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UAV search-and-rescue planning using an adaptive memetic algorithm

Key words: Memetic algorithm; Self-adaptive; Unmanned aerial vehicle (UAV); Search-and-rescue

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Motivation

1. The use of unmanned aerial vehicles (UAVs) is becoming more commonplace in search-and-rescue tasks. However, UAV search planning can be very complex due to limited response time, large search area, and multiple candidate search modes.
2. In this work, we present a UAV search planning problem where the search area is divided into a set of subareas and each subarea has a prior probability that the target is present in it.
3. We aim to determine the search sequence of the subareas and the search mode for each subarea to maximize the probability of finding the target.

Main idea

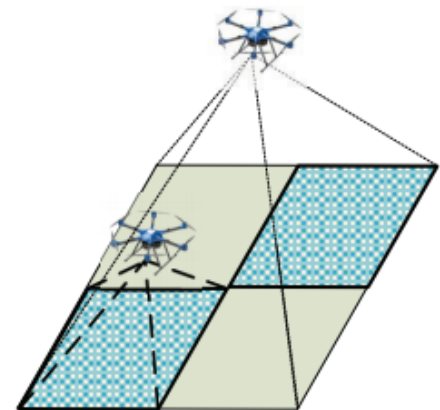
1. We formulate a problem that uses a UAV to search for a target (e.g., a victim) in a search area consisting of m subareas that are not necessarily adjacent.
2. Each subarea i ($1 \leq i \leq m$) is assigned a probability $p(i)$ of target existence, assuming that we have a prior probability distribution function that describes the initial belief of the target location. The (average) altitude of subarea i is denoted as $\alpha(i)$.
3. Update the UAV's velocity and the flying time, set the global search procedure, and adaptively select the local search procedures.

Method

1. Update the UAV's velocity and flying time

$$v(i, k_i, j, k_j) = \frac{F_{\max} \cos \theta - M g \sin \theta}{F_{\max}} v_{\max},$$

$$t_f(i, k_i, j, k_j) = \frac{\sqrt{d^2(i, j) + h^2(i, j)} F_{\max}}{(F_{\max} \cos \theta - M g \sin \theta) v_{\max}}.$$



Method (Cont'd)

2. The objective is to maximize the total time-weighted probability of finding the target, and the problem is formulated as

$$\max \quad f(x, y) = \sum_{i=1}^m \frac{t^U - t(x_i)}{t^U} p_s(x_i, y_i) p(x_i)$$

s.t.

Eq. (7),

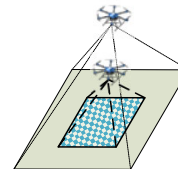
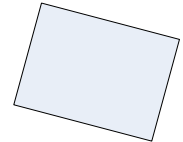
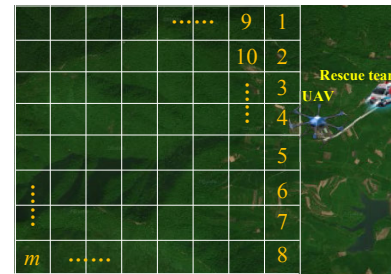
$$t(x_m) \leq t^U,$$

$$x \in \text{perms}(1, 2, \dots, m),$$

$$1 \leq y_i \leq K, \quad i = 1, 2, \dots, m,$$

$$t(x_i) = t_f(0, 0, x_1, y_1) + \sum_{i'=2}^i t_f(x_{i'-1}, y_{i'-1}, x_{i'}, y_{i'})$$

$$+ \sum_{i'=1}^i t_s(x_{i'}, y_{i'}).$$

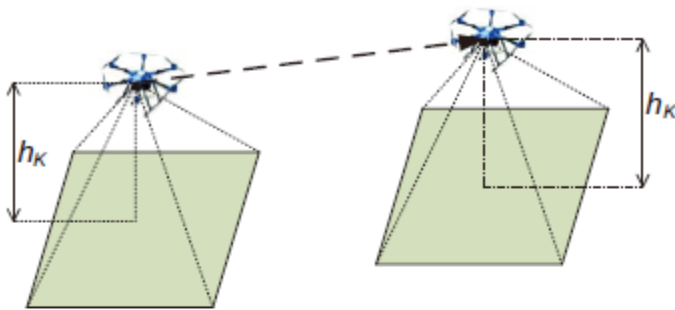


(7)

