



An Investigation of Phased Mission Reliability Analysis for Tethered HAP Systems

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Abstract. High-altitude platforms (HAPs), are becoming a viable option for long-term and cost-effective tasks like environmental monitoring, surveillance, and telecommunications. Tethered HAPs provide better stability, power supply, and data transmission capabilities because they are physically tethered to the ground. Addressing the reliability of a tethered HAP system as a phased mission system (PMS) is crucial due to the integration of many phases, such as launch station-keeping, and descent. Each phase presents unique performance requirements and environmental challenges. Ensuring reliability at every stage is essential for the success of the mission and the safety of operations over the entire lifespan of the system. This article addresses the feasibility and necessity of conducting a reliability analysis of tethered HAP systems, specifically considering them as PMSs with distinct operational stages. A comprehensive reliability analysis has been carried out for every single phase by considering the risks and challenges connected to each phase.

Keywords: Tethered high-altitude platforms · Phased mission system · Repairable components · Markov approach · Reliability

1 Introduction

High-altitude platforms (HAPs) are stations situated on an object at a nominal fixed point relative to Earth, at a height of around 15–50 km. A tethered high-

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altitude platform (tethered HAP) with a lift height of 100–150 m can offer long-term operation. In this platform, engines and payload equipment are powered by copper cables that are connected to ground-based power sources. Currently, there is a rapid advancement in the development of HAPs based on multicopters or unmanned aerial vehicles (UAVs). They are far more advantageous in terms of cost, commissioning, maintenance, portability, and other factors than balloons and airplanes. As a result, work is being done globally to explore and build a new generation of tethered HAP systems based on UAVs.

Free-flying platforms, such as UAVs and HAPs, can enable airborne communications. While these platforms have been receiving significant attention, their endurance and backhaul capacity are limited. These issues are addressed by Networked Tethered Flying Platforms (NTFPs), which guarantee cost-effectiveness and environmental benefits by providing constant power and data via a tether. A comprehensive analysis of NTFPs, including their classifications, components, qualities, uses, advantages, barriers, and regulatory frameworks, is provided in the survey [1]. In order to examine the crucial role that NTFPs play in enabling 6G communications for applications including aerial vehicles, marine operations, and vehicular communications, the publication includes case studies and performance analysis.

Since reliability engineering emerged as a scientific field in the 1950s, numerous reliability models and analytical methods have been developed. However, in the context of tethered HAP systems, only a limited number of these models are commonly used due to the system's unique characteristics and complexity. These models typically include k -out-of- n configurations, failure mode analysis techniques, and phased mission models. In the following sections, we explore various reliability modeling and analysis approaches for tethered HAP systems and subsystems, with a particular emphasis on phased mission modeling.

A summary of the recent state of development for tethered HAPs is given in [14]. It explains these platforms' design concepts, architecture, and scientific and technological difficulties. It also discusses the Institute of Control Sciences' (ICS RAS) experience in developing and implementing these platforms. [16] presents a design process for a high-voltage conducting tether that is meant to transfer power from the ground to a tethered HAP. With an example of numerical calculations, it covers the process for evaluating wave impedance and figuring out the number of cables in the tether to maximize power transfer. Power management in tethered HAP systems using lithium-ion batteries for wireless communication services is examined in [4]. A novel model is introduced that evaluates power usage using a multi-dimensional Markov process, taking into account increased demand during battery depletion. The system operates in three modes and incorporates a retrieval phenomenon.

The authors in [10] present findings on the need for unification of tethered HAP systems. Their analysis explores potential approaches for unification and standardization, along with structural optimization criteria and methods, showing that aligning requirements, components, and systems can improve the efficiency of communication networks. In [5], a model using a multidimensional

Markov process is studied to assess the reliability of a hexacopter-based tethered multirotor HAP. The model factors in component failures and evaluates the impact of failure on the remaining operational elements. [8] proposes a semi-Markov model (SMM) to enhance reliability analysis of tethered HAP systems by examining the redundant rotor system's performance. The SMM provides a more accurate assessment of system failure probability, supported by metrics like reliability indicators, mean time to failure, and steady-state availability.

