NASA/TM–20220009974

Dynamic Path Planning Automation Concept for Advanced Air Mobility

Vivek Sharma and David J. Wing
Langley Research Center, Hampton, Virginia

September 2022

NASA STI Program. . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI Program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Report Server, thus providing one of the largest collection of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI Program, see the following:

- Access the NASA STI program home page at `http://www.sti.nasa.gov`

- E-mail your question to `help@sti.nasa.gov`

- Phone the NASA STI Information Desk at 757-864-9658

- Write to:
  NASA STI Information Desk
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

NASA/TM–20220009974

Dynamic Path Planning Automation Concept for Advanced Air Mobility

Vivek Sharma and David J. Wing
Langley Research Center, Hampton, Virginia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

September 2022

Acknowledgments

The research was performed under the auspices of the Advanced Air Mobility project, as part of the NASA Aeronautics Research Mission Directorate's Integrated Aviation Systems Program.

Available from:

NASA STI Program / Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199
Fax: 757-864-6500

Abstract

Advanced Air Mobility (AAM) aims to develop an air transportation system for novel air vehicles between local, regional, intraregional, and urban places. Safety and efficiency of increasingly complex AAM operations are expected to require extensive use of automation, ranging from controlling the revolutionary new aircraft to managing flights dynamically in the high tempo airspace and aerodrome operations. Both onboard and ground automation will play central roles in assisting AAM operators with managing the flight paths of their fleet. This document presents a concept for dynamic path planning (DPP) automation applicable to AAM and other flight operations. The role of the DPP automation system is fivefold: (1) it creates a flight path with desired qualities of being feasible, deconflicted, harmonized, flexible, and optimal; (2) it monitors the progress of flight in a dynamic operating environment; (3) it supports the user in evaluating continued acceptability of the flight path in changing conditions; (4) it revises the flight path as needed to maintain the desired flight path qualities; and (5) it coordinates the flight path with airspace users and service providers. Key users of the DPP automation system include flight planners, pilots, and airspace service providers. The concept allows for the system to be installed onboard the aircraft as well as on the ground. The system responds automatically to the dynamic operating environment to ensure that a safe and operationally acceptable flight path is available throughout the flight.

Contents

List of Figures

1 Introduction

Advanced Air Mobility (AAM) is an initiative of the National Aeronautics and Space Administration (NASA), the Federal Aviation Administration (FAA), and the industry to develop an air transportation system that moves people and cargo between local, regional, intraregional, and urban places previously not served or underserved by aviation, using revolutionary new aircraft [2, 4, 5]. The initial focus of the AAM research is on passenger and cargo-carrying air transportation services in an urban environment, i.e., Urban Air Mobility (UAM). Realizing NASA's vision for AAM depends on significant reliance on automation and information services to achieve safe, efficient, and scalable operations. NASA is investigating a wide array of capabilities related to aircraft, airspace, infrastructure, and fleet operations, needed to make this vision a reality.

Managing an aircraft's intended flight path in an AAM operational environment is one such fundamental capability. An AAM operator develops an initial flight plan that satisfies the mission objectives, complies with airspace rules and regulations, accounts for atmospheric conditions, and conforms to the aircraft's energy and performance envelopes. This plan includes the intended flight path defined in terms of latitude, longitude, altitude, and energy consumption, as functions of time. The intended flight path requires ongoing management to ensure it remains safe and operationally acceptable as the flight progresses in the dynamic operating environment. This document introduces the idea of dynamic path planning (DPP) to enable effective planning and management of the intended flight path.

1.1 Document Scope

The document presents the concept of a DPP automation system designed to manage an aircraft's flight path dynamically in an increasingly complex AAM operational environment. It defines the need for a DPP automation system, outlines the system goals and objectives, describes a conceptual system architecture, and presents key operational scenarios to illustrate the usage of the system. While the concept in this document is presented in an AAM operational context, it is also applicable to non-AAM operations that rely on automation for dynamic flight path planning.

1.2 Document Purpose

This document serves multiple purposes.

1. It presents a novel concept of an automation system designed to manage aircraft flight paths dynamically in an increasingly complex AAM operational environment.

2. It offers potential users of the DPP automation system an insight into its capabilities, interfaces, and operational usage.

3. It facilitates communication among DPP stakeholders, including NASA, the FAA, AAM fleet operators, service providers, and automation system designers.

