A Novel Communications Protocol Using Geographic Routing for Swarming UAVs Performing a Search Mission

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Abstract—**This paper develops a novel communications protocol for autonomous swarms of unmanned aerial vehicles (UAVs) searching a 2-dimensional grid. The search protocol, the UAV Search Mission Protocol (USMP), combines inter-UAV communication with geographic routing to improve search efficiency in terms of total searches, distance traveled by UAVs, and the minimization of UAV direction changes. By determining where search state updates impact search decisions, messages are geographically routed to improve search efficiency. USMP and the geographic greedy perimeter stateless routing (GPSR) protocol are studied via simulation using OPNET Modeler 12.0. Geographic routing degrades performance by at least 20% in total searches and distance traveled, but improves direction changes by 6.7%. Overall, USMP improves performance by as much as 188% compared to scenarios without inter-UAV communication.**

Keywords-geographic routing; unmanned aerial vehicles; communications

I. Introduction

The US Air Force employs UAVs for reconnaissance, battle damage assessment and direct attack missions. Currently, pilots control UAVs remotely without any automated assistance. The one-to-one relationship between a pilot and a UAV limits UAV mission capability as the number of UAVs working cooperatively is limited by the number of operators and how well they coordinate their efforts. Therefore, important missions like persistent reconnaissance over hundreds of square kilometers using hundreds of UAVs is simply not possible. Shifting from human to autonomous control would enable a swarm of cooperative UAVs to carry out such large scale UAV missions.

Large scale UAV reconnaissance missions have immediate utility to contemporary conflicts. US Forces in Iraq and Afghanistan face a serious threat from improvised explosive devices (IEDs) - aerial imagery and change detection technology can detect such IEDs. A UAV swarm could cooperatively collect imagery for counter-IED operations, thus saving lives.

We examine UAVs performing a "search mission" as defined by Gaudiano, et al. [1] that includes reconnaissance, signal collection and target search missions. A distributed algorithm for cooperative search by ground-based robots [2] is adapted for UAVs. The UAV Search Mission Protocol (USMP) protocol incorporates the communication required by UAVs to cooperatively search under realistic operating conditions.

The geographic greedy perimeter stateless routing (GPSR) is used for cross-layer coupling with USMP for several reasons. First, GPSR has been successfully used as a routing protocol for similar UAV swarms [3]. Second, since both GPSR and the search algorithm view the search area as a 2-dimensional grid, it is hypothesized that the location information used by GPSR can be "harvested" by USMP (aka GPSR harvesting) in lieu of explicitly location update messages. Finally, GPSR can geographically address and forward packets to send search state updates where they will most impact search decisions.

II. Background

A. Sensors

To perform a search mission, UAVs employ various sensors. UAV studies typically do not focus on the precise capabilities of these sensors [1] [4] [5]. As shown in Fig. 1, the search area (bottom) is divided into a 2 or 3-dimensional grid where the cell size (top) roughly corresponds to the surface area a downward-directed sensor can scan in a single time quantum. This is useful since government and private industry have a wide variety of adjustable precision sensors [6] [7]. Thus, search mission performance can adequately model sensor precision by controlling the search grid's cell size relative to the overall search area.

Though abstracting away a sensor's precise capability is useful for experimentation, the distinction between passive and active sensors must still be considered. Active sensors, such as a laser range finder, expend enough energy to require a UAV with limited battery power or fuel to selectively operate the

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sensor so the UAV's flight endurance period is not adversely affected.

In a search mission, therefore, an active sensor is off until it is needed to search a specific cell. Passive sensors, even under continuous operation, typically do not affect flight endurance. Thus, the sensor scans every cell the UAV traverses.

