UAV fleet Routing with Battery Recharging for Nuclear Power Plant Monitoring Considering UAV Failures

Ihor Kliushnikov [1], Vyacheslav Kharchenko [1] and Herman Fesenko [1]

[1]*National Aerospace University "KhAI", st. Chkalov, 17, Kharkiv, 61070, Ukraine*

Abstract
Reliability-based unmanned aerial vehicle (UAV) fleet nuclear power plant (NPP) monitoring mission planning models with battery recharging are developed. Battery recharging is carried out either at the depot or by using autonomous battery maintenance stations (ABMSs) deployed at certain points. A classification and set of the models in accordance with ways for UAVs to follow their routes and recharge their batteries are suggested. Examples of the proposed models application are given. The probability of the successful fulfillment of the plan for the UAV fleet to perform the NPP and other critical infrastructures monitoring mission is used as an indicator when using the proposed models.

Keywords
Unmanned aerial vehicle, routing, reliability, monitoring station, nuclear power plant, autonomous battery maintenance stations

1. Introduction
1.1. Motivation

Recent technologies in onboard equipment allow small-scale UAVs, such as quadrotors, to be used for NPP monitoring [1-8]. A monitoring mission via these quadrotors, can involve, for instance, covering the whole target monitoring stations (MSs) of the NPP to gather data from them on meteorological or radiological parameters in post-accident period, which can be characterized by damaging the wired networks connecting the MSs to the crisis centre (CrS). However, the small battery life time (8–40 min) is a significant barrier to utilize quadrotors for long-term NPP monitoring missions.

To cope with this problem, the UAV's battery has to be charged/changed either at the UAV's depot (QD) or by using ABMSs. Normally, an ABMS serves for quickly charging/changing a depleted UAV battery and simultaneously recharging other batteries to form a battery replacement pool.

1.2. State of the Art

Literature is rich with several methods of using ABMSs, also known as autonomous battery change/charge stations, to ensure that long-term missions via UAVs are per.

Study [9] presents the UAV replacement procedure to guarantee persistent operation of UAV-based aerial networks providing Internet connectivity to ground users. Following the developed algorithm, periodically, a certain UAV return to an ABMS for recharging its battery while a reserve

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EMAIL: i.kliushnikov@csn.khai.edu (I. Kliushnikov); v.kharchenko@csn.khai.edu (V. Kharchenko); h.fesenko@csn.khai.edu (H. Fesenko)
ORCID: 0000-0001-9419-7825 (I. Kliushnikov); 0000-0001-5352-077X (V. Kharchenko); 0000-0002-4084-2101 (H. Fesenko)

UAV comes back in its place. After battery recharging, the UAV is added to the reserve fleet (replacement pool) responsible for replacing other UAVs to be changed.

Work [10] outlines battery charging options that may be considered by a network operator and use simulations to demonstrate the performance impact of incorporating those options into a cellular network where the UAV infrastructure provides wireless service.

According to Yu et al. [11], in order to visit a set of points in the given amount of time, a UAV can be recharged by using either stationary recharging stations, deployed along the UAV route, or unmanned ground mobile recharging stations. Various scenarios covering the proposed ways of UAV battery recharging are proposed and discussed.

Paper [12] proposes an algorithm allowing a UAV fleet to provide continuous uninterrupted missions related to structural inspection. To implement the algorithm, MAVLink protocol should be extended with a set of special messages and commands. Simulation results show the operability of the algorithm.

In work [13] results of evaluation of the three scenarios with different types of targets are presented. The patrolling strategy was able to successfully perform the mission, detecting the targets and safely returning to the recharging stations multiple times.

Paper [14] presents an approach aimed at simultaneous changing and charging a UAV battery via an autonomous battery maintenance mechatronic system in order to significantly extend the operational time and reduce the downtime of UAV fleet. Thus, BMMS can be in demand when enabling missions that require the UAV fleet persistent operation. The obtained flight test results show that the UAV fleet, comprising 3 UAVs with an endurance of 8-10 min, requires more than 100 battery swaps for persistent operation during a 3-h-long mission.

