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Routing an Unmanned Aerial Vehicle During NPP Monitoring in the Presence of an Automatic Battery Replacement Aerial System

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***Abstract*— The paper is devoted to routing an unmanned aerial vehicle (UAV) during the Zaporizhzhia nuclear power plant monitoring without returning to the depot due to the deployment of an automatic battery replacement aerial system in specified places. The monitoring includes the overflight of the 11 monitoring stations to collect radiation monitoring data from them in case of damage of wired networks between the monitoring stations and the crisis centre. The shortest possible UAV route that visits every monitoring station (route point) exactly once and returns to the UAV depot is found by solving the Travelling Salesman Problem. An algorithm for determining the places for deployment of the automatic battery replacement aerial system is presented. A flight schedule both for the UAV and the automatic battery replacement aerial system is developed. The DJI Mavic 2 Enterprise Dual quadcopter is considered as a UAV for monitoring missions. The SL-231 Scout helicopter capable to operate in an unmanned mode is considered as a platform for the automatic battery replacement system.**

Keywords—routing, monitoring, unmanned aerial vehicle, nuclear power plant, automatic battery replacement aerial system, travelling salesman problem, monitoring station

I. INTRODUCTION

In recent years, especially after the Fukushima NPP accident, unmanned aerial vehicles (UAVs) are considered to be used for pre- and post NPP monitoring. NPP monitoring related missions may cover:

- Radiation dose rate measurement, air sampling, surveying or mapping [1]–[3].
- Detection of nuclear sources [4].
- Locating lost radioactive sources [5].
- Characterising remediation effectiveness [6].
- Deployment an Internet of Drone-based multi-version post-severe accident monitoring system [7], [8].

During an NPP monitoring related mission, UAVs can be tasked with flying above a finite set of objects on the ground within 30-km area around the NPP (monitoring area). For example, monitoring stations for the Automated Radiation Monitoring System can be chosen as these objects. It is understandable that the time required to visit all objects on the route should be minimized. In the absence of any additional constraints, this can be formulated as the Travelling Salesman Problem (TSP). However, when the objects are scattered over a wide area, the UAV may not have enough battery life to conduct its mission without retuning to its depot for battery replacement. In this case, scenarios where the UAV can change its battery directly on the route have the right to exist.

Utilizing stationary and/or mobile battery replacement/charging stations is a way to enable missions via the UAV in a single deployment. This leads to a new variant of the TSP where the output involves:

- Finding the shortest possible route for the UAV to carry out the monitoring of all needed objects.
- Determining where, in what way, and how long the UAV and the battery charging/replacement station have to cooperate for enabling the UAV to continue its mission without returning to the depot.
- Routing the the battery charging/replacement station taking into account the necessity of its deployment at designated places to cooperate with the UAV.

The rest of the paper is organized as follows.

In the next section we analyze the existing studies regarding to utilization of mobile charging/replacement stations for persistent conducting missions via UAVs.

Section III presents an approach to routing the DJI Mavic 2 Enterprise Dual quadcopter that conducts the monitoring of assigned sites within 30-km area around the Zaporizhzhia NPP and uses an automatic battery replacement aerial system based on the SL-231 Scout helicopter capable to operate in an unmanned mode.

The proposed approach application and discussion of the obtained results are given in Section IV.

Section V briefly summarizes the main points raised in the paper and presents the next research steps.

II. State-of-the-Art

A greedy strategy for coordination between the mobile refueling unmanned ground vehicle (UGV) and the UAV for successful mission accomplishment is developed in [9]. The authors propose a simulation platform in Matlab to test and validate the strategy.

Study [10] deals with a multirobot scheduling problem in which UAVs must be recharged during a long-term mission. The study introduces a separate team of dedicated charging robots that the UAVs can dock with in order to recharge. The goal of the study is to schedule and plan minimum cost paths for charging robots such that they rendezvous with and replenish the UAVs during the mission.

Work [11] presents the autonomous battery exchange operation for small scale UAVs, using a mobile ground base that carries a robotic arm and a service station containing the battery exchange mechanism. The goal of this work is to demonstrate the means to increase the autonomy and persistence of robotic systems without requiring human intervention.