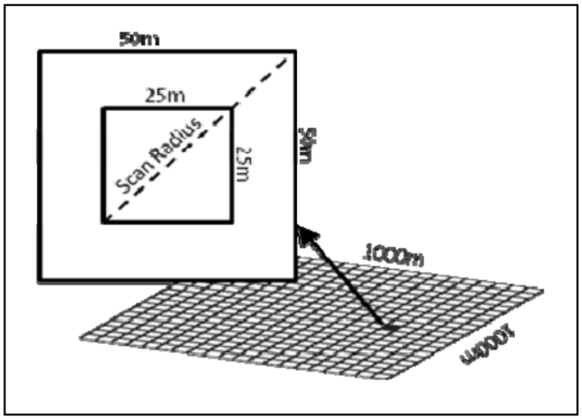

Figure 1. Division of search area into cells

B. *Cooperative Robotic Search and Swarming*

Simple interactions between members of a swarm and their environment result in complex behavior of the swarm itself [8]. Swarming concepts have found near-optimal answers to hard problems in computer science [9] and optimized cooperative robotic searches of 2-dimensional spaces [2]. The behavior of swarm members ("swarm logic") is a simple set of rules applied to the set of cells. Each rule reduces the set of candidate cells until a single, best candidate remains or in the case of a "tie", a cell is randomly selected from the set of equally good candidates.

The rules used are [2]:

1. Number of Searches Rule: Select the least searched cell
2. Distance Rule: Select the closest cell
3. Neighbor Rule: Select the cell farthest away from known neighbors
4. Travel Straight Rule: Select the next cell that requires the least direction change
5. Random Rule: Select a cell at random

These five rules produce an optimal search for two robots in a square, 16-cell search area where robots are placed at opposite corners of the square. The Random Rule was used as a base case and the search performance improved as the Distance, Neighbor and Travel Straight Rules were added in order. The Number of Searches Rule is added to account for the assumption that robots never visit a previously searched cell.

To coordinate the search, the robots share a perfect global search state, which includes the location of all other robots, the search status of all cells in the search area and all robots' waypoint selections. The robotic search makes waypoint decisions serially [2], so no robot ever selects another robot's waypoint and thus there is no need to resolve conflicts. USMP replaces the global state with a communication mechanism, and resolves waypoint selection conflicts.

C. *GPSR*

GPSR is a geographic routing protocol. Geographic routing protocols make routing decisions based on the physical topology (geography) of the network. As specified in [10], devices track their neighbors' locations through periodic location beacons. Data packets routed by GPSR also carry location information. From this information, GPSR builds a neighbor table of locations, device addresses and reception times. When forwarding data packets, a device greedily selects a neighbor geographically closest to the final destination. If no neighbor is closer to the final destination than the current hop, the protocol forwards the packet in "perimeter mode." A description of GPSR's perimeter mode is omitted since it is not enabled in USMP. This makes an examination of GPSR's planarization technique failures under realistic conditions unnecessary [11]. If a planarization failure recovery technique is required, CLDP [12], ALBA-R [13] or [14] should be considered.

III. PROTOCOL

USMP includes two features that provide similar state information within each UAV: Location Update and Waypoint Conflict Resolution. A design that leverages geographic routing features is produced for each USMP feature, and an alternative without geographic routing features is used for comparison.

The Location Update feature propagates neighbor UAV location information to the swarm. UAVs use Location Update messages to build a local search state for waypoint decisions. UAVs also use the location information to determine if the Location Update message provider has searched the cell from which the message was sent.

Two candidate designs for the USMP Location Update feature are implemented. The first generates Location Update messages explicitly, while the second reuses GPSR's location information (aka, GPSR harvesting). With explicit updates enabled, UAVs generate updates every second and upon waypoint arrivals. Since Location Update provides a cell's search status and the search algorithm prioritizes distance, Location Update data impacts decisions made by neighboring UAVs the most and therefore explicit Location Update messages are only broadcast to neighboring UAVs. GPSR beacons are broadcast to neighboring devices at one second intervals by default. When GPSR harvesting is enabled, USMP receives a location update each time GPSR receives a packet since GPSR appends location information to data packets as well as creating location beacons [10].

