The Design of Interfaces for Multi-Robot Path Planning and Control

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Abstract— **The field of human-robot interaction has evolved beyond issues concerning the design and development of one person controlling one robot to exploring HRI for groups of robots and teams. Our design research explores biologically-inspired motion that is initiated by a human operator, applied to a single or a small group of robots, and used to affect the motion and path planning of another subset of robots. This exploratory design study first created a taxonomy to categorize individual robot motions, looking at how they could be categorized and used as building blocks. We then combined individual motions with time and velocity as design variables to guide our interaction design. This work led to the development of a prototype set of motions, which was applied in the development of an iPad interface. We informally evaluated this prototype with nine participants. We present challenges and design recommendations based on this effort.**

I. INTRODUCTION

Robots and humans routinely collaborate in multi-robot teams to perform surveillance, coverage, and other tasks. Robotics has advanced such that teams of robots can be fully autonomous, with the capability of completing multiple tasks in parallel. While interaction with a group of agents is often fully autonomous, other scenarios exist where a group of agents could be fully controlled by the user, or some combination that exists between system and user control.

Our work takes a design approach to understanding how motion and path planning for multi-robot swarms should be designed. We are interested in cases where a human exerts partial control over multiple robots. As HRI designers, we are interested in how to assess the design space for motion design for both the control of the robots and the corresponding response. We explore this design research question in the context of the development of a mobile touch-based interface to control groups of robots.

In this paper, we take the first steps towards understanding the design space for multi-agent path planning in human-robot interaction. Our goal is to create a set of guiding principles that define the organization of movement for multi-agent paths, and to create a schema for categorizing and using motion when designing robot behavior. To do so, we examine the literature on multi-robot cooperation, animal behavior, and interface design and control. We derive concepts from the literature search and use them to create an initial taxonomy of robot motion. We examine these motions individually and collectively by first creating a demonstrational prototype to generate multiple agent paths dynamically with minimal human interaction. Results from this exploration lead to the development of an iPad interface that explores how to apply this motion in decentralized control over a set of agents. We informally evaluate this interface with nine participants. Our contribution takes a first step towards understanding the design of motion and path planning in multi-robot interfaces.

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II. BACKGROUND

A. Dynamic path planning and multi-robot control

A number of path-planning algorithms have been developed for fully autonomous systems. While discrete search methods work for path planning [1], [2], [3], they do not scale well to multiple agents and tasks, nor transfer well to interface and interaction design. Optimized methods such as [4] work for multiple robots, but do not function well in complex environments. Recent approaches have relied on sampling [5] and the process of decomposing a complex planning problem into solvable sub-problems [6], [1], [7], [8], [9]. In terms of motion design, decomposition into sub-problems means that a multi-agent system could easily demonstrate a variety of types of path planning and execution, and one component of the system could have an effect on others.

A body of research exists on multi-robot pursuit evasion that can be drawn on as inspiration for motion design. Ranging from two pursuers are searching for one evader [10] to multiple pursuers searching for multiple evaders [11], [12], a number of algorithms have been designed and tested in simulation to plan the path of pursuers and evaders, taking into account aspects of competitive action. Other work has explored a game structure for pursuit and evasion, where pursuers jointly minimize the motion of evaders and in some cases, learn over time [13].

Research on controlling multiple robots has progressed from understanding how a centralized means for controlling a team compares to other methods such as a playbook style interface. Biological motion has also been an inspiration in multi-robot path planning. Initial work uncovered two basic models for movement: lead by attraction and lead by repulsion. [14] offers a popular bio-inspired model that describes three circular zones around an agent: repulsion, orientation, and attraction. Robots in each of these zones behave in a particular way, depending on the simultaneous presence or absence of other robots in the same zone at any given time.

Because we are developing a touch-based interface, we are interested in cases where users exert partial or full influence

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over the control of multiple robots. These robots may be a subset of all robots being controlled at a given time. To do so, we examined the role of human influence on dynamic trajectory planning. [15] examined how to allow a human to influence a decentralized agent group without resorting to centralized control. This work, combined with bio-inspired models such as [14], inspired us to further explore how a human managing a group of remote robots could leverage aspects of biologically inspired collective behavior. What we learn from this one-way interaction can then be applied to multi-user, multi-robot scenarios.