Shin et al. [12] design an auction-based mechanism to control the charging schedule in multi-drone setting in the presence of mobile charging stations. Charging time slots are auctioned, and their assignment is determined by a bidding process. The main challenge in developing this framework is the lack of prior knowledge on the distribution of the number of drones participating in the auction.

Paper [13] proposes the use of a ground-based refueling vehicle (RV) to increase the operational range of a UAV in both spatial and temporal domains. A two-stage strategy for coupled route planning for UAV and RV to perform a coverage mission is developed. The first stage computes a minimal set of refueling sites that permit a feasible UAV route. In the second stage, multiple Mixed-Integer Linear Programming (MILP) formulations are developed to plan optimal routes for the UAV and the refueling vehicle taking into account the feasible set of refueling sites generated in stage one.

Yu et al. [14] present an algorithm for planning a tour for energy-limited UAV and tours for the UGVs with determining the best locations to place stationary charging stations. The authors study three variants for charging: multiple stationary charging stations, single mobile charging station, and multiple mobile charging stations.

Seyedi et al. [15] address the problem of achieving persistent surveillance over an environment by using energy-constrained UAVs which are supported by mobile charging stations. Specifically, the trajectories of all vehicles and the charging schedule of UAVs are planned by the authors for minimizing the time between two consecutive visits to regions of interest in a partitioned environment.

But while considerable attention is given to ground based mobile charging/replacement stations in the analyzed studies, in our opinion, issues regarding to utilization of aerial based such stations also deserve attention.

Using an aerial vehicle as a platform for a charging/replacement station is a way for the station to quickly travel between designated points of the route specified as places for battery charging/replacement as well as avoid problems related to damaged roads.

In light of the foregoing, the aim of the paper is to develop an approach to routing the DJI Mavic 2 Enterprise Dual quadcopter visiting 11 monitoring stations within 30-km area around the Zaporizhzhia NPP and using an automatic battery replacement aerial system based on the SL-231 Scout helicopter for conducting mission of the quadcopter in a single deployment.

III. Approach to Routing an Unmanned Aerial Vehicle during Zaporizhzhia NPP Monitoring

A. *Abbreviations and Notations*

As there are numerous abbreviations and symbols in the paper, let us present them in Table I.

TABLE I. ABBREVIATIONS/SYMBOLS AND THEIR MEANING

Abbreviation/ symbol	**Abbreviation/symbol meaning**
ABRAS	Automatic battery replacement aerial system based on the SL-231 Scout unmanned helicopter
CrS	Crisis centre
DH	Depot for the ABRAS
DQ	Depot for the quadcopter
h	Hour
km	Kilometer
MS	Monitoring station
min	Minute
NPP	Nuclear power plant
PBR	Place for battery replacement
	Location of a monitoring station
	Location of a monitoring station with a place for battery replacement
	ABRAS
	Quadcopter
	Depot for the quadcopter

B. *Scenario description*

Let us have the following scenario. As a result of Zaporizhzhia NPP accident, the wired networks connecting 11 MSs with the CrS were damaged (Fig. 1).

It is necessary to conduct the monitoring that includes the overflight of the 11 MSs to collect radiation monitoring data from them. The Wi-Fi equipment placed at a MS and the onboard WiFi equipment of the DJI Mavic 2 Enterprise Dual quadcopter (hereinafter the quadcopter) allow performing this mission due to communications between the MS and the quadcopter hovering on the MS during the needed time. The DQ is the starting and ending point of the route for the quadcopter. An MS is a point of the route for the quadcopter to visit.

To ensure the monitoring at a point of the route via the quadcopter without returning to the DQ, the ABRAS based on the SL-231 Scout helicopter is utilized. The ABRAS, having a range of 600 km and endurance of 190 min, in addition to its battery replacement function, can deliver additional quadcopters and needed goods at the proper location as well as evacuate damaged quadcopters.