As such, the tethered HAP system reliability issue is a complex one that involves several hardware, software, and human operator domains. Cross-domain dependencies result from the interactions between the components in various domains, which prevent them from being autonomous. The design principles of the most recent generation of tethered high-altitude telecommunications equipment are examined in [18]. It draws attention to a number of theoretical and technical issues, such as the development of high-power ground-to-aircraft energy transmission using resonance high-frequency energy transfer developed by Nikola Tesla, the creation of a highly dependable unmanned vehicle capable of extended operation, and the creation of a local navigation system that is more accurate in positioning and noise-immune than satellite systems.

Phased Mission Systems (PMSs) are systems that operate through a series of distinct phases, each with its own unique requirements and operational challenges. Reliability analysis of PMSs considers the sequence of phases, where the system's success in one phase is necessary for progression to the next, making the impact of component failures phase-dependent. This approach is essential for complex systems, such as aerospace and defense applications, where mission success relies on reliable performance across multiple stages. [20] provides a comprehensive review of recent advancements in the reliability evaluation and optimization of PMSs, which inspired the study of tethered HAP systems as PMSs. There has not been much research carried out on the reliability analysis of tethered HAP systems employing phased mission modeling. Because of the different demands and possible failure risks experienced during the launch, cruise, and retrieval phases, tethered HAP systems are especially well-suited for phased mission modeling, which evaluates system reliability across distinct operating phases.

The remaining paper is organized as follows. Section 2 briefly describes the system structure and its major subsystems. Section 3 presents the current state-of-the-art of reliability analysis for tethered HAP systems, while Sect. 4 introduces the phased mission modeling approach and provides a detailed reliability analysis specific to tethered HAP systems. Finally Sect. 5 summarizes the analysis.

2 System Description

Figure 1 depicts the components of a tethered HAP system, which includes an aerial platform linked to a Ground Control Station (GCS) by a tether. This tether comprises both power and data transmission cables. The system's navigation

and stabilization rely on on-board sensors and ground-based anchor points to monitor navigation parameters, with stabilization circuits adjusting the platform as needed. The platform receives power from a ground-based source, and an intelligent winch regulates the tether's length.

In a tethered HAP system, a power source failure leads to a complete system shutdown, affecting the rotors, communication, camera, and tether control, thereby causing mission failure across all phases. A communication system failure isolates the HAP, hindering control, data transmission, and real-time monitoring, which compromises both navigation and surveillance capabilities. Rotor failure during deployment would lead to a loss of altitude control, interrupting the deployment process. In the cruise phase, a camera malfunction would prevent effective monitoring, diminishing mission success. Tether failure could destabilize or disconnect the HAP, impacting both deployment and cruise phases, and potentially resulting in a crash or loss of mission control. The failure of each component critically impacts mission outcomes depending on the phase of operation.

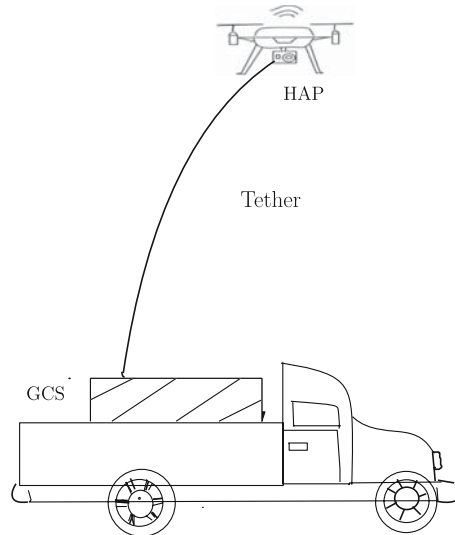


Fig. 1. Abstract view of a tethered HAP system with major components

3 The State-of-Art in Reliability Analysis for Tethered HAP Systems

The state-of-the-art in reliability analysis for tethered HAP systems, has a primary focus on failure-based assessments and the evaluation of major components using a k -out-of- n model framework. The advantage of such analyses is that they provide a straightforward evaluation of system reliability by identifying critical component failures and determining system functionality based on a specified threshold of operational components.

