Reliability Engineering and System Safety 245 (2024) 110011

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

Optimizing time-varying performance and mission aborting policy in resource constrained missions

Gregory Levitin [a,b], Liudong Xing [c], Yuanshun Dai [a,*]

[a] *School of Computing and Artificial Intelligence, Southwest Jiaotong University, China*
[b] *NOGA- Israel Independent System Operator, Israel*
[c] *University of Massachusetts, Dartmouth, MA 02747, USA*

ARTICLE INFO

Key words:
Constrained resource
Mission abort
Time-varying performance
Random shock
Unmanned aerial vehicle

ABSTRACT

Intensive efforts have been devoted to mission aborting systems. However, the existing models mostly assumed static performance or failed to consider limited resources (e.g., energy, budget). Motivated by practical applications like unmanned aerial vehicles (UAV), this paper relaxes those assumptions by modeling a resource-constrained system that must complete a required amount of work for a successful mission and accomplish further a return/rescue phase (RP) to survive the system. The operation phase (OP) of the mission may be aborted depending on the number of external shocks (e.g., electromagnetic interferences, radiations) the system has survived and the operation time elapsed, followed by a RP to save the asset. Probabilistic methods are proposed to evaluate the mission success probability (MSP) and system survival probability (SSP). An optimization problem is formulated and solved, which determines the joint optimal time-varying performance policy and OP aborting policy, maximizing the MSP while providing a required level of SSP. A case study of UAV executing a reconnaissance mission is carried out to demonstrate the suggested model and examine influence of the SSP level as well as shock parameters on the mission performance and optimal policies. The advantage of time-varying performance in enhancing the MSP is also demonstrated.

1. Introduction

Mission aborting is an effective way to control the risk of valuable asset losses in diverse applications, such as aerospace [1,2], healthcare [3], battlefield [4], chemical reactor [5,6], transportation [7], marine [8], etc. The idea is to terminate the operation phase (OP) of the mission when a certain system deterioration event takes place, followed by a rescue or return phase (RP) to save the asset.

For instance, unmanned aerial vehicles (UAV) deployed in missions (e.g., reconnaissance, rescue, target destruction) are usually exposed to electromagnetic interference from various sources like cell phone towers, high voltage power lines, and large metal structure [9,10]. Those interferences often cause deterioration to the UAV or its critical components [11,12]. Thus, it is recommended for the UAV to abort the planned mission and return to the base or the nearest landing location after a certain number of interferences. Aborting the mission too early would reduce the mission success probability (MSP) unnecessarily. On the other hand, aborting the mission too late would incur low system survival probability (SSP). Note that the MSP is the probability that a specific task can be successfully accomplished while the SSP is referred to as the probability that the system performing the task is not lost during the mission. For the UAV example, the MSP may be interpreted as the probability that the UAV can successfully cover a certain distance to a target and send photo images of the target to the base; the SSP is the probability that the UAV can successfully return to the base or fly to the closest landing position. The UAV may survive with or without completing the mission task. A key risk management problem is to design the aborting policy (AP), i.e., the specific condition of triggering the mission abort, to achieve a balance between MSP and SSP.

The AP research can be dated back to 1970s [13,14] and received intensive attention from the reliability community in the past five years [15,16]. While earlier works focused on modeling and designing APs for single-attempt missions, more research efforts have recently been devoted to multi-attempt missions, where the task may be reattempted by the same system after proper maintenance or by a different functioning unit when available. In spite of the abundant studies on AP modeling and optimization (reviewed in Section 2), most of the existing models assumed that the system performance during the mission is constant and failed to consider the limited system resource. In practice,

* Corresponding author.
E-mail address: 1125105129@qq.com (Y. Dai).

https://doi.org/10.1016/j.ress.2024.110011
Received 8 November 2023; Received in revised form 9 January 2024; Accepted 11 February 2024
Available online 12 February 2024
0951-8320/© 2024 Elsevier Ltd. All rights reserved.

Acronyms

AP	aborting policy
CAC	common abort command
TPP	time-varying performance policy
HPP	homogeneous Poisson process
MSP	mission success probability
OP	operation phase
RP	rescue/return phase
SSP	system survival probability
UAV	unmanned aerial vehicle

Notation

W	amount of work in the OP of the mission
E	amount of available resource
$v(t)$	variable system performance (i.e., the amount of work performed per unit time) during the OP
$u(t)$	system performance during the RP activated at time t
V_{min}, V_{max}	minimum, maximum system performance allowed
$\tau(v(t))$	duration of OP under TPP $v(t)$
$e(v(t))$	per unit time resource consumption when the system performance is $v(t)$
$\varphi(t)$	required duration of RP activated at time t
$\vartheta(x)$	amount of RP work as function of the completed OP work x
Λ,λ	shocks rates during OP, RP
ξ	fraction of time from the start of an OP after which it cannot be aborted
m	maximum allowed number of shocks in time interval $[0, \xi)$ of the OP
$P(t,i,\lambda)$	occurrence probability of i shocks in [0,t) given that the shock rate is λ
$q(i)$	probability that a system survives the i th shock
Ω	probability of the first shock survival
ω	shock resistance deterioration factor
$f(\xi, m, v(t))$	probability that the system completes both OP and RP under AP ξ, m and TPP $v(t)$
$h(\xi, m, v(t))$	probability that the system aborts OP and completes RP under AP ξ, m and TPP $v(t)$
$R(\xi, m, v(t))$	MSP under the AP ξ, m and TPP $v(t)$
$S(\xi, m, v(t))$	SSP under the AP ξ, m and TPP $v(t)$
θ	time of the RP activation

the system performance may be varying with the time and different performance incur different rates of resource consumption. Moreover, the system resource is often constrained, posing limit to the system operation time, and thus affecting the MSP and SSP. For example, UAVs may fly with varying speeds incurring different energy consumption and time durations for the OP and RP phases. Both the aborting and performance/flying speed policies adopted would affect the mission outcomes and performance metrics greatly. Therefore, it is relevant and pivotal to jointly model and optimize the AP and time-varying performance policy (TPP).

This work advances the state of the art on the AP research by considering a new single-attempt mission model with time-varying performance and constrained system resource. Under the proposed model, the following contributions are also made:

1) Co-modeling the TPP and the shock-driven dual-parameter AP defined using the number of shocks survived by the system and a fraction threshold of operation time.
2) Developing a probabilistic method of analyzing the MSP and SSP for the considered single-attempt mission system under a given TPP and AP.
3) Formulating and solving the TPP and AP co-optimization problem to maximize the MSP while meeting a certain level of SSP.
4) Examining impacts of the SSP requirement level and shock parameters on mission performance and optimal policies using a case study of a UAV reconnaissance mission system.
5) Demonstrating the advantage of time-varying performance in improving the MSP.

The rest of the paper is arranged as follows: Section 2 reviews some representative related works on APs. Section 3 depicts the system and formulates the TPP and AP co-optimization problem. Section 4 presents the probabilistic method of evaluating MSP and SSP under a given TPP and AP. Section 5 provides the UAV case study. Section 6 gives the conclusion and several future research problems.

2. Related works

Depending on whether the mission task can be reattempted or not, single-attempt mission and multi-attempt mission aborting models can be distinguished. Early research has focused on single-attempt missions and different criteria or conditions have been utilized to define the AP. For example, the AP based on the number of failed units was modeled and optimized for warm standby systems [17], *k*-out-of-*n: G* systems [18], *k*-out-of-*n: F* balanced systems [19], and UAVs [20]. The AP based on the system degradation level was studied for phased-mission systems in [21]. The AP based on the amount of mission work completed was examined for heterogeneous warm standby systems [15], standby systems with propagated failures [22], standby systems with maintenance [23], and standby systems with state-dependent loading [24]. The AP based on the number of shocks survived was designed for single-component systems [3], multi-state systems with inspections [25], systems with random rescue time [26], and drone-truck systems [27]. The AP based on the number of times entering unbalanced states was studied for balanced systems with two multi-state subsystems [28]. The AP based on the system health state revealed via sampling was studied in [29] for safety-critical systems. The AP based on the predictive reliability was investigated for multi-component systems with failure interactions [30].