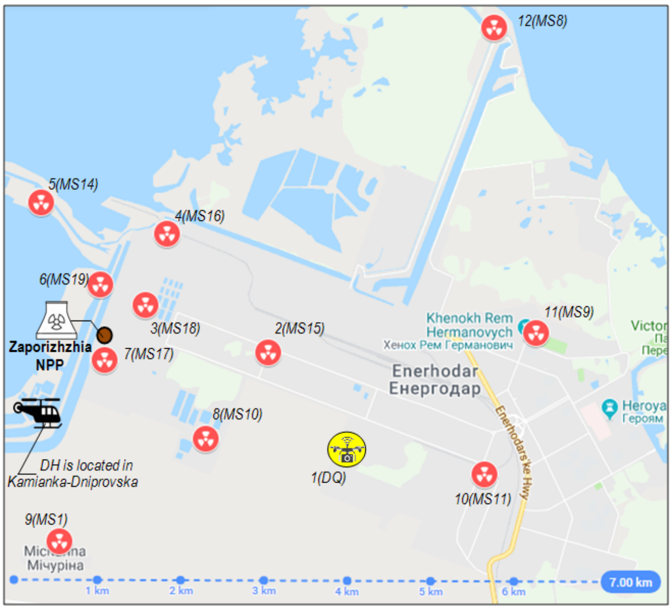

Fig. 1. Zaporizhzhia NPP, the monitoting stations, the depot for the ABRAS, and the depot for the quadcopter

A point of the route should be used as a PBR (place for deployment of the ABRAS) if, after finishing the monitoring at the point, the quadcopter has not enough battery life to get the next point and conduct the monitoring there. The DH is the starting and ending point of the route for the ABRAS.

A PBR is a point of the route for the ABRAS to visit.

C. Algorithm for routing the quadcopter using the automatic battery replacement aerial system

The algorithm for routing the quadcopter during Zaporizhzhia NPP post accident monitoring in the presence of the ABRAS should include the following steps.

1. Finding the shortest possible route for the quadcopter that visits every MS (point of the route) exactly once and returns to its depot.
2. Determining PBRs (places for deployment of the ABRAS).
3. Developing a flight schedule both for the quadcopter and the ABRAS using parameters obtained by means of Eqs. (1)–(15).

$$T^q_{a(i)} = T^q_{a(i-1)} + \frac{D_{i,i-1}}{v_q} \quad (1)$$

where $T^q_{a(i)}$ is the time of arrival of the quadcopter at point i; $T^q_{a(i-1)}$ is the time of arrival of the quadcopter at point $(i-1)$; $D_{i,i-1}$ is the distance between points i and $(i-1)$; v_q is the speed of the quadcopter; $i = \overline{2,n}$; n is the number of the route points (monitoring stations).

$$t^q_{\Sigma(i)} = \begin{cases} t_m + t_{br} \text{ if } i \text{ is a PBR;} \\ t_m \text{ otherwise} \end{cases} \quad (2)$$

where $t^q_{\Sigma(i)}$ is the time spent at point i for the quadcopter; t_m is the time the quadcopter takes to conduct the monitoring at a point of the route; t_{br} is the time for battery replacement.

$$t_{bl(i)} = \begin{cases} 31 \text{ min if } i \text{ is a PBR;} \\ t_m \text{ otherwise} \end{cases} \quad (3)$$

where $t_{bl(i)}$ is the battery life for the quadcopter at the moment of its departure from point i; t_m is the time the quadcopter takes to conduct the monitoring at a point of the route.

$$T^q_{d(i)} = T^q_{a(i)} + t^q_{\Sigma(i)} \quad (4)$$

where $T^q_{d(i)}$ is the time of departure of the quadcopter from point i; $T^q_{a(i)}$ is the time of arrival of the quadcopter at point i; $t^q_{\Sigma(i)}$ is the time spent at point i for the quadcopter.

$$T^q_{a(DQ)} = T^q_{a(n)} + 60\frac{D_{n,DQ}}{v_q} \quad (5)$$

where $T^q_{a(DQ)}$ is the time of arrival of the quadcopter at the DQ; $T^q_{a(n)}$ is the time of arrival of the quadcopter at point n; $D_{n,DQ}$ is the distance between point n and the DQ; v_q is the speed of the quadcopter.

$$T^q_{\Sigma} = 60\frac{\sum_{i=2}^{n} D_{i,i+1}}{v_q} + \sum_{i=2}^{n} t^q_{\Sigma(i)} \quad (6)$$

where T^q_{Σ} is the time spent on the route for the quadcopter; $D_{i,i+1}$ is the distance between points i and $(i+1)$; v_q is the speed of the quadcopter; $t^q_{\Sigma(i)}$ is the time spent at point i for the quadcopter.