3.1 Failure Diagnosis and Reliability Analysis

Failure Modes and Effects Analysis (FMEA) was originally introduced in the 1950s to evaluate failures in military systems. It provides a systematic, qualitative method for examining system components, assemblies, and subsystems to identify potential failure modes, their causes, and their effects on the overall system [13]. This method later evolved into Failure Modes, Effects, and Criticality Analysis (FMECA), which adds a prioritization of failure modes based on their severity or impact. Both FMEA and FMECA are typically applied during the design phase of a system to highlight areas needing improvement to achieve reliability goals.

The steps involved in the failure diagnosis and analysis of tethered HAP systems are Monitoring and Data Collection by continuously tracking system and environmental conditions, and identifying anomalies or malfunctions in the tethered HAP system performance. Tethered HAP systems require failure diagnosis and analysis to identify and evaluate possible failure points in essential components including the tether, platform, payload, and base station. Common problems include malfunctioning sensors, communication breakdowns, structural damage to the platform, and mechanical stress on the tether. The procedure involves keeping an eye on the health of the system, detecting irregularities, recognizing issues, and carrying out root cause analysis—often aided by post-failure inspections and simulation. For HAPs to be more reliable and safe in a variety of applications, preventative measures like redundancy, routine maintenance, better materials, and improved designs are essential. A guard channel strategy gives priority to traffic of higher significance, while the Markovian arrival process (MAP) in [11] models traffic marked by burstiness and self-similarity. After a random interval, traffic tries again when it is blocked because there are no available channels. The dynamics of the model are characterized by a level-dependent quasi-birth-death (LDQBD) process, and the service and retrial procedures are represented by phase-type (PH) distributions with unique characteristics.

3.2 k -Out-of- n Systems

The study of k -out-of- n models is significant from both theoretical and practical perspectives. Theoretically, it offers numerous opportunities for the development of new mathematical methods and applications. Practically, these models are frequently used for reliability analysis in various fields such as telecommunications, transportation, manufacturing, and services. Extensive research has been conducted on the reliability of k -out-of- n systems, with their application being widespread in the analysis of complex systems. However, comprehensive monographs on the subject are lacking, making [17], which explores different k -out-of- n models, analysis methods, and their use in evaluating the reliability of tethered high-altitude telecommunication platforms, especially valuable for students and educators.

One application of these models is described in [15], where the authors analyzed the dependability of a flight module operating on a tethered high-altitude

telecommunication platform using the k -out-of- n : F model. In [3], an analytical framework for the k -out-of- n : G model was proposed under two failure scenarios. [2] introduced a k -out-of- n model that allows for repair in hot standby mode. Improving the reliability of the power, communication cables, and the tether connecting the HAP system to the ground should be a key focus. As outlined in [12], the reliability of tethered HAP systems can be assessed by considering the tether, which is made up of multiple parallel wires. The system continues to operate as long as a sufficient number of wires are functional; however, if the number of working wires falls below a certain threshold, the tether will fail.

The failure-based analysis and reliability analysis of k -out-of- n models are effective for assessing individual component performance and ensuring redundancy. However, the phased mission model offers an equally suitable and more comprehensive approach for reliability analysis, as it accounts for the system's performance across distinct operational phases, making it particularly valuable for capturing the mission-critical dynamics of tethered HAP systems where reliability varies depending on the Phase of the mission. In the next section, a phased mission reliability analysis of tethered HAP systems is presented, offering a detailed assessment of system reliability across different operational phases.

4 Phased Mission Reliability Analysis for Tethered HAP Systems

Many practical systems must achieve their goals over multiple phases, where they perform different tasks under varying conditions and success criteria. A key challenge in assessing reliability arises from the multi-phase nature of these missions, as system functionality, operating conditions, involved components, and stress levels may change from one phase to another. This requires distinct reliability models for each phase. The multi-phase, multi-domain nature of these missions sets them apart from traditional reliability problems, which generally focus on single-phase, single-domain scenarios. In the case of tethered HAP systems, Phased Mission Systems (PMS) offer a framework for evaluating the reliability and performance of these systems across different operational phases.