Authors of [15] focus on issues related to the routing of a given UAV fleet and organizing the battery replacement process (locating swapping depots and determining the frequency of battery replacement) in a way that would guarantee the maintenance of the desired production time.

From authors of [16] point of view, when a drone has a problem linked with landing on a charging station, last should comprise power transmitters and a receiver for charging the drone battery.

However, the analysed works don't consider reliability issues related to both UAVs and ABMSs utilization.

1.3. Goal and Objectives

The goal of the paper is to develop and research reliability-based UAV fleet NPP monitoring mission planning models with battery recharging.

The objectives of the paper are:

- To develop general UAV fleet NPP monitoring mission planning models with battery recharging.
- To develop a set of reliability-based UAV fleet NPP monitoring mission planning models with battery recharging.
- To research reliability-based UAV fleet NPP monitoring mission planning models with various ways for UAVs to follow their routes and recharge their batteries.

2. Development of general UAV fleet NPP monitoring mission planning models with battery recharging

Let us have n groups of MSs. One UAV is used to visit all MSs of each group. All used UAVs is located at the same depot (QD).

In general, a UAV fleet can comprise both main UAVs (MDs) and redundant ones. Each of the last UAVs is ready to rich a point where a failed MD has stopped its monitoring mission, and to continue performing the mission instead of the failed UAV [17]. In this paper, authors focus on application of MDs only.

In order to perform a long-term NPP monitoring mission, UAVs should periodically recharge their batteries either at the QD or by using ABMSs deployed at certain points.

According to the first way of battery recharging, each UAV, after visiting the whole target MSs in its route, should return to the depot, recharge its battery, and repeat its previous route starting from the first visited MS. A UAV fleet monitoring mission planning model with battery recharging at the QD is shown in Figure 1 where:

- MS_{i_ki} is MS k of MS group i where $i = 1,\dots,n$, $fi = 1,\dots,mi$.
- $L_{i\_(fi\text{-}1),fi}$ is the distance between points $(fi\text{-}1)$ and fi. For instance, $L_{i\_0,1}$ is the distance between the QD and MS_{i_1}, and $L_{i\_1,2}$ is the distance between MS_{i_1} and MS_{i_2}.