B. *Animal behavior*

The aggregate motion of a flock of birds, a pack of wolves, or a school of fish is a compelling sight. It is made up of discreet bodies that act collectively to create an overall synchronized motion. Each individual acts on the basis of it's own perception of the world.

Researchers have studied the collective behavior found in nature and have attempted to create computational models to characterize and replicate that behavior. For example, the collective behavior of a school of fish could be modeled to show how a group of robots might respond to an external stimuli. Other research can provide information about how coordinated collective motion could be produced from local interactions between individuals.

As mentioned earlier, a well-leveraged finding is that of Couzin, who created a model for determining group behavior based on aspects of individual behavior [14]. In this work, groups show collective memory, changing group behavior at different points based on prior behavior. For example, quick changes in direction and speed could have a greater influence on the direction and speed of nearby robots. As a group, robots can also exhibit collective memory by resisting change in group behavior. For example, a group could exhibit swarm behavior at intermediate densities before transitioning to a dynamic parallel group, or dissipating altogether. Our work seeks to explore these cause and effect motions for subsets of a robotic swarm.

C. *Interface and interaction design*

We leverage research on the design of interfaces for collaborative control, where humans and robots engage in dialogue to perform tasks and achieve goals [16]. There are three factors which may affect how motion gets planned and communicated in a multi-robot interface: 1) what operators see and control; 2) what the robots sense and control; and 3) what is seen on the interface at an given time.

To begin to understand the design space for both humans and robots in these interfaces, we can leverage a historical model from HCI, which describes a design space from full autonomy to full human control [17]. This design space has been explored through a variety of interface control mechanisms, including policies, maps and waypoint views, playbooks, and other interface control mechanisms [18], [19], [15], [20].

When deciding what information will be seen on the interface at any given time, designers consider what aspects of the interaction need to be most salient, and how attention will be allocated on the interface. Situation awareness is defined as how much attention is commanded to the interface at any given time. Operator workload and attention must be allocated so as to maximize system efficiency. Most studies of workload and situation awareness in HRI have been on single operators [21]. Some created frameworks to understand awareness and path planning [22], [23]. Others created taxonomies to explore the design space [24]. A lesser-explored question is how touch-based interfaces command and direct visual attention, particularly when they lack haptic feedback.

More recently, a number of interface and interaction studies can be found exploring how to control a single and multiple robots [13], [23], [18], [25], [26]. These explore both top-down map views as opposed to a robot-centered view of the world, providing initial design guidance in the form of usability and attention demand. Collectively, these projects advance knowledge about how to design interfaces for individuals and groups to control multiple robots.

III. GENERATIVE RESEARCH: CREATION OF A TAXONOMY

From our literature review, we created a focused area for our interaction design research: how to describe the design space for biologically-inspired motion that would be initiated by a human operator, applied to a single or a small group of robots, and used to affect the motion and path planning of another subset of robots. To do so, we first created a taxonomy to categorize individual robot motions, looking at how they could be categorized and used as building blocks. We then combined individual motions with time and velocity as design variables to guide our interaction design. This work led to the development of a prototype set of motions, which was iteratively tested with users and applied in the development of an iPad interface.

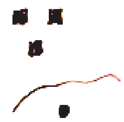
We identified the roles of pursuer and evader to 1) explore biological motion, and 2) examine the effect of having subsets of robots behave in particular ways, with the actions of those robots affecting other subsets of robots. This led to the following basic motions in our taxonomy listed below.

A. *Evader actions*

Our evader motions were comprised of one state and three actions, as listed below and shown in Table I.

- Awareness: Whether or not the evader is aware of the pursuer(s).
- Hiding: Whether or not the evader is hiding or maintaining a covered position from pursuer(s).
- Running: Whether or not the evader is moving away from the pursuer(s).
- Line of sight: Whether or not the evader can see the pursuer(s) by line of sight.