In addition to the single-criterion APs exemplified above, dual-parameter APs were also studied for single-attempt mission systems. For example, the AP based on both system age (or operation time elapsed) and the number of failed units was investigated for standby systems [31] and self-healing systems [32]. The AP based on both the degradation level and work completed was optimized for multi-state systems [33] and safety-critical systems [34]. The AP based on both the degradation level and system age was examined for UAV systems using the deep reinforcement learning [35,36].

Recent AP research has focused more on multi-attempt missions. Depending on the number of available functioning units, multiple attempts may be carried out in a sequential, concurrent, or consecutive manner.

In the case of the sequential multi-attempt, only one system or functioning unit is usually available to perform the attempt; a new attempt cannot start until the previous attempt is aborted and the system is successfully rescued and maintained. For example, the attempt-independent AP based on the number of shocks was optimized for multi-state repairable system in [37]. The attempt-dependent AP based on the system degradation level was considered in [38]. The task-dependent AP based on the number of shocks and operation time elapsed was designed for multi-task systems with unlimited and limited mission time in [9] and [39], respectively.

In the case of the concurrent multi-attempt, multiple functioning units are available to carry out the mission task in parallel to improve the MSP [40]. For example, different attempt-dependent APs were designed for two groups of components concurrently executing the task in [41].

In the case of the consecutive multi-attempt, multiple functioning units are activated one by one with a predefined time interval to carry out the mission task, reducing the cost as compared to the concurrent multi-attempt model. For example, the attempt AP based on the number of shocks and the operation time elapsed and the component activation delay were co-optimized in [42], where upon the mission success (i.e., when any attempt is successful), a common abort command (CAC) is issued to terminate all other ongoing attempts. In [43], the model of [42] was extended to allow the CAC to be issued when any component is close enough to accomplishing the mission; the CAC issuing time, the attempt AP, and the activation delay were jointly optimized to minimize the expected mission losses.

Despite the rich body of AP works, the existing models have mostly assumed that the system has a constant performance during the mission or failed to address the resource constraint practically. Note that the method of [9,39] considered the limited number of attempts but was not linked to any specific system resource consumption model. This work expands the horizons in the AP research by modeling and optimizing the time-varying performance policy under constrained resource and shock-driven AP.

3. Problem formulation

The system's goal is to accomplish a mission. The OP of the mission requires performing amount of work W and is performed in a random environment modeled by a homogeneous Poisson process (HPP) of shocks with rate Λ. To complete the OP, the system must survive all shocks occurring during this phase. The OP duration is determined by the system performance (amount of work performed per unit time) $v(t)$ that can vary within the range (V_{min}, V_{max}). After completing the OP, the system must accomplish the RP and survive all shocks occurring during this phase. The rate of the HPP of shocks during the RP is λ.

The system deteriorates more as the number of shocks it survives increases, leading to larger risks of system failure and loss. Thus, to reduce the probability of the system loss, the OP may be aborted before its completion when the system has survived m shocks during the OP. As the occurrence time of the m-th shock increases, the remaining OP time decreases and it becomes unreasonable to abort the OP when being close to its completion. Therefore, it is assumed that the OP continues if the m-th shock occurs later than at fraction ξ of the OP time since the OP's beginning.

The OP abortion leads to the failure of the mission and is immediately followed by the RP activation. The amount of work in the RP $\varphi(x)$ depends on the amount of work x completed in the OP by the moment of the RP activation.

The system consumes certain resource when performing the mission. The rate of the resource consumption during the OP $e(v(t))$ depends on the system performance. The amount of available resource E is limited. On one hand, the increase of the system performance $v(t)$ leads to a reduction of time required to complete the OP and increases the chance of successful OP completion because the time of exposure to OP shocks decreases. On the other hand, the increase in $v(t)$ leads to a decrease of resource remaining after the OP completion, which limits the system performance during the RP and increases the time of exposure to the RP shocks. In the extreme case, the OP performance can be so high that the system has no enough resource to complete the RP after completing the OP with even minimal performance. For any OP performance $v(t)$ and any time θ of the RP activation (caused by OP completion or abortion), the maximum RP performance $u(v(t),\theta)$ should be chosen that allows the RP completion without violating the remained resource constraint. If such $u\in(V_{min},V_{max})$ does not exist, the RP inevitably fails and the system is lost.

The mission fails if the system either aborts the OP or is lost during the OP. The system survives if it neither fails because of a shock nor runs out of resource before the RP completion. Thus, two metrics characterize the mission accomplishment: MSP R and SSP S. The optimal TPP $v(t)$ and OP's AP m, ξ should be found to maximize the MSP while providing the required SSP level S^*:

$$R(\xi, m, v(t)) \rightarrow \max s.t. \quad S(\xi, m, v(t)) \geq S^*. \tag{1}$$

Consider as an illustrative example a Mars exploration rover powered by photo-voltaic source. After the charge cycle, the rover must explore certain shaded area being exposed by temperature and sandstorm shocks. The shocks can cause deterioration of the rover equipment and it may be decided to abort the mission after some number of shocks. After completion or abortion of the exploration mission, the rover should return to a position where the light conditions allow its optimal charging. Moving with a greater speed can shorten the mission time, but requires greater power consumption. If the rover has no enough power to return to the battery charge position, it can be lost. Another detailed example of an unmanned aerial vehicle is presented in Section 5.

The following assumptions are made in the model:

1. The system state is unobservable during the mission.
2. All the shocks are observable.
3. The resource consumption depends only on the system's performance and does not depend on the number of shocks experienced.
4. The shock rates do not depend on the system's performance.
5. The system resource consumption associated with shock detection and with mode switching from OP to RP is negligible.
6. The time needed to switch from OP to RP is negligible.

4. Determining the MSP and SSP for a given TPP and AP

Since shock arrivals are assumed to follow an HPP, the probability that i shocks occur to the system during $[0,t)$ (measured from the beginning of a mission phase) is

$$P(t, i, \rho) = e^{-\rho t}\frac{(\rho t)^i}{i!}, \text{for } i = 0, 1, 2, \ldots \tag{2}$$

where ρ is the shock rate ($\rho = \Lambda$ for the OP and $\rho = \lambda$ for the RP of the mission).

Typically, as the number of survived shocks increases, the system's loss probability upon the occurrence of a new shock increases or the system survivability reduces. For example, according to [44], the probability that a system can survive the i th shock can be defined as

$$q(i) = \begin{cases} \Omega\omega(i) \text{ for } i > 0 \\ 1 \text{ for } i = 0 \end{cases}, \tag{3}$$

where Ω is the system survival probability in the event of the first shock, and $\omega(i) = \omega^{i-1}, 0 < \omega < 1$. $\prod_{i=0}^{I} q(i)$ gives the probability that the system survives I shocks, which can be evaluated as

$$\prod_{i=0}^{I} q(i) = \Omega^I \omega^{\frac{I(I-1)}{2}}. \tag{4}$$

4.1. MSP evaluation

To complete the OP, the system must accomplish the amount of work W. The time $\tau(v(t))$ needed to complete the OP under TPP $v(t)$ is determined from the equation

$$\int_0^{\tau(v(t))} v(t)dt = W \tag{5}$$

and the resource consumed during the entire OP is

$$\int_0^{\tau(v(t))} e(v(t))dt \tag{6}$$

(in what follows we omit the argument $v(t)$ in $\tau(v(t))$ for the sake of brevity).

According to (2), $P(\tau\xi,i,\Lambda)P(\tau(1-\xi),k,\Lambda)$ gives the probability that i shocks occur in $[0,\tau\xi)$ and additional k shocks occur in $[\tau\xi, \tau)$ during the OP.

$P(\tau\xi, i, \Lambda)\ P(\tau(1-\xi),k,\Lambda)P(t,x,\lambda)$ gives the probability that i shocks occur in $[0, \xi\tau)$, additional k shocks occur in $[\tau\xi, \tau)$ during the OP, and x shocks occur in $[0,t)$ since the beginning of the subsequent RP.