$$T^{ABRAS}_{a(PBR1)} = T^q_{a(i=PBR1)} + t_m - 2 \text{ min} \quad (7)$$

where $T^{ABRAS}_{a(PBR1)}$ is the time of arrival of the ABRAS at PBR1; $T^q_{a(i=PBR1)}$ is the time of arrival of the quadcopter at PBR1; t_m is the time the quadcopter takes to conduct the monitoring at a point of the route.

$$T^{ABRAS}_{d(DH)} = T^{ABRAS}_{a(PBR1)} - 60\frac{D_{DH,PBR1}}{v_{ABRAS}} \quad (8)$$

where $T^{ABRAS}_{d(DH)}$ is the time of departure of the ABRAS from the DH; $T^{ABRAS}_{a(PBR1)}$ is the time of arrival of the ABRAS at PBR1; $D_{DH,PBR1}$ is the distance between the DH and PBR1; v_{ABRAS} is the speed of the ABRAS.

$$t^{ABRAS}_{\Sigma(PBR1)} = T^{q}_{d(i=PBR1)} + 2 - T^{ABRAS}_{a(PBR1)} \quad (9)$$

where $t^{ABRAS}_{\Sigma(PBR1)}$ is the time spent at PBR1 for the ABRAS; $T^{q}_{d(i=PBR1)}$ is the time of departure of the quadcopter from PBR1; $T^{ABRAS}_{a(PBR1)}$ is the time of arrival of the ABRAS at PBR1.

$$T^{ABRAS}_{d(PBR1)} = T^{q}_{d(i=PBR1)} + 2\min \quad (10)$$

where $T^{ABRAS}_{d(PBR1)}$ is the time of departure of the ABRAS from PBR1; $T^{q}_{d(i=PBR1)}$ is the time of departure of the quadcopter from PBR1.

$$T^{ABRAS}_{a(PBRj)} = T^{ABRAS}_{d(PBR(j-1))} + 60\frac{D_{PBRj,PBR(j-1)}}{v_{ABRAS}} \quad (11)$$

where $T^{ABRAS}_{a(PBRj)}$ is the time of arrival of the ABRAS at PBRj; $j = \overline{2,k}$; k is the number of the places for battery replacement; $T^{ABRAS}_{d(PBR(j-1))}$ is the time of departure of the ABRAS from PBR(j-1); $D_{PBRj,PBR(j-1)}$ is the distance between PBRj and PBR(j-1); v_{ABRAS} is the speed of the ABRAS.

$$T^{ABRAS}_{d(PBRj)} = T^{q}_{d(i=PBRj)} + 2\min \quad (12)$$

where $T^{ABRAS}_{d(PBRj)}$ is the time of departure of the ABRAS from PBRj; $T^{q}_{d(i=PBRj)}$ is the time of departure of the quadcopter from PBRj.

$$T^{ABRAS}_{\Sigma(PBRj)} = T^{ABRAS}_{d(PBRj)} - T^{ABRAS}_{a(PBRj)} \quad (13)$$

where $T^{ABRAS}_{\Sigma(PBRj)}$ is the time spent at point PBRj for the ABRAS; $T^{ABRAS}_{d(PBRj)}$ is the time of departure of the ABRAS from PBRj; $T^{ABRAS}_{a(PBRj)}$ is the time of arrival of the ABRAS at PBRj.

$$T^{ABRAS}_{a(DH)} = T^{ABRAS}_{d(PBRk)} + 60\frac{D_{PBRk,DH}}{v_{ABRAS}} \quad (14)$$

where $T^{ABRAS}_{a(DH)}$ is the time of arrival of the ABRAS at the DH; $T^{ABRAS}_{d(PBRk)}$ is the time of departure of the ABRAS from PBRk; $D_{PBRk,DH}$ is the distance between PBRk and the DH; v_{ABRAS} is the speed of the ABRAS.

$$T^{ABRAS}_{\Sigma} = T^{ABRAS}_{a(DH)} - T^{ABRAS}_{d(DH)} \quad (15)$$

where T^{ABRAS}_{Σ} is the time spent on the route for the ABRAS; $T^{ABRAS}_{a(DH)}$ is the time of arrival of the ABRAS at the DH; $T^{ABRAS}_{d(DH)}$ is the time of departure of the ABRAS from DH.