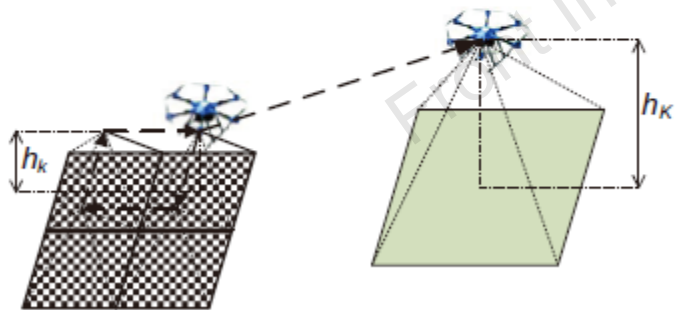
Method (Cont'd)

3. The objective function can be extended to maximize the sum of the (weighted) probabilities of finding all the targets:

$$\max f(x, y) = \sum_{i=1}^m \sum_{j=1}^n \frac{t^U - t(x_i)}{t^U} w_j p_s(x_i, j, y_i) \cdot p(x_i, j)$$



(a)



(b)

Fig. 3 The horizontal distance for the UAV to fly from one subarea to another: (a) the UAV uses search mode K on both subareas, and the horizontal distance is between the centers of the two subareas; (b) the UAV uses search mode $k < K$ on the first subarea, and thus the distance starts from the UAV's last position in the first subarea to the first position in the second subarea

Major results

Table 2 Summary of the test instances of the component selection problem

Instance	m	K	n	Area (km ²)	$\bar{d}$ (km)	$\bar{h}$ (m)
1	20	4	1	11.6	0.9	135
2	20	5	1	11.6	0.9	135
3	27	4	1	9.5	0.7	266
4	32	4	1	13.3	1.3	30
5	39	6	1	19.6	1.5	48
6	46	5	1	17.9	1.3	26
7	56	5	1	22.1	1.2	41
8	56	6	1	22.1	1.2	41
9	60	4	1	35.2	1.8	103
10	60	6	1	35.2	1.8	103
11	88	5	1	39.0	1.5	59
12	96	4	1	39.7	1.2	36
13	27	4	2	9.5	0.7	266
14	39	6	2	19.6	1.5	48
15	56	5	2	22.1	1.2	41
16	39	6	3	11.6	0.9	135
17	56	5	3	19.6	1.5	48
18	60	4	3	35.2	1.8	103

m : number of subareas; K : number of potential search modes;
 n : number of targets; Area: total search area; $\bar{d}$: average
horizontal distance between a pair of subareas; $\bar{h}$: average
vertical distance between a pair of subareas

Major results (Cont'd)