The system completes the OP if fewer than m shocks occur in interval $[0, \tau\xi)$ and the system survives all the shocks in $[0,\tau)$. The occurrence probability of such event (i.e., MSP) is

$$R(\xi,m,v(t)) = \\ = \sum_{i=0}^{m-1} P(\tau\xi,i,\Lambda)\sum_{k=0}^{\infty}P(\tau(1-\xi),k,\Lambda)\prod_{j=0}^{i+k}q(j). \tag{7}$$

4.2. SSP evaluation

The system survives the mission under AP ξ, m in the following two cases: 1) When it completes both OP and RP, and 2) When it aborts the OP and completes the RP.

When the system completes the OP, its resource remaining for the RP is

$$E - \int_0^{\tau} e(v(t))dt. \tag{8}$$

To complete the RP after completing the OP, the system must perform amount of work $\varphi(W)$. Let $u(\tau)$ and $\vartheta(W)$ denote the system performance during the RP and required amount of RP work respectively when the RP is activated at time τ after the OP completion. The RP time is $\varphi(\tau) = \vartheta(W)/u(\tau)$ and the total resource consumption during the RP is

$$e(u(\tau))\vartheta(W)/u(\tau). \tag{9}$$

To reduce the system loss probability, the RP time should be minimized and the maximum allowed performance $u(\tau)\in(V_{min},V_{max})$ should be chosen such that the resource consumption does not exceed the remaining resource, i.e.,

$$e(u(\tau))\vartheta(W)\Big/u(\tau) \le E - \int_0^{\tau} e(v(t))dt. \tag{10}$$

If no value of $u(\tau)$ in the range (V_{min},V_{max}) meets the condition (10), the RP cannot be completed and the system is lost after the OP completion. If condition (10) is met, the RP time takes the value of $\varphi(\tau)$. The system completes the OP and survives both OP and RP when less than m shocks have occurred in $[0, \xi\tau)$ and the system survives all shocks that occur during time τ in the OP and during time $\varphi(\tau)$ in the RP. The probability of such event is

$$f(\xi,m,v(t)) = \\ = \sum_{i=0}^{m-1} P(\xi\tau,i,\Lambda)\sum_{k=0}^{\infty}P(\tau(1-\xi),k,\Lambda)\sum_{j=0}^{\infty}P(\vartheta(W)/u(\tau),j,\lambda)\prod_{j=0}^{i+k+j}q(j) \tag{11}$$

when solution of (10) exists and $f(\xi,m,v(t)) = 0$ otherwise.

The system aborts the OP and survives the subsequent RP if it experiences the m-th shock at time $\theta<\xi\tau$, and survives m shocks in the OP and all the shocks that occur during the RP. The amount of work performed in the OP by the time θ is $\int_0^{\theta} v(t)dt$. Thus, the amount of work to be performed in the RP is $\vartheta(\int_0^{\theta} v(t)dt)$. The amount of resource consumed before the OP abort is $\int_0^{\theta} e(v(t))dt$. The maximum system performance $u(\theta)$ that meets the condition

$$e(u(\theta))\vartheta\left(\int_0^{\theta} v(t)dt\right)\Big/u(\theta) \le E - \int_0^{\theta} e(v(t))dt \tag{12}$$

should be chosen for performing the RP. If no value of $u(\theta)\in(V_{min},V_{max})$ meeting the condition (12) exists, the system has no enough resource to complete the RP; otherwise, the time of the RP after the OP aborting at time θ is

$$\varphi(\theta) = \vartheta\left(\int_0^{\theta} v(t)dt\right)/u(\theta). \tag{13}$$

The occurrence probability of the m-th shock in time interval $[t, t+dt)$ during the OP, where dt is infinitesimal, is

$$P(t,m-1,\Lambda)\Lambda dt. \tag{14}$$

The probability that the system survives the first m shocks in the OP is $\prod_{i=0}^{m} q(i)$. The probability that the system survives all the shocks occurring during the RP after surviving the m-th shock in $[\theta, \theta+d\theta)$ is

$$\sum_{k=0}^{\infty} P\left(\vartheta\left(\int_0^{\theta} v(t)dt\right)/u(\theta)\right)\prod_{i=0}^{k} q(m+i). \tag{15}$$

Therefore, the probability that the system aborts the OP at time not later than $\xi\tau$ and survives the subsequent RP is

$$h(\xi,m,v(t)) = \\ = \Lambda\int_0^{\xi\tau} P(t,m-1,\Lambda)\sum_{k=0}^{\infty}P\left(\vartheta\left(\int_0^{\theta} v(t)dt\right)/\min\left(u_{\max,}u(\theta)\right),k,\lambda\right)\prod_{i=0}^{k+m}q(i)d\theta \tag{16}$$

when solution of (12) exists and $h(\xi,m,v(t)) = 0$ otherwise.

The system survives either when it aborts the OP at time $\theta<\xi\tau$ and survives the RP or when it completes the OP and survives the RP. These two survival cases are mutually exclusive. Therefore, the SSP is

$$S(\xi,m,v(t)) = f(\xi,m,v(t)) + h(\xi,m,v(t)). \tag{17}$$

Having the methodology for evaluating the MSP and the SSP suggested above and representing the function $v(t)$ in a parametric form (see Section 5.2 for an example of such representation), one can solve the constrained optimization problem (1) through applying any standard optimization procedure or the brute force search in the space of parameters.

5. UAV case study

Consider a UAV that must accomplish a reconnaissance mission. To complete the OP of the mission, the UAV must cover a distance $W = 10$ km to a target and send photo images of the target to the base. During the flight to the target, the UAV must remain at an altitude allowing the target detection and is exposed to shocks caused by electromagnetic interference. The shocks may damage the control equipment of the UAV and cause its crash/loss. The number of shocks during flying to the target obeys the HPP with rate Λ=5.7 h^{-1}. The interference filter that protects the UAV control equipment deteriorates as the number of experienced shocks increases due to overheating, causing the decrease of its resistance to shocks. Such deterioration is considered using (3) with Ω=0.9, ω=0.82 [44].

To reduce the risk of the UAV loss, the OP is aborted if m shocks occur to the UAV during time lower than $\xi\tau$, where τ is the time needed to get to the target. If the OP is aborted or completed at time t from its beginning, the UAV flies to the closest landing position (i.e., the RP). There are three possible landing positions (including the base) as depicted in Fig. 1. If the distance covered from the base by time t is $x(t)$, the distance to the closest landing position is

$$\vartheta(x(t)) = min\left(x(t), \sqrt{(x(t)-4)^2+9}, \sqrt{(12-x(t))^2+4}\right). \quad (18)$$

To perform the RP, the UAV descends to the altitude where the electromagnetic interference shocks have a smaller rateλ=4.2 h^{-1}.

The UAV can fly with speed $v(t)$ varying from V_{min}=36 km/h to V_{max}=72 km/h [45]. The power consumption of electric propulsion system of the UAV depends on its speed according to the function $e(v) = \frac{a}{v} + bv^3$ W [46], where $a = 9000$ and $b = 0.004$. The capacity of the UAV battery is $E = 200$ Wh [47]. When the OP is completed/aborted, the UAV's maximum return speed is chosen such the total energy consumption does not exceed the remaining battery charge.

The mission fails if the UAV does not complete the OP. The UAV can be lost either because of shocks occurring during either OP or RP, or if its battery is emptied before the RP completion. The UAV operator should choose the TPP $v(t)$ and the AP m, ξ providing a compromise between MSP and SSP according to (1).

As the MSP and SSP evaluation algorithm is very fast, the brute force enumeration [48,49] can be used in the optimization procedure that determines two AP parameters m, ξ and one or four TPP parameters for constant (Section 5.1) and variable (Section 5.2) UAV speed during the OP, respectively.