Analytical modeling techniques and simulations are the two categories of methodologies that can be utilized to assess the reliability of tethered HAP systems like PMS. Simulations often provide a high level of generality in system representation, but their results are typically approximate, and they can be computationally expensive. The analytical modeling techniques that may usually provide correct findings with a manageable processing overhead are the main emphasis of this study. Any component failure during one Phase affects the system's capacity to complete subsequent phases, often resulting in mission failure. This type of phased mission system is known as non-repairable since repairs cannot be made to the system while it is on mission [6, 7]. For example, if the platform's tether experiences wear and begins to degrade, it cannot be repaired during the mission. In a repairable PMS, components or subsystems of the tethered HAP can be repaired or replaced during the mission [9]. For instance, in the

event that a software error arises during the mission, it can usually be fixed in real-time through interventions, enabling the system to resume operations and restore functionality without causing a major interruption to the mission's main goals.

A component of a tethered HAP system may fail independently or due to common cause failures (CCFs) [23]. CCFs occur when multiple components fail simultaneously due to a shared root cause, either internal or external ([21, 22]). Analyzing the reliability of Phased Mission Systems (PMS) is challenging because component failure behavior and system structure can vary across different phases. The issue is further complicated by functional dependence (FDEP), where the failure of one or more components causes others to become nonfunctional, unavailable, or isolated. In [19], the authors made significant contributions by modeling and analyzing the reliability of PMSs affected by several FDEP groups using a Markov chain-based approach.

4.1 The Phased Mission Reliability Modelling of the Tethered HAP System

A tethered HAP system is a type of HAP that remains connected to the ground via a tether, typically for stability, power supply, or data transmission. When considering a tethered HAP system as a PMS, the operation is divided into distinct phases, each requiring specific management and strategies to ensure mission success. In a tethered HAP system, the operational integrity is contingent upon three primary phases: launch, operational, and retrieval, and is supported by key components including the GCS, tether, and aerial subsystem. While many errors in the GCS and aerial subsystem can be mitigated or resolved through recovery protocols, any malfunction associated with the tether is deemed unrecoverable. This is critical, as the tether not only ensures the physical connection and stability of the aerial subsystem but also plays a vital role in power and data transmission. A failure in the tether can lead to catastrophic outcomes, compromising the entire system's functionality and safety.

Phases of a Tethered HAP System Mission:

- 1 Launch Phase: Successfully launch and ascend the tethered HAP to the desired operational altitude.
- 2 Operational Phase: Execute the primary mission, which could include activities like surveillance, communication relay, or environmental monitoring.
- 3 Retrieval Phase: Safely bring the tethered HAP back to the ground (Fig. 2).

4.2 The State-Space Oriented Reliability Analysis

System states serve as the foundation for building a Markov chain model; each state can be represented by a mix of all functional and defective system components that describe the behavior of the system at any given time. State transitions connect the states; a component failure is typically what initiates or



Fig. 2. Phases of a tethered HAP system

causes a transition between two distinct states. When building a Markov model in the context of system reliability analysis, one begins with an initial state in which every system component is functioning as intended. The system transitions between states as each component fails one at a time until it reaches an absorption state, which usually signifies the total system failure.

The system consists of three subsystems and three phases of the whole mission. The transition time between two consecutive phases is not taken into account. All subsystems initially work perfectly. The whole system is comprised of three major components or subsystems, say, the GCS(C_1), the tether(C_2), and the aerial subsystem(C_3). Every subsystem is crucial and has its own sensitivity in each Phase of the mission. We may categorize the possible failures into two,

- Type *I* failure: Recoverable by a repair process/ doesn't cause mission failure.
- Type *II* failure: Unrecoverable/ leads to mission failure.

The subsystems can exist in one of three states: fully operational, represented by 2; faulty but recoverable (type I failure), represented by 1; and complete failure (type II failure), represented by 0. Two subsystems, C_1 and C_3 , have three possible states, while subsystem C_2 has two states—either functional or failed. The repair of C_1 and C_3 can be performed while the system is still running, and once repaired, each subsystem is restored to an “as good as new” condition. The repair and failure rates of the subsystems are random variables, assumed to follow an exponential distribution and to be independent of each other.