Waypoint Conflict Resolution resolves waypoint selection conflicts between UAVs. Fig. 2 illustrates the Waypoint Conflict Resolution process and indicates when reservation messages are generated. Waypoint reservations are generated when a UAV selects a new waypoint or when a UAV wins a waypoint conflict. When a UAV receives a waypoint reservation, it determines if its waypoint is the same as the advertised waypoint. If so, a conflict is said to occur (i.e., “Same Waypoint” decision in Fig. 2). Conflicts are resolved at the receiving UAV. Regardless of how the receiver resolves the conflict (“Conflict Winner” decision in the figure), a conflict loser selects a new waypoint (“Select Waypoint” event) without responding directly to the conflict winner. The winner sends a reservation message addressed to the conflict loser (“Generate Response Reservation” event). If received, the conflict winner's reservation is processed by the conflict loser like any other reservation. The loser is unaware it has lost the resolution process until it receives the winner's reservation.

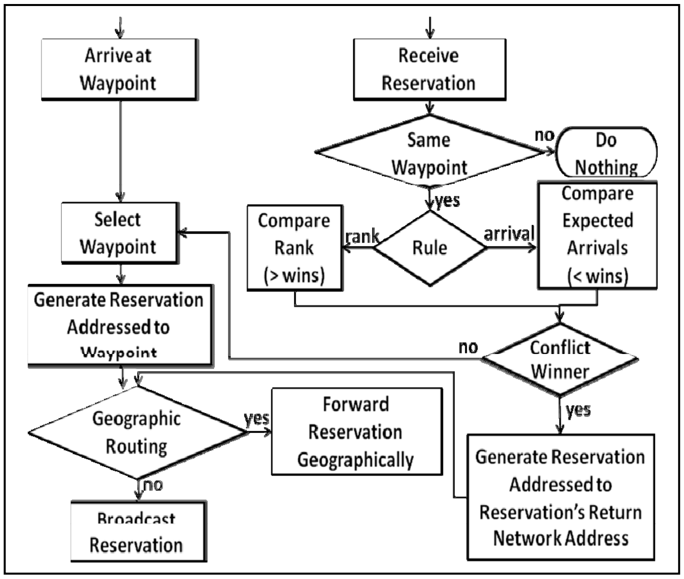

Figure 2. Waypoint Conflict Resolution Process

Waypoint conflicts could occur between any set of two or more UAVs in the network, but the UAV Search System's swarm logic alters the likelihood a UAV will experience conflicts. Since the swarm logic prioritizes distance in waypoint selections, a new waypoint selection is more likely to conflict with waypoint selections by UAVs closer to the intended waypoint. Therefore, Waypoint Conflict Resolution data impacts search decisions of UAVs in the area between the waypoint reservation sender and the intended waypoint.

Waypoint Conflict Resolution data's geographic dependency is exploited by both the routing waypoint reservations and the rules used to process received reservations. USMP exploits routing by greedily forwarding reservation messages to the geographic address of the advertised waypoint. UAVs promiscuously listen for and process any available USMP reservations. Thus, UAVs positioned directly between the sender and the sender's intended waypoint receive and process the sender's reservation. Alternative designs that simply broadcast waypoint reservations to neighbors are used for comparison.

USMP exploits waypoint conflict resolution rules by resolving conflicts in favor of UAVs closest to the waypoint. This is called the Estimated Arrival Rule. The Estimated Arrival Rule compares the estimated arrival time advertised by a received waypoint reservation to the receiver's calculated estimate of waypoint arrival time. If the receiver's expected arrival is sooner than the advertised arrival, it wins the conflict. Otherwise, the receiver loses the conflict.

For comparison, an alternative rule, the Rank Rule, resolves waypoint conflicts based on a unique integer rank assigned to UAVs before the search mission. If the rank of the receiving UAV is higher than the rank advertised in the reservation, the receiving UAV wins the conflict. Otherwise, the receiver loses.

Combining the routing and conflict resolution rule designs produces four candidate Waypoint Conflict Resolution designs: Arrival Broadcast, Arrival Geographic, Rank Broadcast and Rank Geographic. In all designs, waypoint reservation messages serve as location updates by advertising the sender's location information.