5.1. Constant UAV speed during the OP

When the UAV speed during the OP remains constant $v(t) = v$, its power consumption is also constant $e(v) = a/v + bv^3$ and the energy remaining after the OP flight during time t is $E\text{-}e(v)t = E - (a/v + bv^3)t$. If the OP is aborted/completed at time t, the RP flight distance is $\vartheta(vt)$. If the return flight speed is u, the requited return time is $\varphi(t) = \vartheta(vt)/u$ and the UAV's power consumption is $a/u + bu^3$. The energy consumption during the RP flight should not exceed the remaining battery charge at time t. Thus, the maximum return speed u can be obtained from the equality.

$$\left(a/u + bu^3\right)\vartheta(vt)\big/u = E - \left(\frac{a}{v} + bv^3\right)t,$$

which gives

$$u_{1,2}(t) = \sqrt{\frac{\frac{E-\left(\frac{a}{v}+bv^3\right)t}{\vartheta(vt)} \pm \sqrt{\left(\frac{E-\left(\frac{a}{v}+bv^3\right)t}{\vartheta(vt)}\right)^2 - 4ab}}{2b}}.$$

If $\left(\frac{E-\left(\frac{a}{v}+bv^3\right)t}{\vartheta(vt)}\right)^2 < 4ab$ or $u_1(t) < u_2(t) < V_{min}$ or $V_{max} < u_1(t) < u_2(t)$, the UAV has no enough energy to complete the RP and $\varphi(t) = \infty$. If $u_1(t) < V_{max} < u_2(t)$, the speed $u = V_{max}$ should be chosen for the RP and $\varphi(t) = vt/V_{max}$. If $V_{min} < u_2(t) < V_{max}$, the speed $u = u_2(t)$ should be chosen for the RP and $\varphi(t) = vt/u_2(t)$.

Fig. 2 presents the UAV speeds during the OP and RP, distance covered in the OP $x(t)$, required RP distance $\vartheta(t)$, energy consumption $c(t)$, maximum RP speed $u(t)$ and corresponding RP time $\varphi(t)$ as functions of the OP abort time t for $v = 62$ km/h. For t<0.1 h, the UAV has enough energy to fly to the closest landing position with the greatest possible speed v=V_{max}. When $0.1 \le t$<0.138, the UAV must fly with a lower RP speed to avoid the full battery discharge before getting to the closest landing position. When t>0.138, the UAV has no enough energy for the return flight and is inevitably lost. The time required for the OP completion for $v = 62$ is τ=0.160, which means that the UAV has no chance to survive if it completes the OP.

Fig. 3 presents the MSP R and SSP S as functions of the UAV speed v for AP $m = 1$, ξ=0.2 and no abort policy ξ=0. It can be seen that the MSP increases with the increasing speed v because the OP time decreases and fewer shocks can hit the UAV. However, when v>67.6, the UAV has no enough energy to complete the OP and the mission fails ($R = 0$). When $v \le 59.2$, the UAV has enough energy to return to the closest landing position after the OP completion. When v>59.2, the UAV can survive only when it aborts the OP and the SSP sharply drops.

When no aborts are allowed, the SSP is always lower than the MSP because the UAV can survive only if it completes both the OP and the subsequent RP. On the contrary, when the OP aborting with $m = 1$, ξ=0.2 is allowed, SSP exceeds the MSP because the UAV can survive when it either aborts or completes the OP and survives the subsequent RP.

Fig. 4 presents the best obtained TPP v and AP m, ξ and the corresponding MSP and SSP as functions of desired SSP S* for the constant OP speed case. The riskiest mission policy when no aborts are allowed and the OP speed takes the maximum value that allows the OP completion before the battery discharge is $v = 67.6$, which provides the MSP $R = 0.882$ and $S = 0$ (the UAV has no energy to complete the RP after completing the OP). The riskiest mission policy that still gives the UAV a chance to survive is $v = 58.84$ and ξ=0, which provides $R = 0.859$ and S

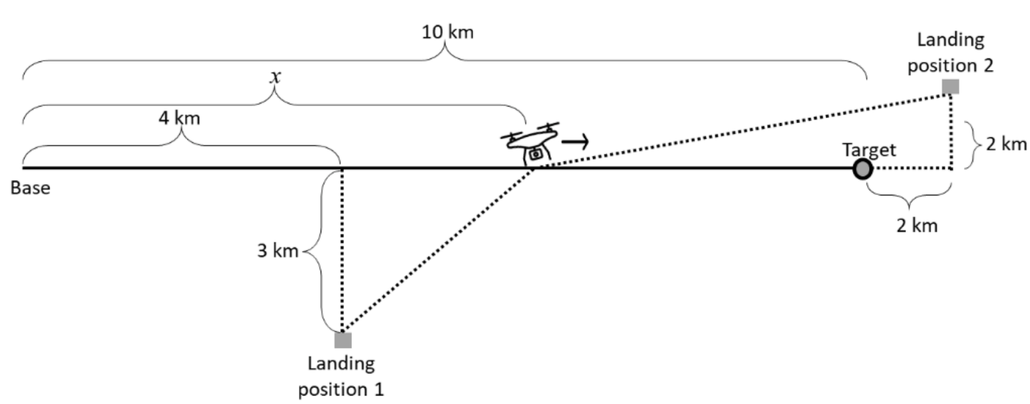

Fig. 1. UAV mission parameters.

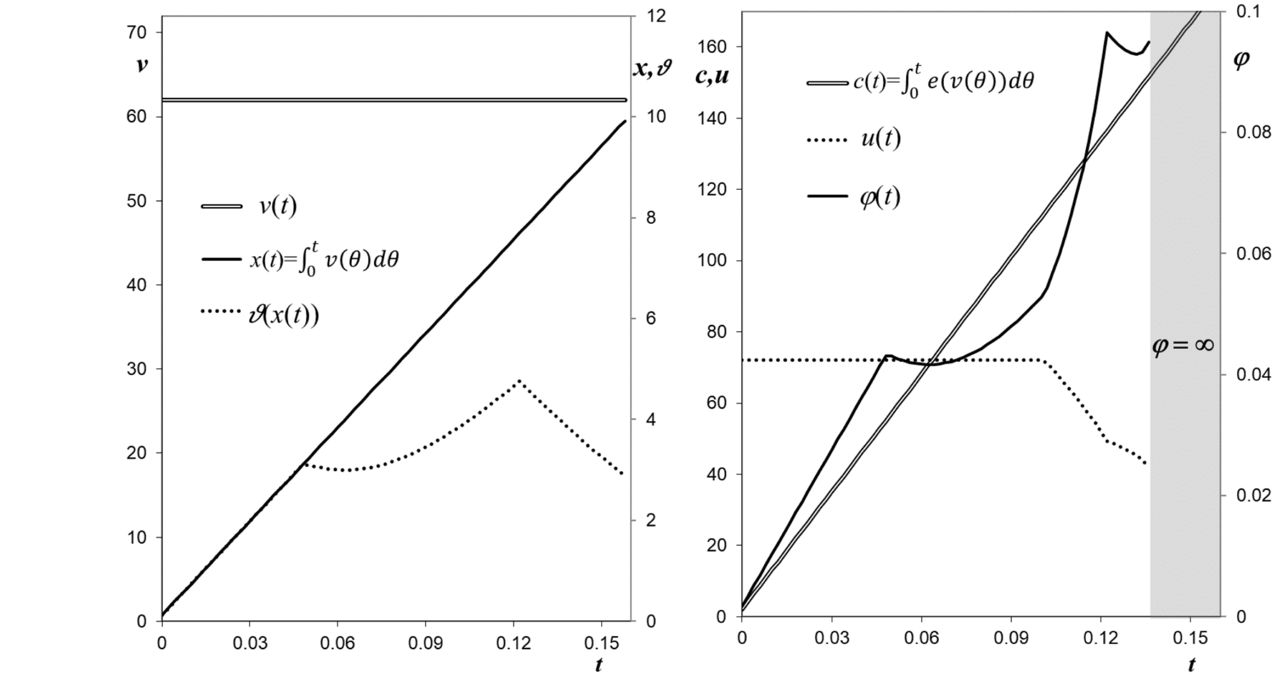

Fig. 2. Metrics of the OP and RP flight for $v = 62$.

