. The visual angles for our animated UAVs and the corresponding distances at which our DJI F330 would form the same visual angle were calculated using equation (1). Table I shows the visual angles and the corresponding real distances tested in our surveys. We again recruited 36 participants for each survey and tested them on four different UAV gestures.

### C. Survey III

For part 3 of our study we tested our third hypothesis by comparing gestures of equal actual size and gestures of equal apparent size over the same distance range. This was done to determine whether the apparent size of the UAV

| Visual Angle (rad) | Distance (m) |
|---|---|
| 0.016 | 17 |
| 0.0058 | 46 |
| 0.0035 | 75 |
| 0.0018 | 151 |

TABLE I: Visual angles and distances

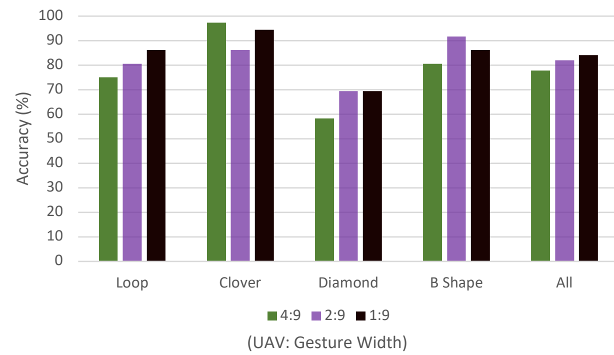


Fig. 5: Identification accuracy for equal visual angles

or the apparent size of the gesture has a greater effect on accuracy. This is useful in determining if UAV operators can increase their ability to use gestural communication over large distances by adjusting the UAV flight path.

## V. Results

### A. Gesture Size Ratio

In Survey 1, participants viewed one of three gesture animations with different UAV-to-gesture size ratios. We compared the accuracy for gestures in which the ratio of the UAV width to the gesture width was 4:9, 2:9, and 1:9 given that the 4:9 ratio reflects a context where a UAV is 4 m away from an observer, the gesture width is 60 cm, and the UAV width is 26.67 cm. The results of this survey can be seen in Figure 5. Overall, there appeared to be improvement in participants' ability to correctly identify the gestures as the size of the gesture relative to the size of the drone increased. However, these results had a p-value of 0.2053 and thus were not statistically significant. As it yielded the highest overall accuracy, we elected to use the 1:9 ratio for the next portion of our study.

### B. Variance in Observer Line-of-Sight Distance

In Survey 2, participants viewed one of four different surveys in which the animations displayed a UAV that appeared to be flying at different distances. In these animations the apparent size of the gesture become smaller as its visual angle decreased. The animations represented same-sized gestures that would subtend smaller visual angles at the greater distances. The approximate distances were calculated using equation (1). The results of this study can be seen in Figure 6. These results show an overall decline in participants' ability to identify the gestures over a 17 m to 151 m range. These results were statistically significant with a p-value of 0.0028. We noted that the greatest decrease in accuracy occurred between 17 m and 46 m. When viewed individually, identification accuracy varies by gesture. The U-shape gesture demonstrated the most degraded accuracy with respect to distance with classification accuracy ranging from 0.86 at the smallest distance to 0.42 at the farthest distance. While the X-Shape and Figure-Eight gestures demonstrated some decrease in accuracy at greater distances, the Undulate gesture demonstrated no significant change in accuracy.

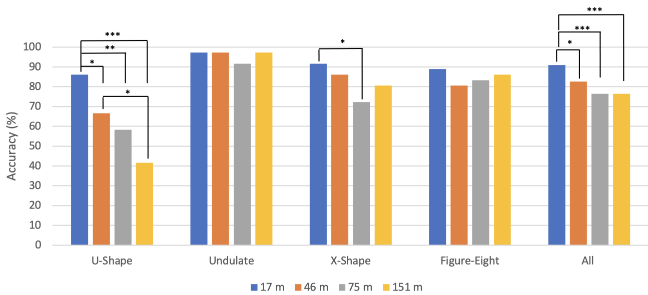


Fig. 6: Gesture classification accuracy for gestures at varying observer line-of-sight distances with * indicating a p-value less than 0.05, ** indicating a p-value less than 0.01, and *** indicating a p-value less than 0.001

Overall, participants showed aptitude to correctly identifying gestures across all line-of-sight distances tested, with over 75% accuracy at even the greatest distance.