Table 3 Comparative results of the algorithms on single-target instances

Scheme	Instance 1					Instance 2					Instance 3				
	Max	Min	Mean	Median	Std	Max	Min	Mean	Median	Std	Max	Min	Mean	Median	Std
B&B	0.409	–	–	–	–	0.362	–	–	–	–	0.383	–	–	–	–
GA	0.409	0.385	†0.406	0.409	0.004	0.362	0.353	†0.360	0.362	0.003	0.383	0.375	†0.380	0.383	0.002
SPSO	0.409	0.409	0.409	0.409	0.000	0.362	0.362	0.362	0.362	0.000	0.383	0.383	0.383	0.383	0.001
QPIO	0.409	0.409	0.409	0.409	0.000	0.362	0.362	0.362	0.362	0.000	0.383	0.379	†0.382	0.383	0.001
KNDE	0.409	0.409	0.409	0.409	0.000	0.362	0.362	0.362	0.362	0.000	0.383	0.383	0.383	0.383	0.000
MA1	0.409	0.409	0.409	0.409	0.000	0.362	0.362	0.362	0.362	0.000	0.383	0.372	†0.380	0.383	0.003
MA2	0.409	0.409	0.409	0.409	0.000	0.362	0.362	0.362	0.362	0.000	0.383	0.375	†0.382	0.383	0.002
MA3	0.409	0.409	0.409	0.409	0.000	0.362	0.362	0.362	0.362	0.000	0.383	0.383	0.383	0.383	0.000
MA4	0.409	0.409	0.409	0.409	0.000	0.362	0.362	0.362	0.362	0.000	0.383	0.383	0.383	0.383	0.000
MA5	0.409	0.409	0.409	0.409	0.000	0.362	0.362	0.362	0.362	0.000	0.383	0.383	0.383	0.383	0.000
MA6	0.409	0.409	0.409	0.409	0.000	0.362	0.362	0.362	0.362	0.000	0.383	0.383	0.383	0.383	0.000
MA-S	0.409	0.409	0.409	0.409	0.000	0.362	0.362	0.362	0.362	0.000	0.383	0.383	0.383	0.383	0.000
MA-BS	0.409	0.409	0.409	0.409	0.000	0.362	0.362	0.362	0.362	0.000	0.383	0.383	0.383	0.383	0.000
MA-B	0.409	0.409	0.409	0.409	0.000	0.362	0.362	0.362	0.362	0.000	0.383	0.383	0.383	0.383	0.000
MA-L	0.409	0.409	0.409	0.409	0.000	0.362	0.362	0.362	0.362	0.000	0.383	0.383	0.383	0.383	0.000
MA-FD	0.409	0.409	0.409	0.409	0.000	0.362	0.362	0.362	0.362	0.000	0.383	0.383	0.383	0.383	0.000

Scheme	Instance 4					Instance 5					Instance 6				
	Max	Min	Mean	Median	Std	Max	Min	Mean	Median	Std	Max	Min	Mean	Median	Std
B&B	0.325	–	–	–	–	0.289	–	–	–	–	0.242	–	–	–	–
GA	0.325	0.313	†0.320	0.320	0.003	0.285	0.263	†0.276	0.278	0.005	0.236	0.225	†0.232	0.230	0.003
SPSO	0.325	0.316	†0.321	0.322	0.001	0.289	0.270	†0.283	0.282	0.003	0.237	0.227	†0.233	0.234	0.002
QPIO	0.325	0.316	†0.323	0.322	0.002	0.285	0.268	†0.281	0.282	0.004	0.237	0.225	†0.232	0.233	0.003
KNDE	0.325	0.321	†0.323	0.324	0.001	0.289	0.273	†0.282	0.282	0.003	0.237	0.230	†0.235	0.234	0.002
MA1	0.325	0.313	†0.322	0.322	0.003	0.285	0.268	†0.279	0.278	0.006	0.237	0.225	†0.232	0.233	0.003
MA2	0.325	0.316	†0.322	0.321	0.003	0.285	0.270	†0.280	0.282	0.004	0.237	0.227	†0.233	0.233	0.002
MA3	0.325	0.316	0.323	0.322	0.002	0.285	0.275	†0.283	0.282	0.003	0.236	0.221	†0.231	0.232	0.003
MA4	0.325	0.316	†0.322	0.322	0.002	0.285	0.273	†0.281	0.280	0.004	0.237	0.230	0.236	0.236	0.002
MA5	0.325	0.313	†0.320	0.320	0.003	0.285	0.268	†0.278	0.278	0.005	0.237	0.227	0.234	0.236	0.002
MA6	0.325	0.313	†0.321	0.320	0.003	0.285	0.270	†0.280	0.282	0.004	0.237	0.227	0.235	0.236	0.002
MA-S	0.325	0.320	0.324	0.325	0.002	0.289	0.275	†0.283	0.284	0.003	0.242	0.233	0.237	0.237	0.002
MA-BS	0.325	0.321	0.324	0.325	0.001	0.289	0.275	†0.284	0.284	0.004	0.242	0.233	0.238	0.238	0.002
MA-B	0.325	0.321	0.324	0.325	0.001	0.289	0.282	†0.286	0.285	0.002	0.242	0.236	0.239	0.238	0.001
MA-L	0.325	0.324	0.325	0.325	0.000	0.289	0.285	0.288	0.289	0.002	0.242	0.236	0.238	0.238	0.001
MA-FD	0.325	0.323	0.325	0.325	0.000	0.289	0.285	0.289	0.289	0.002	0.242	0.236	0.239	0.238	0.001