IV. Example of the Approach Application

Let us have the initial data presented in Table II and distances between points of the route presented in Table III.

TABLE II. INITIAL DATA

Parameter	Value
$T^{q}_{d(DQ)}$	1.00 p.m.
t_m	3 min
t_{br}	2 min
$t_{bl(1)}$	31 min
v_q	40 km/h
v_{ABRAS}	100 km/h

Let us have the following assumptions.

- The ABRAS should arrive at a PBR at least 2 minutes earlier than the quadcopter finishes the monitoring.
- The ABRAS should depart from the PBR 2 minutes later than the quadcopter does.

Following the proposed algorithm and using the given initial data, the following results were obtained.

- The shortest possible route for the DJI Mavic 2 Enterprise Dual quadcopter that visits every monitoring station (route point) exactly once and returns to the quadcopter's depot was found by solving the TSP through the Evolutionary solving method in Excel (Fig. 2).
- The PBRs (places for deployment of the ABRAS) were determined (Fig. 2).
- The flight schedule for joint utilization of the quadcopter and ABRAS on the route was developed and presented in Table IV.

TABLE III. DISTANCES BETWEEN ROUTE POINTS

Point	Points											
	DQ	***MS8***	***MS14***	***MS16***	***MS19***	***MS18***	***MS15***	***MS9***	***MS17***	***MS10***	***MS11***	***MS1***
DQ	0.00	5.35	4.69	3.36	3.53	2.94	1.48	2.68	3.06	1.69	1.70	3.59
MS8	5.35	0.00	5.85	4.89	5.64	5.34	4.75	3.68	6.16	6.03	5.35	8.07
MS14	4.69	5.85	0.00	1.49	1.25	3.77	3.27	6.17	2.05	3.48	6.24	4.04
MS16	3.36	4.89	1.49	0.00	0.79	0.71	1.88	6.16	4.48	2.41	4.82	3.70
MS19	3.53	5.64	1.25	0.79	0.00	0.56	2.21	5.24	0.91	2.30	5.16	3.12
MS18	2.94	5.34	3.77	0.71	0.56	0.00	1.59	4.71	0.85	1.79	4.54	3.03
MS15	1.48	4.75	3.27	1.88	2.21	1.59	0.00	3.25	1.96	1.27	2.99	3.39
MS9	2.68	3.68	6.17	6.16	5.24	4.71	3.25	0.00	5.23	4.15	1.83	6.26
MS17	3.06	6.16	2.05	4.48	0.91	0.85	1.96	5.23	0.00	1.56	4.76	2.27
MS10	1.69	6.03	3.48	2.41	2.30	1.79	1.27	4.15	1.56	0.00	3.39	2.16
MS11	1.70	5.35	6.24	4.82	5.16	4.54	2.99	1.83	4.76	3.39	0.00	5.17
MS1	3.59	8.07	4.04	3.70	3.12	3.03	3.39	6.26	2.27	2.16	5.17	0.00