Fig. 3 shows waypoint conflict resolution at work using the expected arrival rule. Gray lines indicate direction of travel, the dashed circle shows communication range and locations A-E are unsearched portions of the grid. UAVs 2 and 3 are already traveling toward A. UAV 1 has just arrived at its waypoint and selects A as its new waypoint. It generates a reservation and greedily forwards it to location A. The reservation traverses the links indicated by dashed arrows. UAVs 2 and 3 detect a conflict, win the resolution and separately generate return reservations addressed to the location of UAV 1. UAV 3 also overhears and evaluates the return reservation from UAV 2. UAV 1 first receives the return reservation from UAV 2, loses the conflict and begins the waypoint selection process again. UAV 2 then receives the return reservation from UAV 3, loses the conflict and restarts the selection process. UAVs 1 and 2 ignore any further return reservations from UAV 3 since a conflict no longer exists.

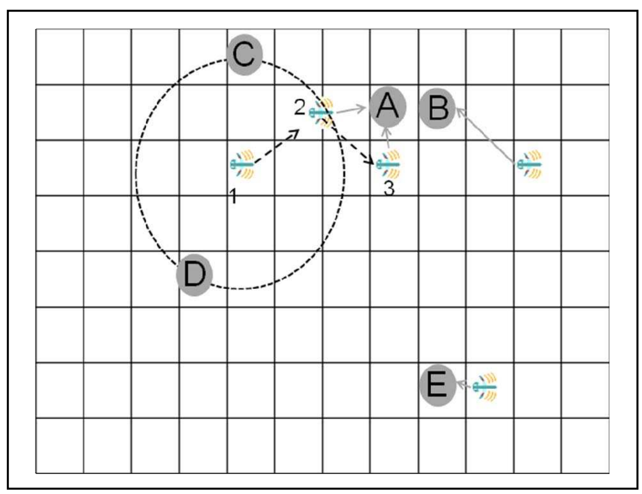

Figure 3. Waypoint Conflict Resolution Example

IV. Metrics

The following metrics measure the search mission performance for each experiment.

A. Total Searches

Total Searches is the sum of searches performed by UAVs during the search mission. Lower values for Total Searches are better, and the best achievable score is equal to the cell count since the search completes after each cell is searched once.

B. Average Distance Traveled

Average Distance Traveled is the sum of Euclidean distances in meters traveled by all UAVs divided by the swarm size. Lower values for Average Distance Traveled indicate more efficient search performance.

C. Average Direction Changes

Average Direction Changes measures the number of direction changes a UAV makes during a search mission. Changing direction expends more energy than flying straight and level. This metric is calculated by dividing the total number of UAV direction changes by the swarm size. A lower Average Direction Changes indicates a more efficient search.

While changing directions during flight consumes energy, the energy is still consumed in flying the UAV. Total Searches and Average Distance Traveled relate directly to the energy used to move UAVs through space. Therefore, Total Searches and Average Distance Traveled are more dominant measures of search performance than Average Direction Changes.

V. METHODOLOGY

The effect of USMP on search efficiency is studied under varying transmission power levels, sensor types, swarm sizes and initial locations. Table I summarizes these factors and their associated levels. Transmission power is the power required for desired transmission range.

TABLE I. SUMMARY OF FACTOR LEVELS

Factor / Workload	Levels		
Transmission Power	75%	Optimal	Full
Swarm Size	13	25	38
Sensor Type	Active	Passive	
Initial Location	170-179		

Xu and Kumar showed that if each device in an ad hoc wireless network can communicate with 5.177 log *n* neighbor devices in a network, "the network is asymptotically connected with probability approaching one as *n* increases" [15]. The optimum transmission range is the minimum transmission range required for each device to average 5.177 log *n* neighbors over the network's lifetime. The optimum transmission range given the number of devices and the network area for a uniform distribution of devices is

$$r \approx \sqrt{\frac{5.771 A \log n}{\pi \cdot n}} \quad (1)$$

where r is the ideal transmission range for a connected network, and A is the physical network area (or area of the search mission) [3]. Substituting (1) into the simple free-space path loss equation results in

$$path\ loss_{dB} = 32.5 + 20 \log F + 20 \log d \quad (2)$$

where F is wireless channel frequency. Using (2) in

$$transmit\ power_{dBm} = path\ loss_{dB} + receiver\ sensitivity_{dBm} \quad (3)$$

and converting from dBm to milliwatts produces

$$\text{power}_{\text{mW}} = 10^\wedge\left(\frac{\left\{32.5 + 20 \log F + 20 \log \sqrt{\frac{5.771 \cdot A \log n}{\pi \cdot n}} + -90\,dBm\right\}}{10}\right). \quad (4)$$

The above equations assume a uniform distribution of UAVs. Equations (2) and (4) assume no external interference, a receiver sensitivity of -90 dBm and an IEEE 802.11b network with a center frequency of 2.46 GHz. The simulation incorporates these assumptions.