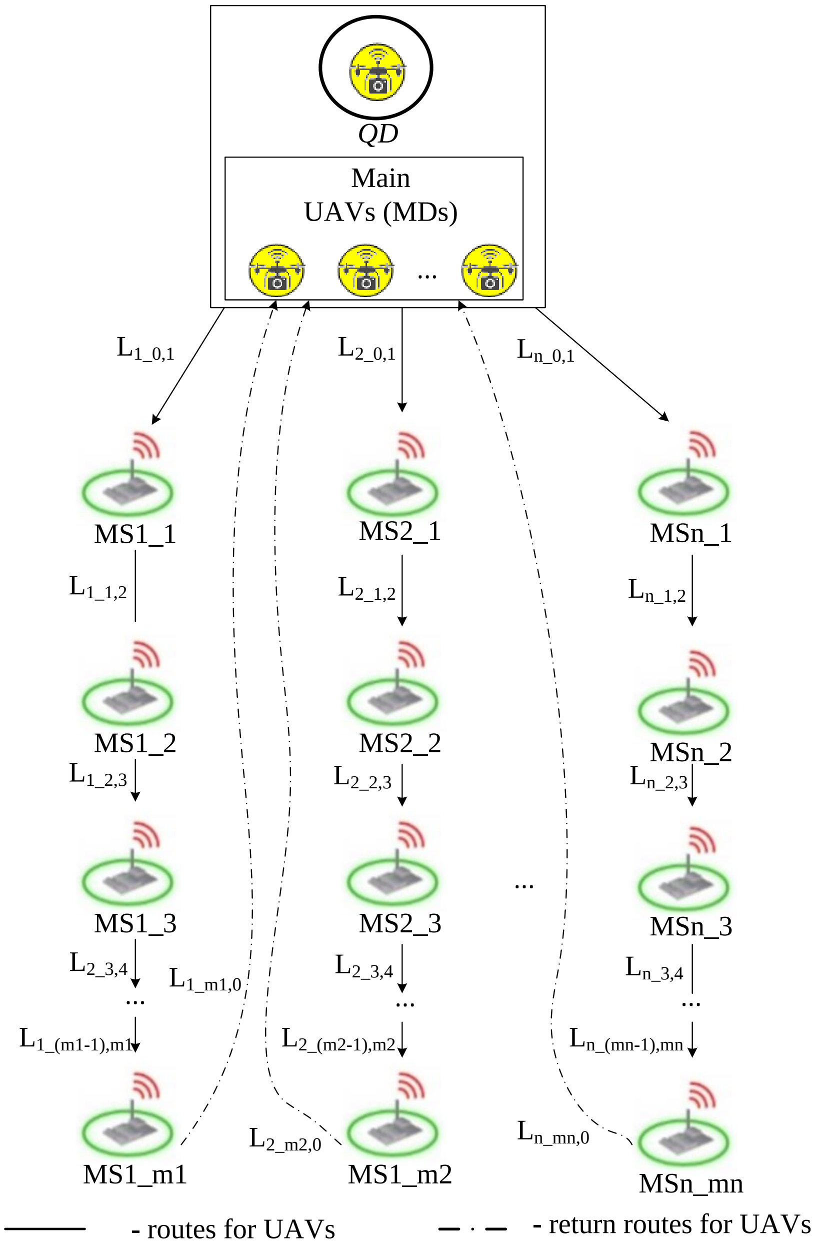

Figure 1: General UAV fleet NPP monitoring mission planning model with battery recharging at the depot

According to the second way of battery recharging, each UAV, after visiting the whole target MSs in its route, should rich an ABMS, recharge its battery, and repeat its previous route starting from the last visited MS. A UAV fleet monitoring mission planning model with battery recharging via an ABMS is shown in Figure 2.