TABLE I: EVADER TAXONOMY

Motion	Example
Hide	
Move away	
Line of sight	

B. Pursuer actions

Our pursuer motions were comprised of seven actions and eight formations, as listed below and shown in Table II.

- Planned Attack: A preconceived forward aggressive motion by pursuer(s).
- Unplanned Attack: An ad hoc forward aggressive motion by pursuer(s).
- Disrupt formation: A motion to perturb an existing swarm formation.
- Block: Creating a formation to ward off an aggressive attack.
- Patrol: Pursuers maintain coverage over an area by moving repeatedly through it.
- Feint and distract: A mock attack or movement designed to draw attention away from the evader.
- Monitor/follow: Pursuers keep motions of evader in the line of sight; possibly mirroring the motions of the evader.

C. Pursuer formations

- Act as individuals: Each pursuer moves on its own accord, with no consideration for the path and movement of other pursuers.
- Line formation: Pursuers group together to move in a vertical line.
- Row formation: Pursuers group together to move in a horizontal line.
- Loose or tight pack: Pursuers group together with purposeful and orderly formations in close or distant proximity.
- Pair formation: Pursuers create dyads that move collectively.
- V formation: Pursuers make a V-formation that moves collectively.
- Maximize line of sight: Pursuers assume a formation that maximizes what any individual can see at one time.
- Spread the pack to make distance: Pursuers maintain greater space between each individual robot to cover more ground.

In the taxonomy, the design variables of time and velocity can be used to create a richer palette of motion. For example, with the addition of time and velocity, the attack motions could be expressed as scooting (slow, low velocity) or firing forward (quick, high velocity).

IV. GENERATIVE RESEARCH: DIRECT MANIPULATION INTERFACE

We next leveraged our taxonomy, combining individual motions to build collective and cooperative means for path planning and execution in the control of robot swarms. While surface and direct touch computing can offer challenges in the forms of less traditional input than the keyboard and mouse, it offers a direct means of controlling elements through multitouch freehand gestures [27]. When extended to groups, touch and gesture interfaces can offer means for collaboration through referencing aspects of the interface as a group [28].

A number of systems have explored interface and interaction designs to explore the difference between 1-, 2-, 3-, and 5-finger gestures in controlling physical robot agents [29], [30]. In our work, we strove to understand how simple and direct multi-touch interaction could allow the user to create motion paths that affected subsets of robots, which would in turn affect others. Our work combines motions from the taxonomy with Wobbrock's user-defined gesture set, a verified set of gestures that can be used successfully in surface computing [27].

Our initial design explorations for the iPad interface covered 1-, 2-, and 4-finger interactions. We focused on object-related actions as described in touch gesture design [31]. We sought to find the most natural means for controlling a subset of robots that would in turn control the paths of other robots in the group (Figure 1).

Fig. 1: Interface concepts for 1-, 2-, and 4-finger interaction.

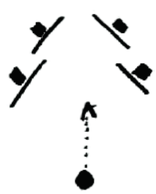
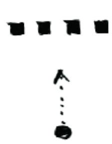
A. One finger interaction

Our first design explored controlling a subset of robots with one finger. A swarm of robots would freely move around the space subtended by the offset area created by one finger touching the iPad. Informal tests of this concept revealed that this did not feel like a natural interaction for control, due to the fact that one finger normally controls one discrete item in a touch interface.

B. Two finger interaction

We also explored controlling a subset of robots with two fingers. A swarm of robots can freely move around the space subtended by the offset area created by two fingers touching the iPad. Informal tests of this concept revealed that users often wanted to place a third finger to control the robots. This is because two finger interactions are commonly used for interactions like pinch and spread.

TABLE II: PURSUER TAXONOMY

Motion	Example
Individual actions	
Pack actions	
Line	
Row	
Offensive attack	
Surprise attack	
Defense formation	
Disruptive formation	

C. Multi finger interaction

Our final design, an the one we chose, explored controlling a swarm of robots with up to ten fingers.