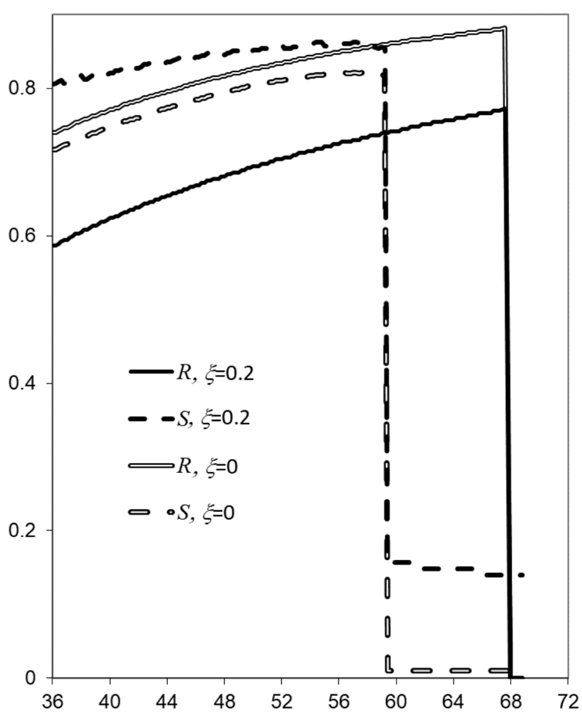

Fig. 3. MSP and SSP as functions of UAV speed during the OP.

$= 0.82$. Therefore, for $0<S^*<0.82$, this no abort policy remains unchanged. When the desired SSP S^* increases above 0.82, the AP becomes more cautious or conservative, allowing the OP aborting during an increased time. The optimal value of the allowed number of shocks always remains $m = 1$. The value of ξ increases and the OP speed decreases, which gives the UAV a chance to complete the RP after a later OP aborts. The maximum possible SSP $S = 0.91$ is achieved for $v = 55.56$ and ξ=0.875. The MSP for this policy is $R = 0.41$.

5.2. Variable UAV speed during the OP

The UAV can move with constant acceleration/deceleration not exceeding 600 km/h^2. In this subsection, we consider an example in which the UAV has an initial speed v_0, flies with acceleration a_1 during time t_1 and with acceleration/deceleration a_2 during the rest of the OP (see Fig. 5). The four parameters v_0, t_1, a_1 and a_2 determine the TPP such that $V_{min} \le v_0 \le V_{max}$ and $-600 \le a_1,\ a_2 \le 600$, and t_1 can be chosen freely to maximize the MSP under the SSP constraint.

According to this TPP

$v(t) = min(V_{max}, max(V_{min}, v_0 + a_1 t))$ when $t \le t_1$ and

$$v(t) = \min(V_{\max}, \max(V_{\min}, v(t_1) + a_2(t - t_1)) \text{ when } t > t_1. \quad (19)$$

The resource consumption is a non-linear function of system performance. Therefore, through varying the performance, one can achieve lower resource consumption for the same OP time than under the constant performance. In addition, in combination with aborting rules, variable performance allows more flexible balancing between the MSP and the SSP.

Compared with the constant OP flight speed in Section 5.1, the accelerated flight provides some improvement of the MSP when high values of the SSP are required. The best obtained TPP and AP solution for S^*=0.91 is v_0=37.2 km/h, $t_1 = 0.04h$, a_1=520 km/ h^2, a_2=0, $m = 1$ and ξ=0.807, i.e., the UAV accelerates from speed 37.2 km/h to speed 52.8 km/h during the first 0.04h=2.4 min of the OP and then continues flying with the constant speed. In this case, the OP takes time τ=0.19 h = 11.4 min (see Fig. 6). The OP should be aborted if a shock occurs during time $\tau\xi$=9.2 min from the OP beginning. Such TPP and AP provide MSP $R =$ 0.435 and $S = 0.91$. Observe that the accelerated flight provides MSP, which is by 6 % greater than the MSP $R = 0.41$ achieved for $S = 0.91$ under the constant speed flight. For required values of the SSP $S^*<0.89$, the accelerated flight does not improve the MSP achieved under the constant speed flight.

Fig. 7 presents the MSP and SSP for the best obtained TPP and AP as functions of shock rate Λ for S^*=0.9. The maximum possible MSP corresponding to no aborts and $v = 67.6$ is given for comparison. Table 1 presents some TPP and AP solutions. It can be seen that the fraction of the OP when the aborting is permitted increases with the increasing

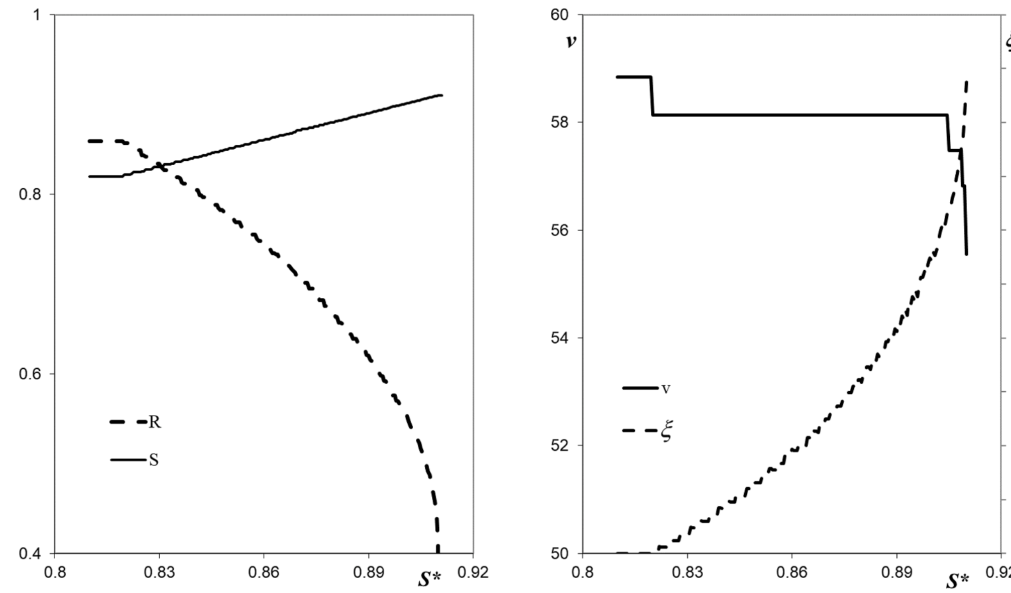

Fig. 4. Best obtained TPP and AP and corresponding MSP and SSP as functions of desired SSP S^* for constant OP speed.

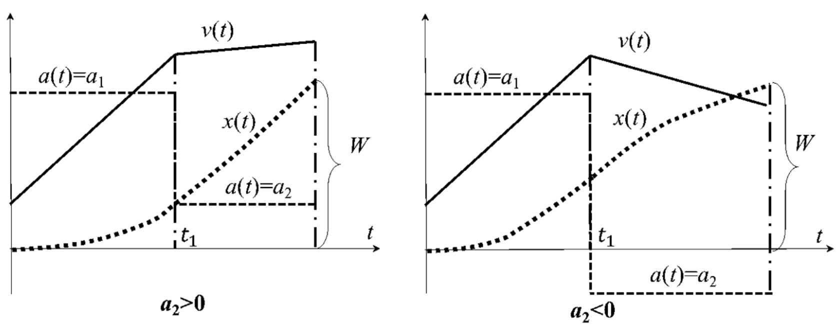

Fig. 5. Example of UAV speed variation during the OP for $a_2>0$ and $a_2<0$.

shock rate to keep the desired SSP level. The initial UAV speed tends to decrease to save the energy for the return flight. Keeping the constant SSP is achieved by decreasing the MSP.