Let $\bar{P}_i$ denotes that the Phase i is complete with all subsystems in the operational state and let P_{iI} denote Phase i completion with some subsystems in a faulty but operational state(level 1), for each $i = 1, 2, 3$. Then the fault tree representation of the system is given in Fig. 3.

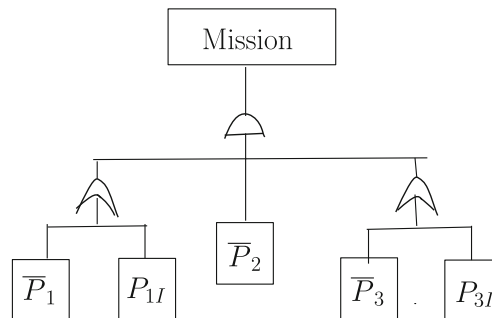


Fig. 3. Fault tree for the tethered HAP system mission

At any time, the state of the system is denoted by (C_1, C_2, C_3) where C_1 and C_3 take values in $\{0, 1, 2\}$. But C_2 has only two levels either 2 or 0. Since workloads of a subsystem may change over each phase, failure rates may fluctuate from Phase to Phase. Assume that the failure rates of a subsystem C_j in Phase i associated with type I and type II failures are α_{jI}^i and α_{jII}^i respectively and the repair rates are given by β_j^i , $i, j \in \{1, 2, 3\}$. The possible states of the system are listed as follows

$$\begin{aligned} S_1 &= (2, 2, 2), S_2 = (1, 2, 2), S_4 = (0, 2, 2), \\ S_3 &= (2, 2, 1), S_5 = (2, 0, 2), \\ S_6 &= (2, 2, 0). \end{aligned}$$

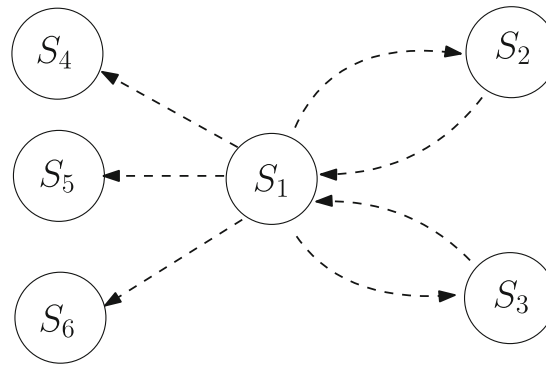


Fig. 4. The possible state transitions during any Phase in the tethered HAP system

The state transitions possible for each Phase are the same, as depicted in Fig. 4. But the mission success or failure and hence the reliability of the system in each Phase is defined in different ways. The mission consists of three sequential phases, each with specific success criteria. Phase 1 always begins with the system in state S_1 . For this Phase to be considered successful, it must conclude in one of the states S_1 , S_2 , or S_3 . Phase 2 then starts with whichever state Phase 1 ended successfully. For the success in Phase 2 and to proceed to Phase 3, the system ideally ends in S_1 . Since Phase 2 is the operational Phase and the main task is to be completed in this Phase all the faults of type II must be cleared and all the subsystems must be brought into a completely functioning state before the end of this Phase 2. If Phase 2 concludes in S_2 or S_3 , the system can make a transition to Phase 3 but the mission will be considered as failed. In Phase 3, the mission is considered successful as long as the Phase is completed, even if it ends with recoverable errors, indicating that the system is reliable enough to achieve overall mission success despite minor issues (Table 1).

4.3 Reliability Analysis in Phase 1

Assume the total mission duration is T hours, with the three phases having duration T_1, T_2 , and T_3 hours, respectively. The mission begins with Phase 1,

Table 1. Initial and final states for three phases of the tethered HAP system mission