In order to model the overall change in gesture classification accuracy across observer line-of-sight distances, we conducted a logistic regression analysis on all participant responses. Fig. 7 shows the logistic model of an observer's ability to identify the shape of the UAV's motion at a given distance. The logistic regression models a significant relationship with a p-value less than 0.05. Red dots indicate the average identification accuracy that we observed in our study and the dashed line predicts how further increasing the distance between UAV and observer could affect accuracy.

### C. Constant Actual and Apparent Size Over Distance

In Survey III, we compared participants' ability to identify gestures at different distances given a gesture of the same apparent size and a gesture of the same actual size. Fig. 4 (a) demonstrates how an observer may perceive a gesture when the actual size remains constant over distance while in (b), the apparent gesture size remains constant over distance. To maintain a constant apparent size, the actual size of the gesture is proportionally increased to maintain a constant visual angle. Figure 8 outlines the participant

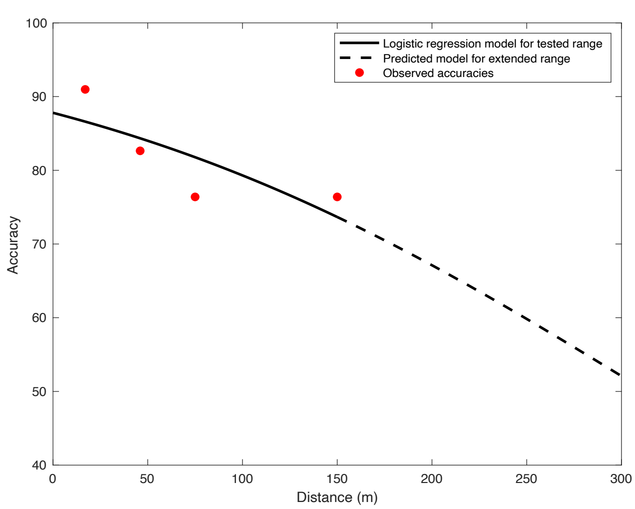


Fig. 7: Logistic regression model for participant gesture identification accuracy

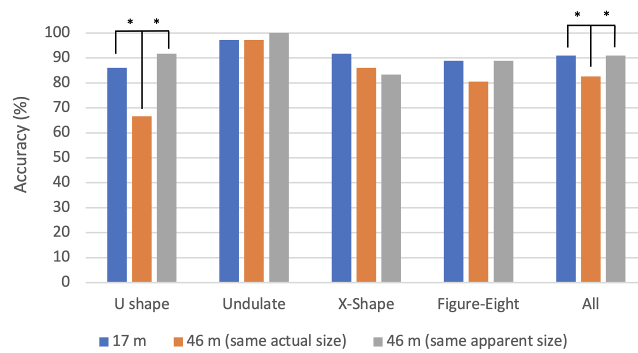


Fig. 8: Identification accuracy of actual equal-sized and apparent equal-sized gestures with * indicating a p-value less than 0.05

response results from Survey III for identification accuracy at 17 m and 46 m. The accuracy at 46 m represents accuracy at identifying gestures of either equal actual size or equal apparent size compared to the gestures performed at 17 m. Overall, maintenance of a constant apparent size yielded significantly higher response accuracy when compared with responses from animations with a constant actual size. To evaluate this relationship, we conducted a two-proportion z-test between response accuracy values in both conditions and the results are significant with a p-value less than 0.05. The U-Shape demonstrated a significant change in accuracy when comparing apparent and actual gesture size responses. While other gestures demonstrate a similar trend, the resulting differences between each condition are not significant. Overall, maintaining a constant visual angle results in similar identification accuracy at 17 m and 46 m while identification of equal-sized gestures at 46 m was significantly lower than identification at 17 m.