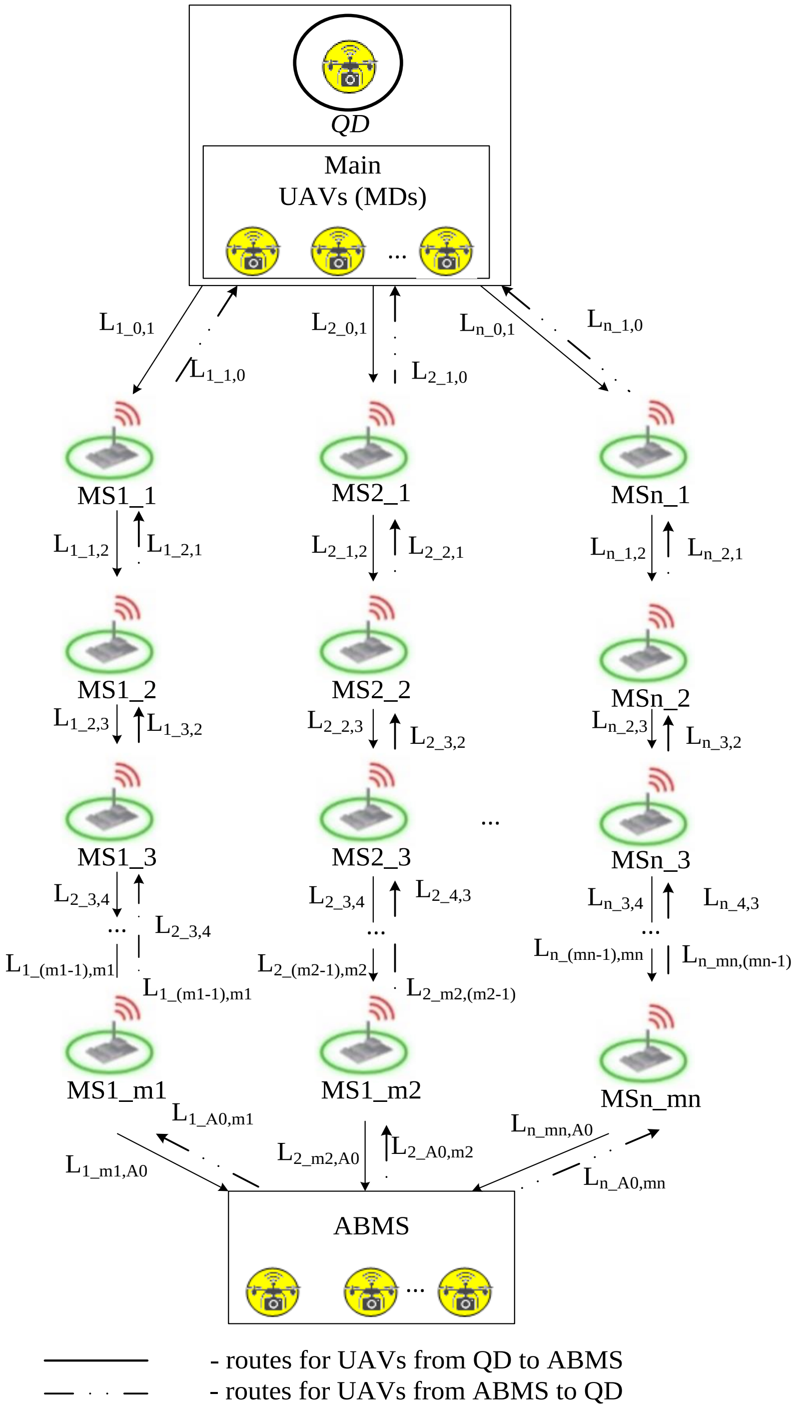

Figure 2: General UAV fleet NPP monitoring mission planning model with battery recharging via an ABMS

3. Reliability-based UAV fleet NPP monitoring mission planning models with battery recharging

3.1. Classification of reliability-based UAV fleet planning models with battery recharging

In order to take into account failures of UAVs, it is reasonable to propose a set of reliability-based UAV fleet NPP monitoring mission planning models with battery recharging. First of all, a classification of these models should be given. To describe the proposed models, data tuple S(n[m],k,b) is introduced where:

- *n* is the number of the main routes;
- *m* is the number of route sections;
- *k* is the number of redundant UAVs (N_{RD});
- *b* is the number of ABMSs.

The following assumptions have been made in developing the models:

- The models do not consider utilization of redundant UAVs, but take into account various ways for UAVs to follow their routes and recharge batteries.
- The NPP monitoring mission for each UAV of the fleet involves visiting the whole target MSs of the NPP twice.
- The probability of the successful plan fulfilment for the UAV fleet to perform NPP monitoring mission (P_{SPF}) is used as an indicator.

3.2. Model S(1[4],0,0)

The graphical presentation of model S(1[4],0,0) is shown in Figure 3.

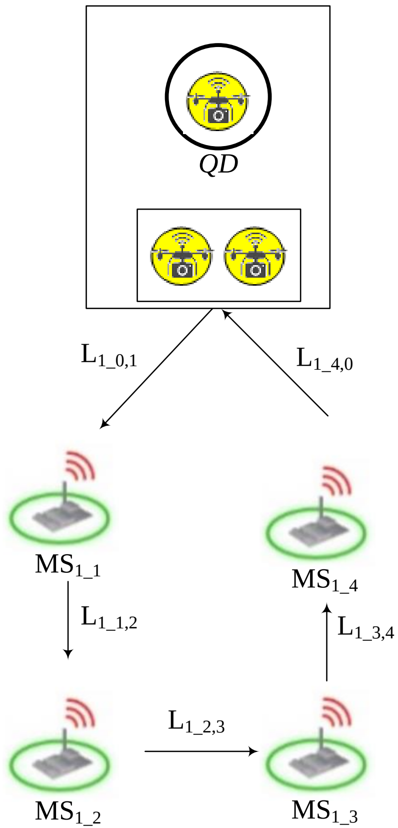

Figure 3: Graphical presentation of model S(1[4],0,0)