Major results (Cont'd)

Table 3 continued

Scheme	Instance 7					Instance 8					Instance 9				
	Max	Min	Mean	Median	Std	Max	Min	Mean	Median	Std	Max	Min	Mean	Median	Std
B&B	0.217	–	–	–	–	0.205	–	–	–	–	0.133	–	–	–	–
GA	0.203	0.176	†0.192	0.190	0.006	0.185	0.159	†0.172	0.174	0.006	0.118	0.093	†0.107	0.109	0.008
SPSO	0.206	0.184	†0.195	0.199	0.006	0.188	0.161	†0.177	0.181	0.006	0.121	0.100	†0.111	0.111	0.007
QPIO	0.206	0.179	†0.195	0.195	0.008	0.188	0.161	†0.176	0.176	0.009	0.118	0.098	†0.108	0.109	0.009
KNDE	0.210	0.188	†0.198	0.198	0.005	0.190	0.161	†0.179	0.181	0.005	0.124	0.105	†0.115	0.115	0.006
MA1	0.210	0.190	†0.199	0.198	0.005	0.188	0.169	†0.179	0.181	0.005	0.121	0.098	†0.109	0.111	0.007
MA2	0.210	0.190	†0.202	0.203	0.005	0.192	0.169	†0.181	0.181	0.007	0.121	0.098	†0.112	0.115	0.006
MA3	0.203	0.183	†0.195	0.193	0.004	0.185	0.169	†0.177	0.179	0.004	0.121	0.103	†0.113	0.115	0.005
MA4	0.206	0.193	†0.201	0.199	0.004	0.188	0.169	†0.184	0.188	0.005	0.124	0.102	†0.112	0.115	0.007
MA5	0.206	0.188	†0.197	0.197	0.005	0.188	0.161	†0.178	0.181	0.007	0.121	0.098	†0.112	0.115	0.007
MA6	0.203	0.176	†0.192	0.193	0.007	0.185	0.159	†0.175	0.178	0.008	0.118	0.098	†0.109	0.109	0.005
MA-S	0.213	0.197	0.206	0.206	0.005	0.196	0.177	0.188	0.188	0.005	0.124	0.111	†0.117	0.118	0.004
MA-BS	0.213	0.199	0.208	0.206	0.004	0.198	0.180	0.190	0.188	0.005	0.124	0.105	†0.116	0.116	0.006
MA-B	0.217	0.203	0.210	0.211	0.004	0.198	0.177	0.188	0.190	0.007	0.124	0.114	0.118	0.121	0.003
MA-L	0.217	0.199	0.210	0.208	0.005	0.202	0.180	0.188	0.188	0.006	0.124	0.111	0.118	0.118	0.004
MA-FD	0.217	0.197	0.209	0.208	0.004	0.198	0.180	0.190	0.190	0.004	0.124	0.118	0.119	0.121	0.002