## VI. Discussion

In the following section we discuss our three hypotheses in light of the results yielded by this study. We also address some limitations of our study and consider how physical constraints may limit UAV operators' ability to adjust their flight paths to benefit visual communication as we propose.

### A. Hypotheses

**Hypothesis 1:** *Observers ability to accurately identify gestures will gradually improve, then plateau, as the size of the gesture relative to the UAV increases.* For the three UAV-to-gesture ratios tested, there was not a significant difference between observers' ability to identify the gesture shape. While further investigation may reveal that larger ratios have a more noticeable effect on gesture identification, there are also practical constraints on the ability of UAV operators to manipulate the size of their flight paths as are detailed below. Thus there is a need to weigh the benefits of manipulating flight paths to aid observers' visibility of them against other considerations for UAV operators such as time, battery power, and flight mission.

Additionally, this study demonstrates how gestures of the same visual angle are perceived. The gestures all formed a visual angle of 0.0016 radians and had the same apparent size to the participant. There was not a significant change in the participants' ability to identify the gestures which supports the hypothesis that observers will have similar success rates in identifying gestures of the same apparent size.

**Hypothesis 2:** *Observers ability to accurately identify gestures will degrade as the distance between the drone and the observer increases.* Between 17 m and 151 m there was an overall decline in participants' ability to identify the gestures at the tested distances. This suggests that distance will hinder the effectiveness of visual human-UAV communication and should be considered by UAV operators. Interestingly, the most significant decrease in accuracy occurred between the two closest distances while accuracy appeared to remain fairly consistent between 75 m and 151 m.

**Hypothesis 3:** *Observers' ability to identify gestures of the same visual angle will remain constant even as the UAV's distance from the observer increases.* In our comparison of identification accuracy between gestures with the same actual size and gestures with the same apparent size, we found that participants' ability to identify gestures with the same actual size decreased over the tested distance range, but remained steady over the same range when viewing gestures with the same apparent size. This indicates that the apparent size of the gesture is a greater factor than the apparent size of the UAV and thus we propose that visual communication can be maintained over larger distances by adjusting the UAV's flight path to perform larger gestures if attempting to communicate with an observer positioned farther away. However, as noted previously there are constraints on the ability and usefulness of operators to do so that should be considered.

### B. Variance Among Gestures

We found that the individual gestures tested showed varying identification accuracy and variation due to changes in distance from the observer. This may have been caused by the fact that some gestures were more similar to others in the gesture set, such as the U-Shape and the Checkmark, and thus more easily mistaken for each other. Another possible cause of this variation is the speed of the UAV motion. The gestures in this study were defined by a consistent number of waypoints and thus the animations displayed each of the gestures over a constant period of time. This meant that simpler gestures such as the Diamond and U-shape, which had the lowest overall accuracy of the tested gestures, appeared to move at slower speeds than more complex gestures. This could indicate that observers had more difficulty determining the shape of the UAV's motion for slower gestures. Table II lists the estimated average speeds of a UAV performing the 1:9 ratio gestures from Part 1 and their accuracy for that size. Table III lists the estimated average speeds of a UAV performing the gestures from Part 2 in the same 13 second time frame as our animated gestures and the average identification accuracy of those gestures. While more testing would be needed to confirm a correlation between gesture speed and identification, it is useful to consider that there may be a lower bound on the speed at which most observers can identify gestures.

| Gesture | Average Speed (m/sec) | Accuracy(%) |
|---|---|---|
| Clover | 1.30 | 94.4 |
| Loop | 1.87 | 86.1 |
| B-Shape | 0.953 | 86.1 |
| Diamond | 0.997 | 69.4 |