Swarm size determines the swarm's workload by changing the ratio of cells to UAVS and is scaled by one fourth from factor levels in [3] to reduce simulation time and preserve workload. Initial locations of UAVs are determined by a uniform random distribution and the seeds listed in Table I. The data rate is 11 Mbps. The physical layer and MAC protocol are standard 802.11b as modeled by OPNET Modeler 12.0. USMP communication overhead is ignored in favor of determining the usefulness of geographic protocols in cooperative search. Since the wireless channel's data rate is set to 11 Mbps and no background traffic is modeled, the data rate far exceeds the expected demand of USMP.

A full factorial experiment is performed for all USMP features and their design options, and 10 repetitions with different random seeds are performed for each combination of USMP feature options. The simulated swarm is contained within a subnet whose span is 1 km x 1 km. Simulations run until search completion or 1 simulation hour, which is the flight endurance for a typical mini-UAV [16]. At the beginning of each simulation, UAVs are placed in uniformly random locations across the search area. UAVs may not leave the search area, and new UAVs may not enter. The search area is assumed to be free of obstacles, and UAVs never collide (i.e., the system allows multiple UAVs to occupy the same physical space). Between direction changes, a UAV travels in a straight line toward its waypoint. An actual protocol implementation would adjust location update frequency according to UAV speed changes, but this study reduces complexity by assuming a constant speed of 25 m/s. All UAVs fly at the same altitude, and direction changes occur instantaneously. Each UAV is assumed to use a GPS device to accurately know its own location.

The UAV node model modifies the standard *manet_station_adv* OPNET node model by adding UAV swarm logic and USMP process models. The GPSR process model, *gpsr_rte*, is registered as a child process of the new UAV node model's *ip* process, which makes it selectable as a routing protocol in the MANET [3]. The process that executes the swarm logic and generates USMP messages is *uav_search* which checks its parent UAV's location in the subnet every 0.1 seconds to determine if the UAVs location constitutes a cell search and whether the UAV has arrived at its waypoint. A UAV arrives at a waypoint if it is less than or equal to a threshold of t_w meters away from a waypoint, where

$$t_w = UAV\ Speed_{m/s} \cdot location\ check\ interval + 0.1\text{s} \qquad (5)$$

The same threshold determines if any two distance values are approximately the same, including when UAVs apply the Distance Rule. This prevents small distances (< 2.5 m) from unfairly biasing the swarm's search decisions.

Cell searches occur when a UAV enters the center quarter of a new cell. The UAV updates its local state by incrementing a private count of the cell's number of searches by one. The UAV also updates a global state, which the simulation uses to calculate search performance metrics and to determine when the search has completed.

VI. RESULTS

Collected data is examined using analysis of variance (ANOVA), a standard statistical method that measures how much each of the experimental factors and their interactions contribute to the variance in the data. A general linear model of all factors and second through fifth order interactions are developed and compared to the response variable using an ANOVA. Minitab generates plots of the residuals to demonstrate independence and normal distribution of residual values. If the plot of residuals versus fits shows a pattern, the response is transformed using logarithmic, square root and reciprocal transformations of the response in that order and retested until the data meets ANOVA assumptions for the general linear model [RaS02]. Confidence intervals with a significance of 0.05 are generated using the Tukey-Kramer method. Sample means whose pairwise comparison produce a p-value less than 0.05 are considered to be statistically different indicating differences in performance between the levels of each factor. The raw data collected did not conform to the ANOVA's assumptions of normal and independent residuals, so transformed data is examined instead. Total Searches uses a reciprocal transformation, and the remaining metrics use a logarithmic transformation.