Scheme	Instance 10					Instance 11					Instance 12				
	Max	Min	Mean	Median	Std	Max	Min	Mean	Median	Std	Max	Min	Mean	Median	Std
B&B	0.106	–	–	–	–	0.058	–	–	–	–	0.030	–	–	–	–
GA	0.088	0.065	†0.076	0.077	0.007	0.063	0.033	†0.049	0.049	0.008	0.052	0.029	†0.040	0.038	0.006
SPSO	0.095	0.068	†0.081	0.080	0.008	0.068	0.037	†0.056	0.058	0.008	0.059	0.035	†0.047	0.049	0.008
QPIO	0.088	0.065	†0.077	0.079	0.011	0.063	0.035	†0.050	0.052	0.012	0.056	0.030	†0.044	0.045	0.009
KNDE	0.095	0.069	†0.083	0.084	0.009	0.068	0.039	†0.055	0.056	0.009	0.059	0.038	†0.050	0.051	0.006
MA1	0.095	0.072	†0.084	0.086	0.005	0.065	0.033	†0.050	0.056	0.009	0.059	0.032	†0.046	0.045	0.009
MA2	0.095	0.072	†0.084	0.086	0.005	0.068	0.036	†0.053	0.051	0.010	0.059	0.038	†0.051	0.056	0.005
MA3	0.088	0.069	†0.084	0.085	0.004	0.068	0.039	†0.055	0.056	0.007	0.058	0.029	†0.043	0.040	0.009
MA4	0.095	0.072	0.087	0.088	0.005	0.068	0.046	†0.058	0.061	0.007	0.059	0.038	†0.049	0.051	0.008
MA5	0.093	0.077	†0.083	0.086	0.005	0.068	0.037	†0.054	0.056	0.008	0.058	0.029	†0.045	0.047	0.010
MA6	0.088	0.068	†0.079	0.081	0.005	0.063	0.035	†0.051	0.047	0.008	0.056	0.030	†0.043	0.042	0.008
MA-S	0.095	0.077	0.087	0.089	0.006	0.072	0.056	0.064	0.064	0.004	0.063	0.053	0.058	0.058	0.003
MA-BS	0.095	0.075	†0.086	0.086	0.007	0.068	0.058	†0.062	0.061	0.003	0.059	0.051	0.056	0.056	0.003
MA-B	0.095	0.079	0.088	0.089	0.006	0.072	0.058	0.063	0.063	0.003	0.066	0.052	0.060	0.060	0.004
MA-L	0.096	0.077	0.089	0.088	0.006	0.076	0.058	0.067	0.066	0.004	0.063	0.051	0.058	0.058	0.002
MA-FD	0.095	0.077	0.088	0.088	0.005	0.076	0.058	0.064	0.066	0.004	0.066	0.051	0.059	0.058	0.003

Major results (Cont'd)

Table 4 Comparative results of the algorithms on multi-target instances

Scheme	Instance 13					Instance 14					Instance 15				
	Max	Min	Mean	Median	Std	Max	Min	Mean	Median	Std	Max	Min	Mean	Median	Std
B&B	0.309	—	—	—	—	0.232	—	—	—	—	0.049	—	—	—	—
GA	0.308	0.277	†0.292	0.289	0.007	0.220	0.190	†0.207	0.210	0.008	0.063	0.042	†0.052	0.055	0.007
SPSO	0.308	0.286	†0.296	0.297	0.007	0.222	0.197	†0.211	0.212	0.008	0.070	0.049	†0.063	0.063	0.006
QPIO	0.309	0.280	†0.295	0.293	0.010	0.220	0.192	†0.208	0.210	0.007	0.067	0.046	†0.058	0.060	0.006
KNDE	0.309	0.286	†0.297	0.298	0.006	0.224	0.197	†0.212	0.212	0.006	0.070	0.049	†0.061	0.063	0.007
MA1	0.308	0.280	†0.295	0.297	0.009	0.222	0.203	†0.214	0.216	0.005	0.070	0.049	†0.060	0.060	0.007
MA2	0.308	0.280	†0.294	0.297	0.008	0.222	0.203	†0.214	0.218	0.006	0.070	0.049	†0.061	0.062	0.007
MA3	0.308	0.286	†0.298	0.303	0.007	0.222	0.200	†0.212	0.214	0.007	0.067	0.046	†0.057	0.058	0.005
MA4	0.308	0.285	†0.300	0.306	0.006	0.222	0.201	†0.214	0.219	0.006	0.067	0.046	†0.060	0.063	0.005
MA5	0.306	0.285	†0.295	0.295	0.007	0.220	0.197	†0.212	0.216	0.007	0.063	0.039	†0.057	0.058	0.007
MA6	0.306	0.286	†0.297	0.295	0.006	0.220	0.197	†0.210	0.212	0.008	0.063	0.045	†0.055	0.057	0.005
MA-S	0.309	0.295	0.303	0.306	0.003	0.226	0.210	†0.219	0.220	0.005	0.073	0.056	†0.064	0.065	0.005
MA-BS	0.309	0.295	0.303	0.306	0.005	0.226	0.207	†0.218	0.220	0.006	0.073	0.056	†0.066	0.065	0.007
MA-B	0.309	0.303	0.305	0.306	0.002	0.232	0.207	0.221	0.222	0.005	0.073	0.058	0.066	0.067	0.004
MA-L	0.309	0.297	0.304	0.306	0.003	0.232	0.212	0.223	0.224	0.004	0.077	0.056	0.067	0.069	0.005
MA-FD	0.309	0.298	0.305	0.306	0.003	0.232	0.210	0.222	0.224	0.004	0.077	0.056	0.068	0.069	0.005