Let p_{MD}, p_{ret}, and p_{QD} are the reliability functions of a MD in each route sections, the probability of MD successful return to the depot, and reliability function of the QD, respectively. The reliability function is constant during the mission.

Assume that $L_{1\_0,1} = L_{1\_1,2} = L_{2\_0,1} = L_{2\_1,2}$, and $p_r = p_{QD} = 0.9$.

In this case, P_{SPF} is calculated as

$$P_{SPF\left(S\left(1[4],0,0\right)\right)} = \left(p_{MD}{}^{4} p_{ret}\right)^{2} p_{QD} \tag{1}$$

If $p_{MD} = 0.9$, $P_{SPF\left(S\left(1[4],0,0\right)\right)} = 0.314$.

3.3. Model S(2[2],0,0)

The graphical presentation of model S(2[2],0,0) is shown in Figure 4.

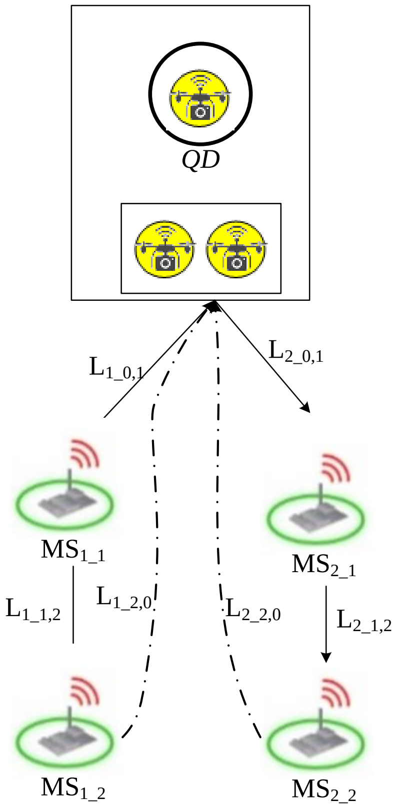

Figure 4: Graphical presentation of model S(2[2],0,0)

Assume that $L_{1\_0,1} = L_{1\_1,2} = L_{2\_0,1} = L_{2\_1,2}$, and $p_r = p_{QD} = 0.9$.

In this case, P_{SPF} is defined as

$$P_{SPF\left(S\left(2[2],0,0\right)\right)} = \left(p_{MD}{}^{2} p_{ret}\right)^{4} p_{QD} \tag{2}$$

If $p_{MD} = p_{ret} = p_{QD} = 0.9$, then $P_{SPF\left(S\left(2[2],0,0\right)\right)} = 0.254$.

3.4. Model S(2[2],0,1)

The graphical presentation of model S(2[2],0,1) is shown in Figure 5.