A swarm of robots can freely move around the space subtended by the shape by the fingers touching the iPad. [27] describes four-finger gestures as a "gray area'. Our pilot testing revealed that this gesture might be the most natural when controlling the swarm. However, our study rating showed that the use of four fingers happened infrequently as it led to occlusion problems.

The fingers created a natural shape that could be used to direct a subset of the swarm, which in turn generated motion paths for the remainder of the robots.

V. IMPLEMENTATION

We implemented a multi-finger touch design on an iPad app. Our design is meant to control a swarm of robots with simple behavior and low connectivity. The individuals are able to sense other individuals within a certain range. We assume each individual has its own goals, and in absence of user input would generate a plan and move accordingly.

To model the autonomous behavior of the individuals, we implemented a simulation environment where robots move following a vector field. The vector field is obtained from an xml file containing biological data (velocities from real swarms, flocks, etc.)

Three potential features contribute to the final behavior displayed on the iPad: biological data, user input, and local interaction rules (Figure 2).

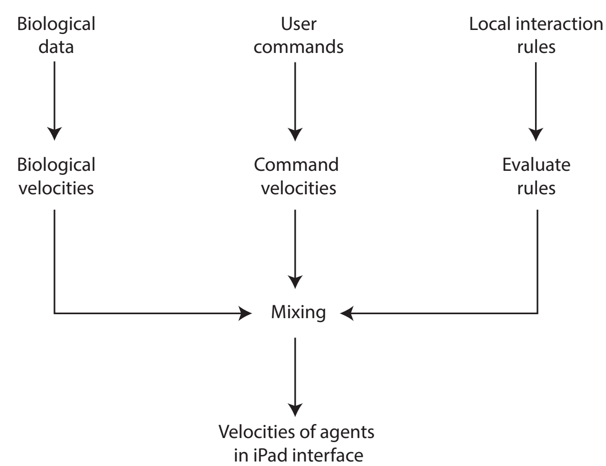


Fig. 2: Design features that contribute to the motion behavior displayed on the iPad.

First, observed velocities from the biological data create basic motions, paths, and behaviors. If there are no other inputs, then the behavior displayed by the iPad would exactly match the observed swarm behavior. Second, the user has a multi-finger touch mechanism to input commands.

For example, the user could control a subset of the robots, making them virtual leaders in the swarm. The other robots would then adopt motion and trajectories based on the virtual leaders. Third, basic swarm interaction rules are added to the simulation (for example, rules that generate basic flocking behavior. This is different from the observed velocities, which are directly measured from real swarms). The velocities commanded by the biological data, user commands, and local interaction rules are combined with weighted averages. The simulated agents then flow along the final, combined velocity command.

The multi-finger design enables a direct manipulation of the swarm behavior. The system is initialized with a swarm of robots, packed in a grid with fixed space between robots (Figure 4a).

The fingers that touch the iPad create a virtual leader behavior at the position of the touch. Raising a finger from the surface corresponds to the removal of that leader from the swarm. As the user slides her fingers on the touch surface, the swarm reacts by following the leaders.

This behavior is coupled with additional interaction rules that make sure robots will avoid collisions and will try to stay with the group.

Following from [14], we define three different zones relative to each robot:

- Zone of repulsion (ZOR). Each individual attempts to maintain a minimum distance from others within a “zone of repulsion”.
- Zone of orientation (ZOO). An individual will attempt to align itself with neighbors within the “zone of orientation”.
- Zone of attraction (ZOA). An individual will attempt to move toward the position of leaders within the “zone of attraction”.

The swarm behavior can be shaped by user input (finger movements) and parameter settings. A desired set of parameters can be set and saved for future simulations by using a drop-down panel (see Figure 4a). The panel also allows users to explore the real-time effects of a parameter change, in effect, making the app also usable for motion design. Users can design a variety of behaviors by modifying and saving the settings. For example, Figure 4h shows how a “surround” behavior was obtained through 4-finger interaction.