During the short initial part of the flight, the UAV accelerates and then either keeps a constant speed or flies with much lower acceleration. This TPP allows keeping a lower speed and a shorter distance from the base when the OP aborting is allowed and reaching a greater speed when the aborting is forbidden. When the shock rate Λ exceeds the value of

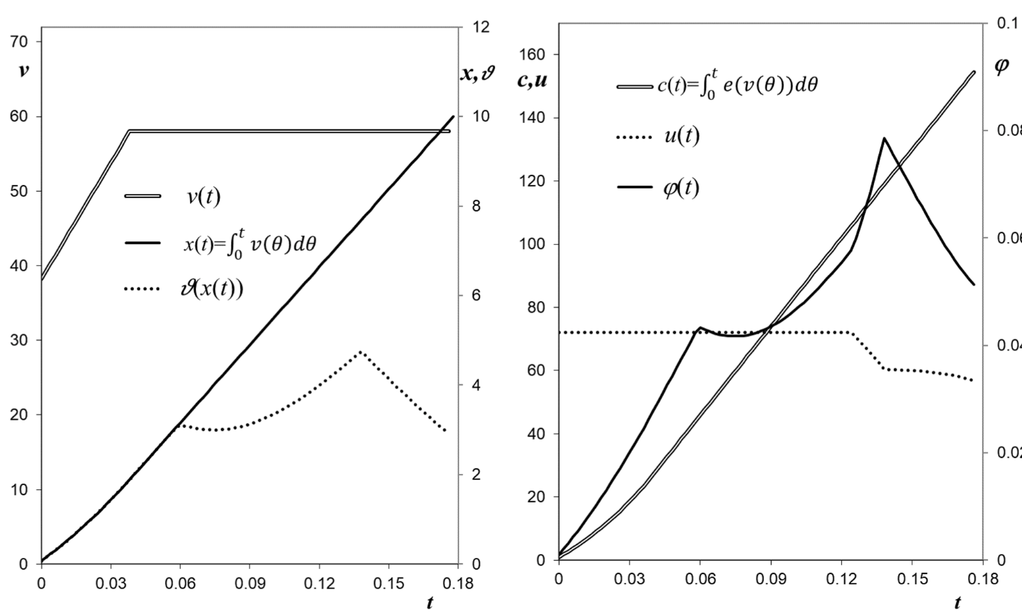

Fig. 6. Metrics of the OP and RP flight for the best obtained TPP providing $R = 0.435$ and $S = 0.91$.

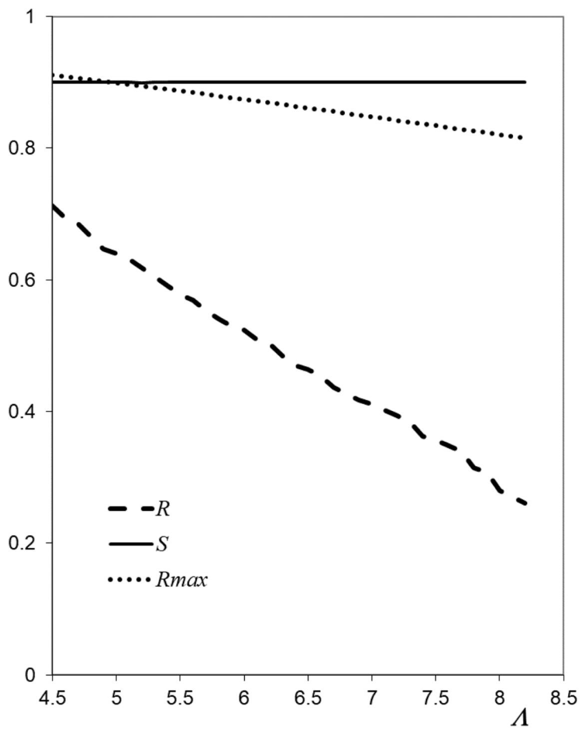

Fig. 7. MSP and SSP for the best obtained TPP and AP as functions of shock rate Λ for S^*=0.9.

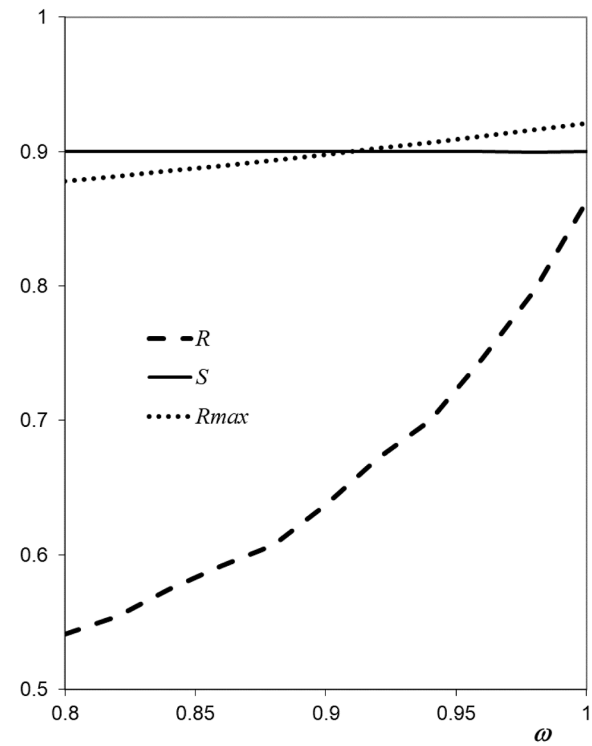

Fig. 8. MSP and SSP for the best obtained TPP and AP as functions of the UAV shock resistance deterioration factor ω for S^*=0.9.

Table 1
Best obtained TPP and AP and corresponding MSP and SSP for S^*=0.9 and different values of shock rate Λ.

Λ	m	ξ	v_0	a_1	a_2	t_1	R	S
4.5	1	0.35	49.7	380	0	0.02	0.713	0.9
5.5	1	0.50	40.7	500	20	0.03	0.578	0.9
6.0	1	0.57	44.0	540	40	0.02	0.524	0.9
6.5	1	0.64	37.8	540	0	0.04	0.464	0.9
7.0	1	0.69	37.5	500	20	0.04	0.411	0.9
7.5	1	0.75	36.0	380	20	0.06	0.357	0.9
8.0	1	0.93	39.7	480	80	0.03	0.279	0.9

Table 2
Best obtained TPP and AP and corresponding MSP and SSP for S^*=0.9 and different values of shock resistance deterioration factor ω.

ω	m	ξ	v_0	a_1	a_2	t_1	R	S
0.80	1	0.57	45	450	50	0.02	0.541	0.9
0.84	1	0.50	41	450	0	0.04	0.575	0.9
0.88	1	0.46	54	500	0	0.01	0.607	0.9
0.92	1	0.33	47	300	0	0.04	0.672	0.9
0.96	1	0.21	46	400	0	0.03	0.746	0.9
1.00	1	0.06	45	450	−50	0.04	0.863	0.9

8.2, the SSP level of 0.9 cannot be reached.

Fig. 8 presents the MSP and SSP for the best obtained TPP and AP as functions of the UAV shock resistance deterioration factor ω for S^*=0.9. The maximum possible MSP corresponding to no aborts and $v = 67.6$ is given for comparison. Table 2 presents some of the best obtained TPP and AP solutions. It can be seen that when the UAV becomes less sensitive to the shocks, the AP becomes riskier and the fraction of the OP when the aborting can be permitted decreases. With an increase in the UAV shock resistance, the MSP increases. During the short initial part of the flight, when the OP aborting is allowed, the UAV accelerates and then either keeps a constant speed or flies with much lower acceleration. When the UAV shock resistance does not deteriorate (i.e., ω=1) the UAV can apply the riskiest AP with ξ=0.06. Initially it should fly with acceleration, and during the rest of the OP flight, it slightly decelerates.

Fig. 9 presents the MSP and SSP for the best obtained TPP and AP as functions of the UAV battery capacity E for different values of the desired SSP S^*. Table 3 presents some of the obtained TPP and AP solutions and the corresponding mission metrics.