Table II summarizes the results of the ANOVA. An examination of Table II shows that initial location and sensor type account for less than 2% of total variation for each metric. Conversely, the USMP features or their interaction contribute significantly to variation in all cases. Whenever transmission power contributes significantly to variation it magnifies the effect of USMP as power increases without emphasizing differences between feature designs. This effect remains constant, so it does not warrant further discussion.

Fig. 4 shows the main effect of USMP features on variance for reciprocal total searches. Enabling Location Update increases Reciprocal Total Searches by at least 188%, and explicit updates outperform GPSR harvesting by 3.2%. The broadcast Waypoint Conflict Resolution designs outperform geographic routing designs by 13.5% and 13.9% respectively for the Expected Arrival and Rank Rules. The Expected Arrival Rule improves performance by 3% when Waypoint Conflict Resolution messages are broadcast and by 3.3% when geographically routed.

Analysis of Log Average Distance Traveled shows the same trends as seen in Fig. 4 for relative performance differences. In the original scale, using broadcasts over geographic routing decreases Average Distance Traveled by 20%, and using the Expected Arrival Rule versus the Rank Rule reduces Average Distance Traveled by about 4%.

TABLE II. SUMMARY OF ANOVA RESULTS

		Percent Variation Contributed by Metric		
	Source	Reciprocal Total Searches	Log Average Distance Traveled	Log Average Direction Changes
Main Effects	Initial Location	0.08%	0.54%	0.05%
Main Effects	Swarm Size	1.15%	36.19%	2.77%
Main Effects	Waypoint Conflict Resolution	8.03%	8.61%	18.23%
Main Effects	Transmission Power	30.86%	7.88%	23.71%
Main Effects	Sensor Type	1.79%	Not significant	0.22%
Main Effects	Location Update	37.06%	24.60%	1.31%
Interactions	Transmission Power Location Update	6.40%	0.64%	10.22%
Interactions	Waypoint Conflict Resolution Location Update	2.71%	10.59%	18.25%
Interactions	Transmission Power Waypoint Conflict Resolution	1.44%	0.46%	10.56%
	Error	8.22%	8.97%	2.50%
	R-Sq (adj)	90.64%	90.82%	90.36%

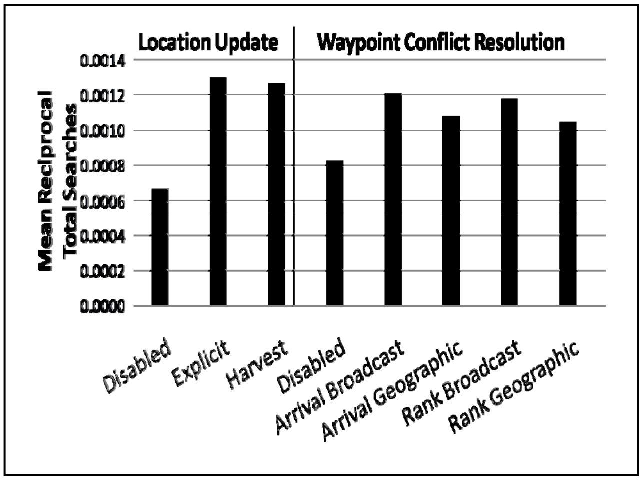

Figure 4. Reciprocal total searches main effects

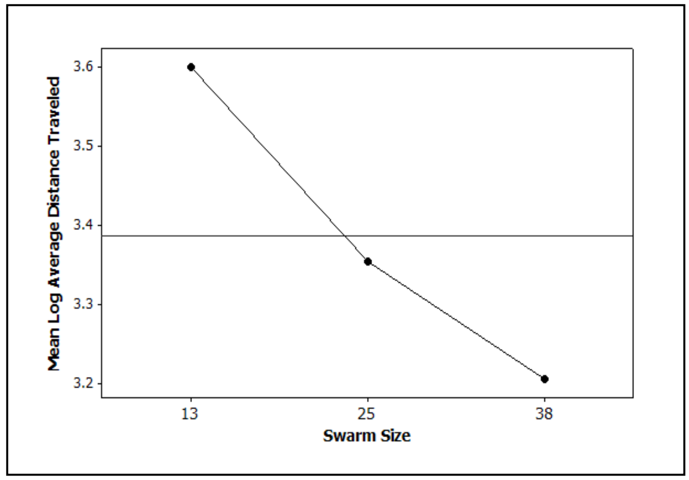

Figure 5. Effect of swarm size on Average Distance Traveled

Enabling Waypoint Conflict Resolution reduces Log Average Distance Traveled by 4.1%, and enabling Location Update reduces Log Average Distance Traveled by 8.3%. Explicit updates outperform GPSR harvesting by 0.6% (6% in the original scale). Fig. 5 shows how swarm size reduces average distance traveled by decreasing the ratio of cells to UAVs, which is consistent with how workload is defined.