TABLE IV. FLIGHT SCHEDULE FOR JOINT UTILIZATION OF THE QUADCOPTER AND ABRAS ON THE ROUTE

Point (i)	Aerial vehicle	Parameters					
		Arrival	t_m *(min)*	t_{br} *(min)*	*Time spent at point* i *(min)*	*Departure*	$t_{bl(i)}$ *(min)*
1(DQ)	Quadcopter	-	-	-	-	1.00 p.m.	31
2(MS15)	Quadcopter	1.02 p.m.	3	0	3	1.05 p.m.	26
3(MS18)	Quadcopter	1.07 p.m.	3	0	3	1.10 p.m.	21
4(MS16)	Quadcopter	1.11 p.m.	3	0	3	1.14 p.m.	17
5(MS14)	Quadcopter	1.16 p.m.	3	0	3	1.19 p.m.	12
6(MS19)	Quadcopter	1.21 p.m.	3	0	3	1.24 p.m.	7
7(MS17 & PBR1)	Quadcopter	1.25 p.m.	3	2	5	1.30 p.m.	3→31
	ABRAS	1.26 p.m.	-	-	6	1.32 p.m.	-
8(MS10)	Quadcopter	1.33 p.m.	3	0	3	1.35 p.m.	26
9(MS1)	Quadcopter	1.38 p.m.	3	0	3	1.41 p.m.	20
10(MS11)	Quadcopter	1.49 p.m.	3	0	3	1.52 p.m.	9
11(MS9 & PBR2)	Quadcopter	1.55 p.m.	3	2	5	2.00 p.m.	3→31
	ABRAS	1.35 p.m.	-	-	27	2.02 p.m.	-
12(MS8)	Quadcopter	2.06 p.m.	3	0	3	2.09 p.m.	22
1(DQ)	Quadcopter	2.17 p.m.	-	-	-	-	14

TABLE V. FLIGHT SCHEDULE FOR THE ABRAS

Point	Parameters		
	Arrival	Time spent at a point	Departure
DH	-	-	1.17 p.m.
7(MS17 & PBR1)	1.26 p.m.	6	1.32 p.m.
11(MS9 & PBR2)	1.35 p.m.	27	2.02 p.m.
DH	2.13 p.m.	-	-

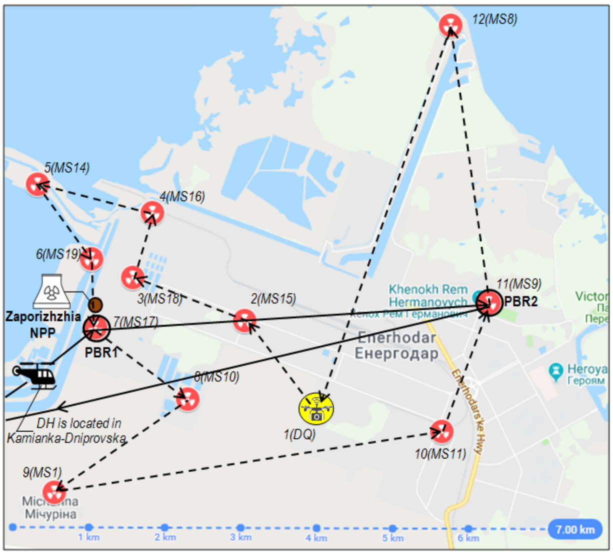

Fig. 2. Shortest possible route for the quadcopter, places for deployment of the ABRAS, and the route for the ABRAS

The flight schedule for the ABRAS only was developed and presented in Table V. Based on the obtained results, we can make the following conclusions.

- To allow the quadcopter to visit each of the 11 points (MSs) on the route without returning to the quadcopter's depot, PBR1 and PBR2 should be deployed at point 7 (MS17) and point 11 (MS9), respectively (Fig. 2).
- The time spent on the route for the quadcopter is 77 min.
- The time spent on the route for the ABRAS is 56 min.
- The quadcopter conducts its mission 22 minutes longer than the ABRAS.

V. CONCLUSION AND FUTURE WORK

In the paper, we present an approach to routing the DJI Mavic 2 Enterprise Dual quadcopter visiting 11 monitoring stations within 30-km area around the Zaporizhzhia NPP and using an automatic battery replacement aerial system based on the SL-231 Scout unmanned helicopter for conducting mission of the quadcopter in a single deployment.

Following the algorithm and given initial data, the shortest possible route for the DJI Mavic 2 Enterprise Dual quadcopter that visits every monitoring station (route point) exactly once and returns to its depot was found by solving the TSP through the Evolutionary solving method in Excel.

It is determined that point 7 (MS17) and point 11 (MS9) are the places for battery replacement.The flight schedule for joint utilization of the quadcopter and ABRAS as well as the flight schedule of utilization of the ABRAS only were developed.

According to the schedules, the time spent on the route for the quadcopter and ABRAS is 77 and 56 min, respectively.

Thus, the quadcopter perform its mission 22 minutes longer than the ABRAS. In future work, we are planning to develop an algorithm for utilization of multiple quadcopters and multiple ABRAS during NPP monitoring related missions.

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