When S^*=0, the solution of the unconstrained optimization problem provides the maximum possible MSP, which is achieved when the mission is never aborted (ξ=0). When the battery capacity E<260, the UAV speed variation is chosen such that the UAV has enough energy to complete the OP, but has no energy to complete the RP flight after completing the OP. When E = 260, the UAV has enough energy to fly with the maximal possible speed to the target, but still has no energy for the return flight. The flight with the maximal speed provides the greatest possible MSP because in this case, the UAV's exposure to the OP shocks is minimal. A further increase of the battery charge does not affect the MSP (because the OP flight time cannot be reduced anymore), but causes an increase in the SSP because the UAV has energy to perform the RP flight after the OP completion.

When S^*=0.8 and 180<E<250, the required SSP can be achieved without aborting the mission. However, the speed during the OP is lower than that for S^*=0 because some energy should remain for the RP flight. However, when E>250, the UAV can fly with the maximal speed during the OP and has enough energy to complete the RP. In this case, the maximum possible MSP is achieved. For greater values of the desired SSP S^*, the mission aborting is required to provide the SSP level. The MSP increases with an increase of the battery charge because the UAV can fly with a greater speed. Observe that the desired SSP level S^*=0.91 can never be achieved when E<210 and the level S^*=0.92 can never be achieved when E<270 because the UAV has no enough energy to fly with the speed required for providing such SSP levels.

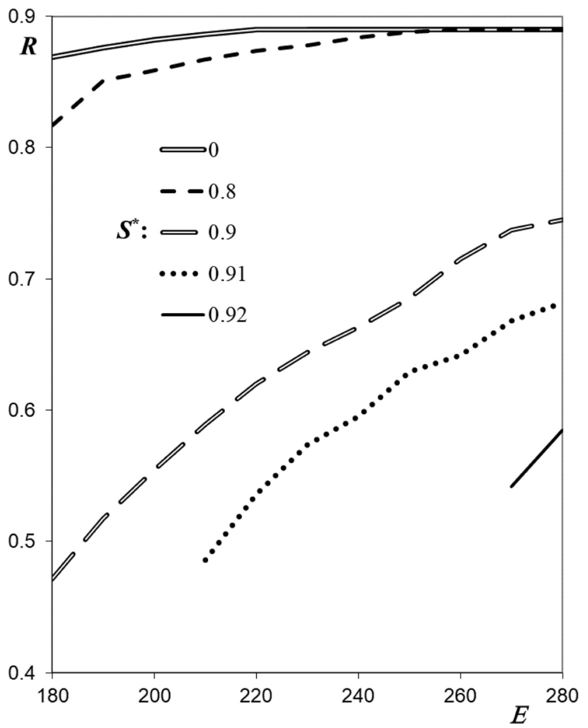

Fig. 9. MSP and SSP for the best obtained TPP and AP as functions of the UAV battery capacity E and different values of S^*.

Table 3
Best obtained TPP and AP and corresponding MSP and SSP for different values of battery capacity E and desired SSP S^*.

S^*	E	m	ξ	v_0	a_1	a_2	t_1	R	S
	180	–	0	46	515	50	0.03	0.869	0.0
	200	–	0	60	330	45	0.01	0.882	0.0
	220	–	0	64	445	0	0.02	0.89	0.0
0	240	–	0	72	0	0	–	0.89	0.0
	260	–	0	72	0	0	–	0.89	0.85
	280	–	0	72	0	0	–	0.89	0.87
	180	1	0.03	50	450	0	0.01	0.817	0.80
	200	–	0	56	350	10	0.01	0.859	0.82
	220	–	0	61	470	5	0.01	0.874	0.83
0.8	240	–	0	66	315	10	0.01	0.884	0.84
	260	–	0	68	410	20	0.01	0.890	0.86
	280	–	0	68	410	20	0.01	0.890	0.87
	180	1	0.66	45	360	20	0.01	0.471	0.90
	200	1	0.56	53	540	25	0.01	0.554	0.90
	220	1	0.45	53	375	35	0.01	0.620	0.90
0.90	240	1	0.40	57	350	25	0.02	0.663	0.90
	260	1	0.33	63	355	20	0.01	0.715	0.90
	280	1	0.28	66	350	100	0.01	0.745	0.90
	210	1	0.69	42	320	30	0.04	0.486	0.91
	220	1	0.63	48	310	30	0.04	0.536	0.91
0.91	240	1	0.54	54	320	30	0.03	0.595	0.91
	260	1	0.48	59	330	15	0.03	0.642	0.91
	280	1	0.4	57	455	95	0.03	0.682	0.91
0.92	270	1	0.69	43	545	90	0.05	0.542	0.92
	280	1	0.65	65	370	70	0.01	0.585	0.92

6. Conclusion and future research directions

This paper contributes by suggesting a new system mission model with limited resource and time-varying performance during the OP and RP phases incurring different rates of resource consumption. Random shocks with different shock rates take place during the two phases, deteriorating and even crashing the system. According to the predefined AP, when a certain number of shocks occur before a certain operation time threshold, the OP is aborted to reduce the risk of system losses. Probabilistic methods are put forward to assess the MSP and SSP of the considered system under any given TPP and AP. The optimal TPP and AP are further determined to balance the MSP and SSP for a UAV system executing a reconnaissance mission. Influences of the required SSP level and shock rate and resistance parameters have been examined using the UAV case study. The major findings include (1) In the case of no OP aborting being allowed, the SSP is always lower than the MSP; otherwise, the SSP may exceed the MSP since the system survives when the OP is either aborted or completed and the subsequent RP is completed. (2) For meeting higher requirements of SSP, more cautious policies with larger ξ and lower performance $v(t)$ (thus lower resource consumption rate) are desired. (3) When high levels of the SSP are required, the time-varying performance of the system may enhance the MSP, outperforming the constant system performance case. (4) As the shock rate increases, the AP with larger ξ and TPP with lower initial performance are desired to meet the SSP requirement. (5) As the system becomes less sensitive (or more resistant) to shocks, riskier APs with smaller ξ are desired and the MSP increases. (6). An increase in the amount of available resource allows achieving greater MSP and SSP.

In the proposed model, a single task is executed during the OP and the task may be attempted only once. The model may be extended to consider missions with multiple independent tasks [9] and a task may be attempted multiple times following a successful RP to maintain the system [37]. The task-dependent TPP and AP may also be explored.

CRediT authorship contribution statement

Gregory Levitin: Conceptualization, Software, Writing – original draft. **Liudong Xing:** Formal analysis, Writing – original draft, Writing – review & editing. **Yuanshun Dai:** Data curation, Visualization.

Declaration of competing interest

There is no conflict of interests associated with this paper.

Data availability

Data will be made available on request.

Acknowledgement

The work of L. Xing was partially supported by the National Science Foundation under Grant No. 2302094.

References

[1] Dong T, Luo Q, Han C, Xu M. Parameterized design of abort trajectories with a lunar flyby for a crewed mission. Adv Space Res 2023;71(6):2550–65.
[2] Ryan S. The Difficulties With Replacing Crew Launch Abort Systems With Designed Reliability. J Syst Saf 2023;58(1):19–24. https://doi.org/10.56094/jss.v58i1.216.
[3] Levitin G, Finkelstein M. Optimal mission abort policy for systems operating in a random environment. Risk Anal 2018;38(4):795–803.
[4] Zhao X, Fan Y, Qiu Q, Chen K. Multi-criteria mission abort policy for systems subject to two-stage degradation process. Eur J Oper Res 2021;295(1):233–45.
[5] Cheng G, Li L, Shangguan C, Yang N, Jiang B, Tao N. Optimal joint inspection and mission abort policy for a partially observable system. Reliab Eng Syst Saf 2023;229:108870.
[6] Levitin G, Xing L, Dai Y. Mission aborting in n-unit systems with work sharing. IEEE Trans Syst Man Cybern 2022;52(8):4875–86.
[7] Mayrhofer M, Wächter M, Sachs G. Safety improvement issues for mission aborts of future space transportation systems. ISA Trans 2006;45(1):127–40.
[8] Thompson F, Guihen D. Review of mission planning for autonomous marine vehicle fleets. J Field Rob 2019;36(2):333–54.
[9] Levitin G, Xing L, Dai Y. Optimal task sequencing and aborting in multi-attempt multi-task missions with a limited number of attempts. Reliab Eng Syst Saf 2023;236:109309.
[10] Xing L, Johnson BW. Reliability theory and practice for unmanned aerial vehicles. IEEE Internet of Things J 2023;10(4):3548–66. https://doi.org/10.1109/JIOT.2022.3218491.