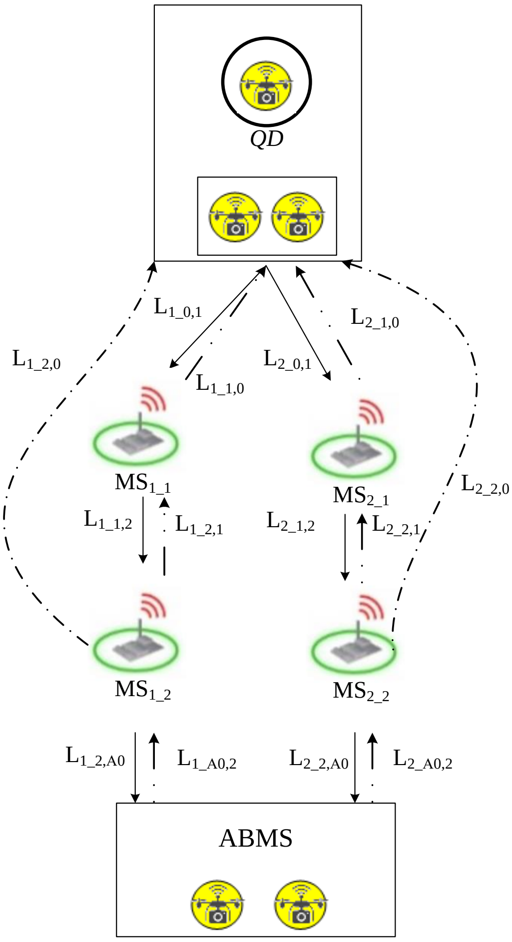

Figure 5: Graphical presentation of model S(2[2],0,1)

According to this model, each UAV, after visiting the whole target MSs in its route, if the ABMS has failed, should return to the depot, recharge its battery, and repeat its previous route starting from the first visited MS.

P_{SPF} when using model S(2[2],0,1) may be calculated as

$$P_{SPF}\left(S\left(2[2],0,1\right)\right)=p_{MD}^{12}p_{ABMS}+\left(p_{MD}^{2}p_{ret}\right)^{4}p_{QD}\left(1-p_{ABMS}\right), \qquad (3)$$

where p_{ABMS} is reliability function of the ABMS.

If $p_{MD}=p_{ret}=p_{QD}=p_{ABRAS}=0.9$, then $P_{SPF\left(S\left(2[2],0,1\right)\right)}=0.302$.

3.5. Model S(2[2],0,2)

The graphical presentation of model S(2[2],0,2) is shown in Figure 6.

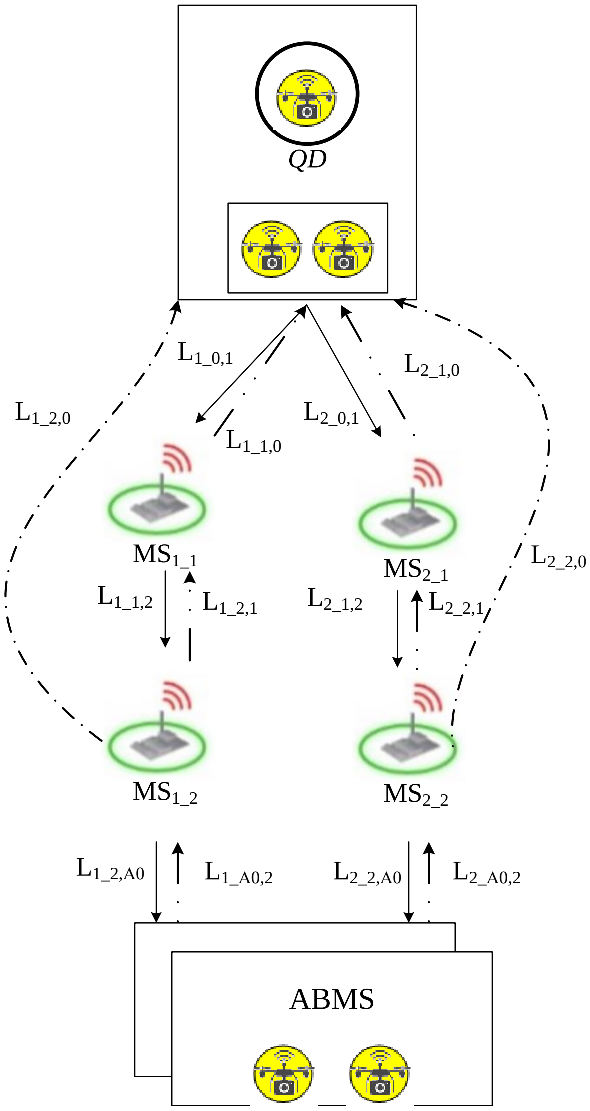

Figure 6: Graphical presentation of model S(2[2],0,0)