Scheme	Instance 16					Instance 17					Instance 18				
	Max	Min	Mean	Median	Std	Max	Min	Mean	Median	Std	Max	Min	Mean	Median	Std
B&B	0.206	—	—	—	—	0.017	—	—	—	—	0.006	—	—	—	—
GA	0.200	0.179	†0.190	0.192	0.006	0.046	0.032	†0.038	0.037	0.003	0.014	0.011	†0.012	0.012	0.001
SPSO	0.208	0.183	†0.198	0.200	0.008	0.051	0.037	†0.044	0.045	0.003	0.015	0.012	†0.014	0.014	0.001
QPIO	0.205	0.179	†0.192	0.192	0.008	0.047	0.034	†0.040	0.040	0.005	0.014	0.012	†0.013	0.013	0.001
KNDE	0.208	0.183	†0.198	0.199	0.005	0.051	0.037	†0.045	0.046	0.004	0.016	0.012	†0.014	0.014	0.001
MA1	0.203	0.181	†0.194	0.197	0.007	0.046	0.034	†0.040	0.040	0.003	0.014	0.011	†0.013	0.013	0.001
MA2	0.206	0.181	†0.195	0.199	0.007	0.047	0.034	†0.042	0.043	0.004	0.014	0.012	†0.013	0.013	0.001
MA3	0.208	0.186	†0.199	0.203	0.006	0.046	0.034	†0.041	0.043	0.003	0.015	0.012	†0.013	0.013	0.001
MA4	0.208	0.183	†0.197	0.200	0.006	0.047	0.036	†0.042	0.042	0.003	0.016	0.012	†0.014	0.014	0.001
MA5	0.210	0.197	†0.203	0.203	0.003	0.048	0.037	†0.044	0.046	0.004	0.015	0.012	†0.014	0.014	0.001
MA6	0.210	0.192	†0.203	0.206	0.005	0.046	0.033	†0.040	0.040	0.004	0.015	0.012	†0.014	0.013	0.001
MA-S	0.213	0.197	†0.206	0.206	0.005	0.056	0.043	0.050	0.049	0.003	0.017	0.012	0.015	0.015	0.001
MA-BS	0.213	0.197	†0.206	0.205	0.005	0.053	0.045	0.049	0.050	0.002	0.018	0.012	0.016	0.015	0.002
MA-B	0.219	0.203	0.210	0.211	0.004	0.056	0.049	0.053	0.053	0.004	0.021	0.012	0.017	0.017	0.002
MA-L	0.215	0.206	0.211	0.211	0.002	0.060	0.049	0.055	0.054	0.003	0.019	0.012	0.015	0.016	0.002
MA-FD	0.219	0.203	0.211	0.213	0.003	0.060	0.049	0.054	0.054	0.002	0.019	0.012	0.016	0.016	0.001

Conclusions

1. The paper presented a UAV search planning problem where the search area is divided into a set of subareas with different prior probabilities of target existence, and for each subarea the UAV can perform search at different altitudes with different precisions.
2. The problem was to determine the search sequence of the subareas and the search mode on each subarea, such that the total weighted probability of finding the target is maximized.
3. The proposed adaptive memetic algorithm combined a GA with six local search procedures and dynamically determined which procedure to apply based on their suitability in a previous period of the problem-solving process. Computational experiments showed that the adaptive memetic algorithm outperforms some global search heuristics and non-adaptive memetic algorithms.