[11] Kim SG, Lee E, Hong IP, Yook JG. Review of intentional electromagnetic interference on UAV sensor modules and experimental study. Sensors (Basel) 2022; 22(6):2384. https://doi.org/10.3390/s22062384.
[12] Li X, Wang S, Li H, Zhou Y, Guo H. Electromagnetic interference of unmanned aerial vehicle in high voltage environment. J Phys Conf Ser 2023;2522(1). https://doi.org/10.1088/1742-6596/2522/1/012034.
[13] Filene RJ, Daly WM. The reliability impact of mission abort strategies on redundant flight computer systems. IEEE Trans Comput 1974;C-23(7):739–43.
[14] Hyle CT, Foggatt CE, Weber BD, Gerbranchtt RJ, Diamant L. Abort planning for Apollo missions. In: Proceedings of the 8th Aerospace Sciences Meeting, West Germany; 1970. https://doi.org/10.2514/6.1970-94.
[15] Levitin G, Xing L, Dai Y. Mission abort policy in heterogeneous non-repairable 1-out-of-N warm standby systems. IEEE Trans Reliab 2018;67(1):342–54.
[16] Rodrigues A, Cavalcante C, Alberti A, Scarf P, Alotaibi N. Mathematical modelling of mission-abort policies: a review. IMA J Manage Math 2023;34(4):581–97. https://doi.org/10.1093/imaman/dpad005.
[17] Zhao X, Liu H, Wu Y, Qiu Q. Joint optimization of mission abort and system structure considering dynamic tasks. Reliab Eng Syst Saf 2023;234:109128.
[18] Myers A. Probability of loss assessment of critical K-out-of-N: G systems having a mission abort policy. IEEE Trans Reliab 2009;58(4):694–701.
[19] Wu C, Zhao X, Qiu Q, Sun J. Optimal mission abort policy for K-out-of-N: F balanced systems. Reliab Eng Syst Saf 2021;208:107398.
[20] Zhao X, Lv Z, Qiu Q, Wu Y. Designing two-level rescue depot location and dynamic rescue policies for unmanned vehicles. Reliab Eng Syst Saf 2023;233:109119.
[21] Liu B, Huang H, Deng Q. On optimal condition-based task termination policy for phased task systems. Reliab Eng Syst Saf 2022;221:108338.
[22] Levitin G, Xing L, Luo L. Influence of failure propagation on mission abort policy in heterogeneous warm standby systems. Reliab Eng Syst Saf 2019;183:29–38.
[23] Levitin G, Xing L, Dai Y. Joint optimal mission aborting and replacement and maintenance scheduling in dual-unit standby systems. Reliab Eng Syst Saf 2021; 216:107921.
[24] Levitin G, Xing L, Dai Y. Co-optimization of state dependent loading and mission abort policy in heterogeneous warm standby systems. Reliab Eng Syst Saf 2018; 172:151–8.
[25] Levitin G, Finkelstein M, Xiang Y. Optimal inspections and mission abort policies for multistate systems. Reliab Eng Syst Saf 2021;214:107700.
[26] Levitin G, Xing L, Dai Y. Optimal aborting policy for shock exposed missions with random rescue time. Reliab Eng Syst Saf 2023;233:109094.
[27] Yan R, Zhu X, Zhu XN, Peng R. Optimal routes and aborting strategies of trucks and drones under random attacks. Reliab Eng Syst Saf 2022;222:108457.
[28] Fang C, Chen J, Qiu D. Reliability modeling for balanced systems considering mission abort policies. Reliab Eng Syst Saf 2024;243:109853.
[29] Yang L, Wei F, Qiu Q. Mission risk control via joint optimization of sampling and abort decisions. Risk Anal 2023. https://doi.org/10.1111/risa.14187. in press.
[30] Cheng G, Shen J, Wang F, Li L, Yang N. Optimal mission abort policy for a multi-component system with failure interaction. Reliab Eng Syst Saf 2024;242:109791.
[31] Levitin G, Xing L, Dai Y. Mission abort policy for systems with observable states of standby components. Risk Anal 2020;40(10):1900–12.
[32] Qiu Q, Cui C, Wu B. Dynamic mission abort policy for systems operating in a controllable environment with self-healing mechanism. Reliab Eng Syst Saf 2020; 203:107069.
[33] Levitin G, Xing L, Dai Y. Optimal mission aborting in multistate systems with storage. Reliab Eng Syst Saf 2022;218(Part A):108086.
[34] Zhao X, Li R, Cao S, Qiu Q. Joint modeling of loading and mission abort policies for systems operating in dynamic environments. Reliab Eng Syst Saf 2023:108948.
[35] Liu L, Yang J. A dynamic mission abort policy for the swarm executing missions and its solution method by tailored deep reinforcement learning. Reliab Eng Syst Saf 2023;234:109149.
[36] Liu L, Yang J, Yan B. A dynamic mission abort policy for transportation systems with stochastic dependence by deep reinforcement learning. Reliab Eng Syst Saf 2024;241:109682.
[37] Levitin G, Finkelstein M, Xiang Y. Optimal mission abort policies for repairable multistate systems performing multi-attempt mission. Reliab Eng Syst Saf 2021; 209:107497.
[38] Zhao X, Dai Y, Qiu Q, Wu Y. Joint optimization of mission aborts and allocation of standby components considering mission loss. Reliab Eng Syst Saf 2022;225: 108612.
[39] Levitin G, Xing L, Dai Y. Optimal task aborting and sequencing in time constrained multi-task multi-attempt missions. Reliab Eng Syst Saf 2024;241:109702.
[40] Levitin G, Xing L, Dai Y. Optimizing partial component activation policy in multi-attempt missions. Reliab Eng Syst Saf 2023;235:109251.
[41] Levitin G, Xing L, Dai Y. Using kamikaze components in multi-attempt missions with abort option. Reliab Eng Syst Saf 2022;227:108745.
[42] Levitin G, Xing L, Dai Y. Optimal task aborting policy and component activation delay in consecutive multi-attempt missions. Reliab Eng Syst Saf 2023;238:109482.
[43] Meng S, Xing L, Levitin G. Optimizing component activation and operation aborting in missions with consecutive attempts and common abort command. Reliab Eng Syst Saf 2024;243:109842.
[44] Levitin G, Finkelstein M. Optimal mission abort policy for systems in a random environment with variable shock rate. Reliab Eng Syst Saf 2018;169:1–17.
[45] Jovanovic, I. (2023). How Fast Do Drones Fly? UASolutions, https://uasolutions.ch/how-fast-do-drones-fly/#:~:text=The%20most%20commonly%20used%20models,reaching%20an%20astonishing%20360km%2Fh, accessed in January 2024.
[46] Thibbotuwawa A, Nielsen P, Zbigniew B, Bocewicz G. Energy consumption in unmanned aerial vehicles: a review of energy consumption models and their relation to the UAV routing. In: Świątek J, Borzemski L, Wilimowska Z, editors. Information Systems Architecture and Technology: Proceedings of 39th International Conference on Information Systems Architecture and Technology – ISAT 2018. ISAT 2018. Advances in Intelligent Systems and Computing. 853. Cham: Springer; 2019. https://doi.org/10.1007/978-3-319-99996-8_16.
[47] Rajendran P, Smith H. Review of solar and battery power system development for solar-powered electric unmanned aerial vehicles. Adv Mat Res 2015;1125:641–7.
[48] Levitin G, Xing L, Dai Y. Optimal component loading in 1-out-of-N cold standby systems. Reliab Eng Syst Saf 2014;127:58–64.
[49] Boddu P, Xing L, Levitin G. Energy consumption modelling and optimisation in heterogeneous cold-standby systems. Int J Syst Sci 2014;1(3):142–52. https://doi.org/10.1080/23302674.2014.945980.