Log Average Direction Changes reversed the trends seen in the waypoint conflict resolution main effect in Fig. 4. The geographic routing designs significantly reduce direction changes compared to their broadcast alternatives—6.5% for the Rank Rule and 6.1% for the Expected Arrival Rule (21.4% and 69.7% in the original scale). The most significant reduction in Log Average Direction Changes from varying Waypoint Conflict Resolution levels, 18.4%, results when Waypoint Conflict Resolution is disabled. As expected, employing Waypoint Conflict Resolution increases Average Direction Changes since a successful conflict resolution often results in a direction change. The Estimated Arrival Rule performs better than the Rank Rule by 1.1% (36.1% in the original scale) for geographic routing, while broadcast versions with different resolution rules fail to differ significantly.

Analysis of the second order effects for Average Direction Changes show that disabling either Location Update or Waypoint Conflict Resolution, but not both, results in significant Log Average Direction Changes decreases. When Location Update is enabled, Waypoint Conflict Resolution geographic routing designs significantly reduce Log Average Direction Changes by 6.7% compared to their broadcast counterparts for the same Location Update level. When Waypoint Conflict Resolution is enabled, explicit updates reduces Log Average Direction Changes by 2.4% versus GPSR harvesting for the same level of Waypoint Conflict Resolution.

The results for Log Average Direction Changes suggest that reducing, but not eliminating the dissemination of search information improves search performance by reducing Average Direction Changes. Since the Neighbor Rule does not make search decisions based directly on a search performance metric, it is conjectured that limiting the information available to the Neighbor Rule could reduce Average Direction Changes without negatively impacting the other search metrics.

Overall, USMP has a positive effect on search performance. In all cases except Average Direction Changes, enabling Location Update and Waypoint Conflict Resolution improves search performance as demonstrated in Table III. Statistical analysis clearly indicates that performance gains from enabling Location Update or Waypoint Conflict Resolution are at least twice the performance gains of any pair of different Waypoint Conflict Resolution or Location Update designs.

TABLE III. SUMMARY OF POSITIVE USMP EFFECTS

Metric	Location Update	Waypoint Conflict Resolution
Reciprocal Total Searched	188%	29.90%
Log Average Distance Traveled	8.30%	4.10%

VII. CONCLUSIONS

The experimental results reject the hypothesis that leveraging geographic routing for Waypoint Conflict Resolution improves search performance. Using geographic routing actually degrades search performance for Total Searches and Average Distance Traveled compared to broadcasting Waypoint Conflict Resolution messages. While geographic routing improves Average Direction Changes versus broadcast, Total Searches and Average Distance Traveled should dominate measures of search performance.

The results also reject GPSR harvesting as a replacement for explicit location updates, though performance differs by only 3%-6% for each metric, and further experimentation may alter this conclusion. Since GPSR treats every data packet as a source of location updates, GPSR harvesting in a network with higher background traffic would likely rival explicit updates. At the very least, GPSR harvesting and explicit updates could be combined for greater performance.

For Waypoint Conflict Resolution, the results prove that the Expected Arrival Rule outperforms or matches the Rank Rule for every search metric, whether simple broadcast or geographic routing is used. The Expected Arrival Rule should be used by Waypoint Conflict Resolution in USMP.

This research successfully developed a communications protocol for a swarm of searching UAVs. Despite the failure of geographic routing to improve search efficiency, it is the first known protocol to have a positive effect on the search performance of the swarm logic used. The protocol brings the UAV Search System closer to real-world implementation since the system has been shown to operate successfully under realistic communication conditions.

VIII. ACKNOWLEDGMENT

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