P_{SPF} when using model S(2[2],0,2) can be written as

$$P_{SPF}\left(S\left(2[2],0,2\right)\right) = p_{MD}^{12} p_{ABRAS}^{2} + 2 p_{MD}^{12} p_{ABRAS}\left(1 - p_{ABRAS}\right) + \\ + \left(p_{MD}^{4} p_{ret}^{2}\right)^{2} p_{QD}\left(1 - p_{ABRAS}\right)^{2}. \quad (4)$$

If $p_{MD} = p_{ret} = p_{QD} = p_{ABRAS} = 0.9$, then $P_{SPF\left(S\left(2[2],0,2\right)\right)} = 0.327.$

3.6. Research of models

The next step is to research P_{SPF} for a UAV fleet visiting 4 intended MSs using the following models: S(1[4],0,0), S(2[2],0,0), S(2[2],0,1), and S(2[2],0,2) (Figure 7).

Assume that $L_{1\_0,1} = L_{1\_1,2} = L_{2\_0,1} = L_{2\_1,2}$, $p_{QD} = p_{ABRAS} = p_{ret} = 0.9$, p_{MD} =[0.5…1]. Results obtained are presented in Figure 7.

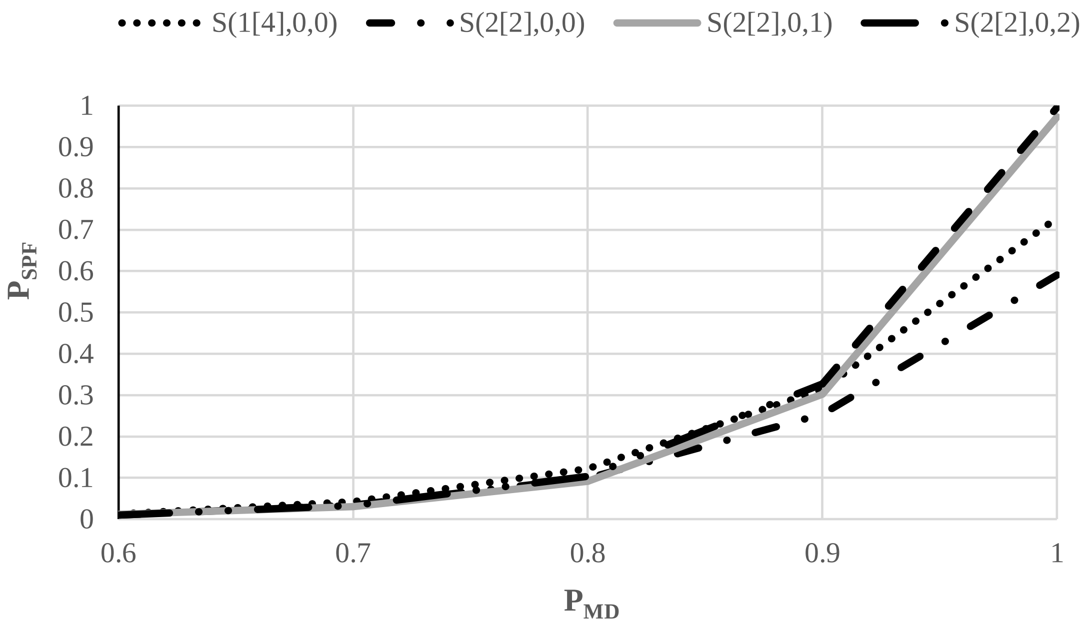

Figure 7: Dependencies showing the relationship of P_{SPF} for a UAV fleet visiting 4 intended MSs to the MD reliability function for various models used

A flight schedule for UAVs performing NPP monitoring mission with battery recharging where models S(1[4],0,0), S(2[2],0,0), S(2[2],0,1), and S(2[2],0,2) are used is shown in Figure 8.