VI. EVALUATION

We informally evaluated the iPad interface with nine participants who had a range of experience with touch devices. We asked participants to use two different instances of the interface, one to test the pursuer behavior and the other to test the evader behavior. In the pursuer condition, the iPad screen is filled with mobile targets, and participants are asked to control the swarm in order to pursue as many targets as possible. In the evader condition, mobile pursuers attack the swarm and the participant’s goal is to avoid as many pursuers as possible. Participants were given three minutes for each of the two tasks. Within that time they were allowed to make multiple attempts to iteratively refine their pursuing and evading strategies. Design studies of this type are useful for observing direct interaction with the interface and to understand how to refine the interaction between user and system. At the end, participants filled in a short questionnaire to talk about their experience of testing the interfaces.

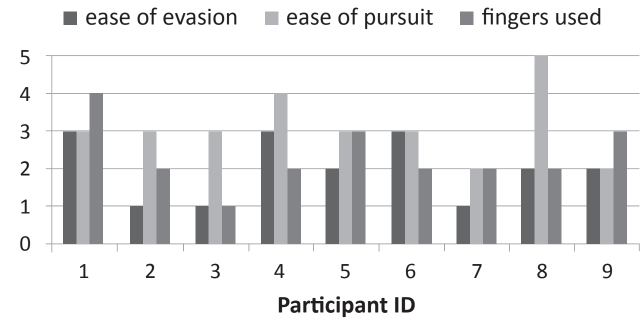


Fig. 3: Results from post-study survey, showing ranking for ease of evasion and pursuit and number of fingers used.

The results from this pilot study show that participants preferred some pursuit and evasion strategies more than others.

For pursuing, the following strategies were utilized most frequently:

- Spread (Figure 4f)
- Line formation (Figure 4e)
- Pack actions (Figure 4g)
- Disruptive attack (Figure 4h)

For evading, the following strategies were utilized most frequently:

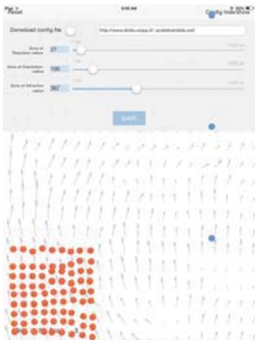
- Hide (Figure 4c)
- Split in subgroups (Figure 4d)
- Using few individuals to draw the pursuer’s attention from the main group (Figure 4b)

The most frequently used strategies were: spreading the swarm when pursuing and hiding when evading. In both situations, participants tried to take as much advantage of the swarm’s motion as they could. In general, evading was considered difficult (average score of 2 out of 5 in a 5-point likert scale), while pursuing was considered easier (3.11 out of 5). The most natural interaction was with two fingers (Figure 3). However, this seems strictly related to these strategies. The only participants who used additional fingers (three to five fingers) were those who tried to obtain complicated formations with the goal of surrounding the targets.

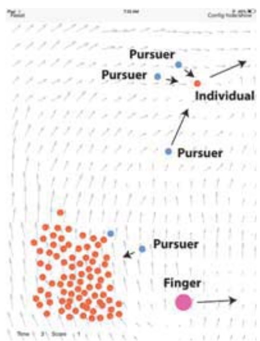
VII. DESIGN RECOMMENDATIONS AND CHALLENGES

Based on our experience of designing our motion taxonomy, our iPad interface, and its evaluation, we offer the following design challenges and recommendations gleaned from this work.

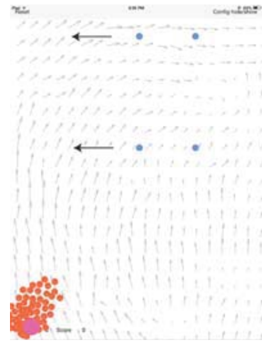
The first challenge is that the default palette of touch gestures, as described by [31], can seem to be a limitation in that they are used for well-defined actions such as pinch and stretch. Therefore, our first design recommendation is that users should be able to leverage natural motions to