TABLE II: Average UAV speeds for gesture set 1

| Gesture | Average Speed (m/sec) | Accuracy(%) |
|---|---|---|
| Undulate | 1.38 | 95.8 |
| Figure-Eight | 1.72 | 84.7 |
| X-Shape | 1.36 | 82.6 |
| U-Shape | 0.844 | 63.2 |

TABLE III: Average UAV speeds for gesture set 2

### C. Physical Constraints

While this study seeks to determine how size and distance can be manipulated to improve observers' gesture classification accuracy, there are some practical constraints on the drone operator's ability to do so. The first is that an observer's ability to identify a small UAV over great distances is limited. In this paper, we have followed the guideline established by Li et al. that 300 m is the maximum distance at which a small UAV can be seen by a majority of individuals with normal visual acuity [17]. Conversely, a UAV may be unable to communicate effectively using gestural communication if it is flying too close to an observer for the observer to have the full motion in their field of view.

An additional constraint is that increasing a gesture's size requires increasing either the time required to complete the gesture or the speed at which the gesture is performed. Increasing the time at which the gesture is performed may impractical. As we are investigating the use of gestures as a communication method, there is a clear incentive for gestures to be completed in a timely manner as more time-consuming gestures would hinder the drone operator's ability to communicate important information quickly or may interfere with the UAV operator's main mission. However, there is also a limit on the capability of the operator to increase the speed of the UAV to perform larger gestures more quickly based on the hardware limitation of their UAV or the operator's ability to fly safely at higher speeds. In addition, changing the speed or duration of the gesture may negatively affect observers' ability to identify the gesture if the gesture is too large or moving too quickly for them to identify the flight pattern. Thus there is a need to weigh the potential benefits of manipulating flight paths to aid observers' visibility against other considerations for UAV operators such as time, speed, battery power, and flight mission.

## VII. Limitations

We conducted animation surveys in order to reduce the potential for confounding effects such as variance in light environments of visual background noise. However, the results of this work have yet to be confirmed or applied in field contexts with real UAVs. Although visual angle and apparent image size provide an approximation of how observers will perceive UAV flights, there are additional factors that may affect an observer's visual perception of gestural motion which are not addressed via digital animation. While other factors may affect the specific accuracy values yielded from studies conducted in field settings, we expect the results to demonstrate similar relationships to those discussed in this work, including the relationship between line-of-sight distance and gesture identification accuracy.

While we conducted studies on two separate gesture sets in this work, this study does not represent an exhaustive test across many gesture sets. The U-Shape demonstrated significant accuracy degradation across observer distances, however, the same degree of change in accuracy was not observed across all gestures. Similarly, the Undulate gesture demonstrated little change in accuracy across observer distances. While this may be the case, we also did not observe any significant improvement in response accuracy as observer distance increased. We suggest that some gestures may be easier to identify than others such that increasing the line-of-sight distance degrades response accuracy at different rates for different gestures. In addition to having investigated a limited gesture set in this study, we also restricted our study to the assumption that participants are viewing the gestures from a single perspective where the UAV is directly in front of the observer and the UAV's full motion is visible and unobstructed. This may not be the case in a field setting where a UAV may be flying above the observer's eye level and where the drone's motion may be partly obscured by an object or by the observer's viewpoint.

## VIII. Conclusion and Future Work

Based on the results of this study, we find that distance does have an effect on an observers ability to perceive UAV visual communication such that there was an overall decline in observers' ability to identify equal-sized gestures between 17 m and 151 m. However, there was no significant difference in participants' ability to identify gestures of equal apparent size, even as the apparent size of the UAV decreased. Thus, we suggest that UAV operators can manipulate the size of their flight paths in order to maintain visual communication with observers over large distances. Additionally, we found that participants' ability to identify the shape of the UAV's motion varied among the tested gestures and propose that the speed of the UAV may affect observer's perception of the UAV's motion. Future work is planned to verify the findings of this study with real UAV gestures and further explore the impact that variation in distance, gesture size, speed, and duration have on gesture identification accuracy.

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