	Phase 1	Phase 2	Phase 3
Initial states	S_1	S_1, S_2, S_3	S_1
Final states indicating Phase success	S_1, S_2, S_3	S_1	S_1, S_2, S_3

where all three subsystems are fully operational. The initial probabilities for Phase 1 are $[1, 0, 0, 0, 0, 0]$. The state equations for the Markov model are given by the following differential equation in matrix form:

$$\mathbf{Q}'(t) = \mathbf{R} \cdot \mathbf{Q}(t) \quad (1)$$

where $\mathbf{Q}(t)$ is the state probabilities vector at time t and $\mathbf{Q}'(t)$ is differential of $\mathbf{Q}(t)$. The matrix $\mathbf{R}$ is the infinitesimal generator matrix that includes the rates of state transitions as indicated in Fig. 4. To evaluate the state probabilities, $\mathbf{Q}(t) = (q_1(t), q_2(t), q_3(t), q_4(t), q_5(t), q_6(t))$, where $q_k(t), k \in \{1, 2, \dots, 6\}$ is the occurrence probability of state S_k at any time $t > 0$, the differential equations in (1) can be solved using the Laplace transform method based on the initial state probabilities. Using the initial state probabilities $[1, 0, 0, 0, 0, 0]$, the state equations of Phase 1 in the form of (1) can be solved and obtain the state probabilities at the end of Phase 1 (i.e., mission time = T_1 h) as $(q_1(T_1), q_2(T_1), q_3(T_1), q_4(T_1), q_5(T_1), q_6(T_1))$. With the system state probability, all the reliability indices of this multi-state system can be computed easily. The system is said to be reliable at the end of Phase 1 only if the system states are any of S_1, S_2 or S_3 . Hence the reliability of the system at the end of the Phase 1, denoted by $R_{P_1}(T_1)$, is given by,

$$R_{P_1}(T_1) = q_1(T_1) + q_2(T_1) + q_3(T_1). \quad (2)$$

4.4 Reliability Analysis in Phase 2 and Phase 3

In this multi-Phase system, the final-state occupation probabilities from one Phase are assumed to serve as the initial-state occupation probabilities for the next, allowing a continuous probabilistic flow through each phase. Phase 2 starts with any of the states S_1, S_2 or S_3 . Simplify the Markov chain corresponding to Phase 2 by only including state transitions relevant to that phase. Using the initial probabilities derived from the previous phase's final-state probabilities, i.e., $(q_1(T_1), q_2(T_1), q_3(T_1), q_4(T_1), q_5(T_1), q_6(T_1))$, the Markov chain for Phase 2 is solved to obtain the system state probability vector at the end of the Phase 2 of duration T_2 as $(q_1(T_2), q_2(T_2), q_3(T_2), q_4(T_2), q_5(T_2), q_6(T_2))$. At the end of Phase 2, the reliability of the system, denoted by $R_{P_2}(T_2)$, is given by

$$R_{P_2}(T_2) = q_1(T_2). \quad (3)$$

The duration of Phase 3 is assumed as T_3 and that of the whole mission as T . The initial state probability vector for Phase 3 is derived from the final

state probability vector of Phase 2. By applying the equations in (1) to Phase 3 and solving them, we obtain the state probabilities, which represent the probability of the system being in each respective state at the end of Phase 3, $(q_1(T_3), q_2(T_3), q_3(T_3), q_4(T_3), q_5(T_3), q_6(T_3))$. Then the reliability of the system at the end of Phase 3, denoted by $R_{P_3}(T_3)$, which is same as the overall system reliability, $R_{\text{sys}}(T)$. It can be determined using the state probabilities and is given by

$$R_{\text{sys}}(T) = R_{P_3}(T_3) = q_1(T_3) + q_2(T_3) + q_3(T_3). \quad (4)$$

5 Conclusions and Future Work

This work presents a comprehensive reliability analysis of a tethered HAP system by modeling it as a PMS. A Markov-based state space approach was employed to account for the varying mission requirements and operational conditions across each phase. The model effectively captures system failures and state transitions, allowing for a detailed evaluation of failure probabilities and system downtime specific to each phase. This analysis identifies critical phases with higher failure risks and suggests phase-specific maintenance and redundancy strategies to improve overall system reliability, thereby supporting the safe and efficient deployment of tethered HAP systems in non-terrestrial applications.

As part of future work on the phased mission reliability analysis of a tethered HAP system, the study can be extended by incorporating additional phases and components to better reflect a practical operational scenario. This will involve modeling more complex mission profiles, where each phase may introduce different system configurations and failure modes. By expanding the analysis to cover these realistic conditions, comprehensive numerical simulations can be performed and detailed reliability results could be generated.

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