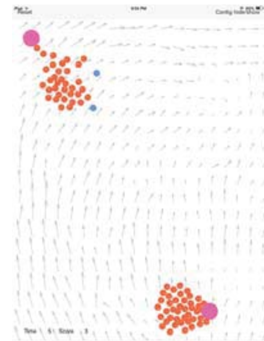
(a) Setting parameters



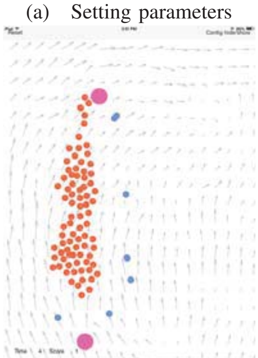
(b) Draw attention (evasion)



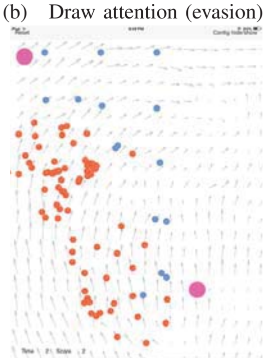
(c) Hide (evasion)



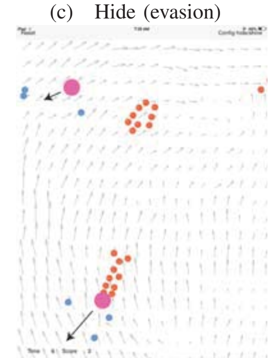
(d) Split in subgroups (evasion)



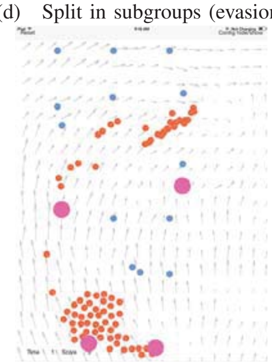
(e) Line formation (pursuit)



(f) Spread (pursuit)



(g) Pack actions (pursuit)



(h) Surround (pursuit)

Fig. 4: iPad interface and strategies from the study

control a swarm of robots. In our iPad app, we achieved this by enabling up to 4-finger interaction to create motion paths for robot control, and by making 2-finger interaction as straightforward as 4-finger interaction.

The second challenge is that it may be difficult to understand how touch input affects the resulting output path and motion. This is because it is often not intuitive how robots respond to the touch patterns applied to the screen, especially when behaviors of our test participants spanned both pursuit and evasion. Our second design recommendation is that direct mappings should be created between touch input and the resulting path and motion output. We achieved this in our iPad app by creating a set of specifications, accessed on a dropdown panel, that allow users to specify motion parameters. This panel can serve to help investigate the design space of motion, and to guide motion design.

The third challenge is that users may want or need to understand which robots are directly controlled by their touch on the iPad interface, and which robots are being controlled by the motions of other robots. This is particularly important when designing motion for swarms that are comprised of individuals with different behaviors. Our third design recommendation is that signification could be used to differentiate motion paths within a swarm of robots. Our current iPad interface treats all robots in the swarm with the same visual signification. Future versions of the iPad app will explore new visual designs to better signify differences in robot behavior.

VIII. CONCLUSIONS

The field of human-robot interaction has evolved beyond issues concerning the design and development of one person controlling one robot to robots and humans working in multi-robot teams. Our research explores biologically-inspired motion that is initiated by a human operator, applied to a single or a small group of robots, and used to affect the motion and path planning of another subset of robots. We first created a taxonomy to categorize individual robot motions, looking at how they could be categorized and used as building blocks. We then combined individual motions with time and velocity as design variables to guide our interaction design. This work led to the development of a prototype set of motions, which was applied in the development of an iPad interface. Our process was iteratively evaluated with users to make sure we are creating something that meets operators' needs. We present challenges and design recommendations based on this work.

Our next steps are to link our iPad interface with real world data and control scenarios. We also hope to further vary the appearance and behavior of robots based on the actions of other robots. In the future, we will work to support interfaces that scale to teams rather than individuals, to create default patterns that can be customized in non-autonomous mode, and to create interface and interaction designs that better support the limits of human attention.

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