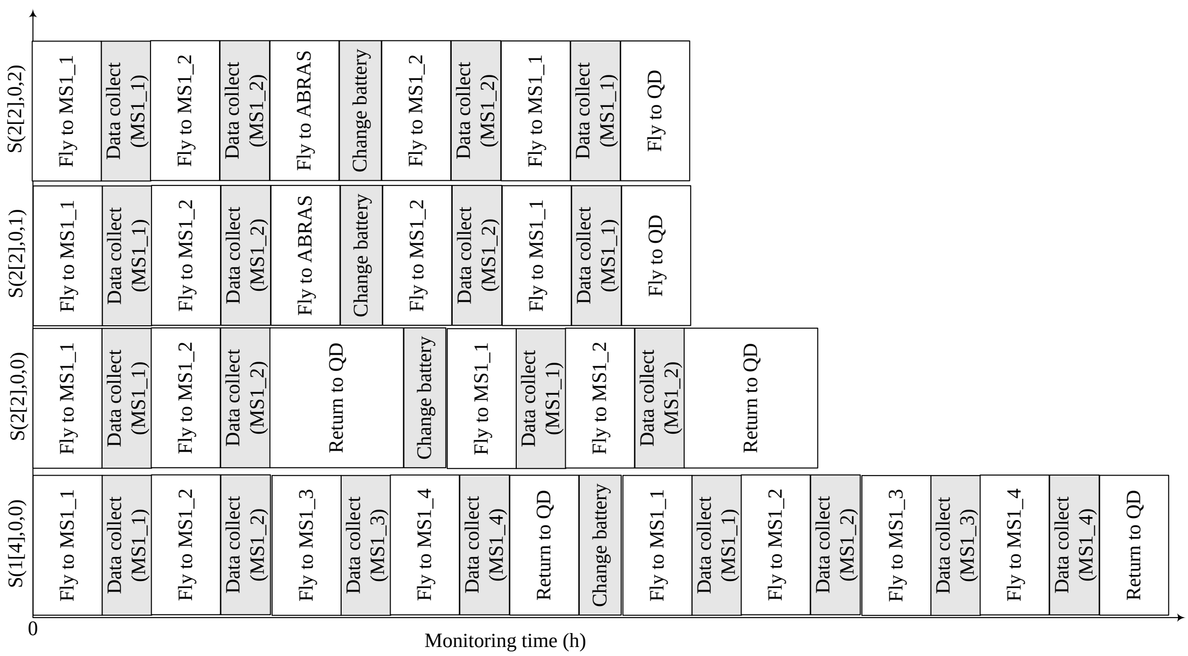

Figure 8: Flight schedule for UAVs performing NPP monitoring mission with battery recharging where models S(1[4],0,0), S(2[2],0,0), S(2[2],0,1), and S(2[2],0,2) are used

Thus, utilization of ABMSs for battery recharging does not significantly affect the probability of the SPF for the UAV fleet to perform the NPP monitoring mission, but allows reducing time needed to perform this mission.

4. Conclusion

General UAV fleet NPP monitoring mission planning models with battery recharging are developed. These models consider two ways for battery recharging. According to the first one, each UAV, after visiting the whole target MSs in its route, should return to the depot, recharge its battery, and repeat its previous route starting from the first visited MS. According to the second one, each UAV, after visiting the whole target MSs in its route, should rich an ABMS, recharge its battery, and repeat its previous route starting from the last visited MS. A classification of reliability-based UAV fleet NPP monitoring mission planning models with battery recharging and graphical presentation some of them are given.

The dependencies showing the relationship of the probability of the SPF for a UAV fleet visiting 4 intended MSs to the MD reliability function for various models used are obtained and explored.

Researched models are base for developing and implementing the strategies of the UAV fleet application in case of UAV failures. The next steps will be devoted to extending the model base through considering different reasons of drone failures including cyber attacks on Internet of Drone systems [18].

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