4. It provides NASA researchers with a frame of reference in which to develop design guidelines, means of compliance recommendations, and operational requirements for a reference DPP automation system.

5. It represents the first step toward establishment of community standards for system architecture, design, implementation, verification, and validation activities for formally developed DPP automation systems.

1.3 Document Organization

The document is organized as follows, based on concept description guidance from [1].

§1 provides the scope, purpose, and organization of the document.

§2 describes the environment in which the system is envisioned to operate.

§3 outlines the goals, objectives, rationale, and usage of the system.

§4 defines elements of the DPP conceptual architecture.

§5 presents key operational scenarios of the DPP automation system.

§6 summarizes salient features of the concept and future research activities.

Appendices provide lists of references, abbreviations, and glossary.

> The document contains helpful tips designed to highlight key points, provide related information, and answer frequently asked questions.

2 Operations Overview

This section describes the current and envisioned states of dynamic path planning, and the scope and operating environment of the proposed DPP automation system.

2.1 Current State

In current operations, flight paths are generally managed by humans (e.g., flight planners, dispatchers, pilots, and air traffic controllers, often collaboratively) assisted by various tools, procedures, and operational information. It is commonplace and acceptable for a flight planner to build an initial flight path with a flight planning tool, and for the pilot to manage it thereafter using aeronautical experience, judgment, and situation awareness tools, especially if the flight is conducted under visual flight rules (VFR) in benign weather conditions. Flights under VFR exercise significant flexibility in selecting flight paths, while pilots see and avoid traffic and other hazards. As changes to the operating environment are encountered, tactical deviations from the planned path are not uncommon. For flights under instrument flight rules (IFR), the pilot (continuing to see and avoid traffic and hazards) receives traffic separation services from an air traffic controller. Controllers use surveillance technologies, traffic displays, clearance generators, and tactical instructions to aid pilots with this task. Thus, dynamic path planning is managed by pilots under VFR, and by pilots and controllers collaboratively under IFR.

2.2 Envisioned State

The AAM vision has expectations of high operational tempos, increased traffic densities, smaller traffic separation volumes, and complex operating environments. Such conditions are expected to stress the conventional VFR and IFR procedures as operational complexity grows, especially given the limited energy reserves of AAM aircraft. Eventually, the AAM environment will likely require an alternative operating mode that employs the agility and precision of automation to ensure safety under these more complex conditions. For example, a candidate new operating mode, Digital Flight, has been proposed in which aircraft operators hold responsibility for traffic separation regardless of flight visibility, and they meet this responsibility through reliance on digital information and automation [6]. Under proposed Digital Flight Rules, operators would employ cooperative practices embedded in DPP automation and supported by digital information connectivity and services to operate with flexibility similar to VFR, but in both visual and instrument meteorological conditions. Under an operational mode like Digital Flight, DPP automation would play a safety critical role in the conduct of every such flight.

2.3 Scope of Dynamic Path Planning Automation

The scope of DPP automation in this document is a system that plans and updates an aircraft's flight path dynamically to meet the mission objectives and to account for the dynamic operating environment. Figure 1 highlights the role of the proposed concept in the context of mission management, flight path execution, and tactical maneuver management [7]. The DPP automation expects to receive a mission specification, and it develops and makes available a safe and operationally acceptable flight path to the users.

Mission Management is concerned with real-time decision-making about the mission goals and objectives. It continually assesses mission completion feasibility, adjusts mission specification based on evolving conditions, and develops contingency and risk mitigation plans should the mission need to change substantially. While mission management functions do not manipulate the intended flight path directly, they do establish the objectives to be achieved and are therefore an executive input and oversight to DPP.

Dynamic Path Planning supports flight path decision-making within the boundaries of established (and potentially evolving) mission parameters. These functions maintain awareness of airspace constraints, monitor for conflicts or other events that would compel a flight path change, and identify optimization opportunities within the established degrees of freedom. DPP function replans the flight path when warranted while ensuring safety, maintaining consistency with the mission objectives, and coordinating with other airspace users.

Tactical Maneuver Management is an independent layer of safety designed to detect and respond to near-term hazards that are not predicted or otherwise non-conformant to established operational rules. Typically driven by independent sensors, these functions produce guidance for a rapid response to such hazards, overriding DPP and suspending mission objectives until safety is restored.

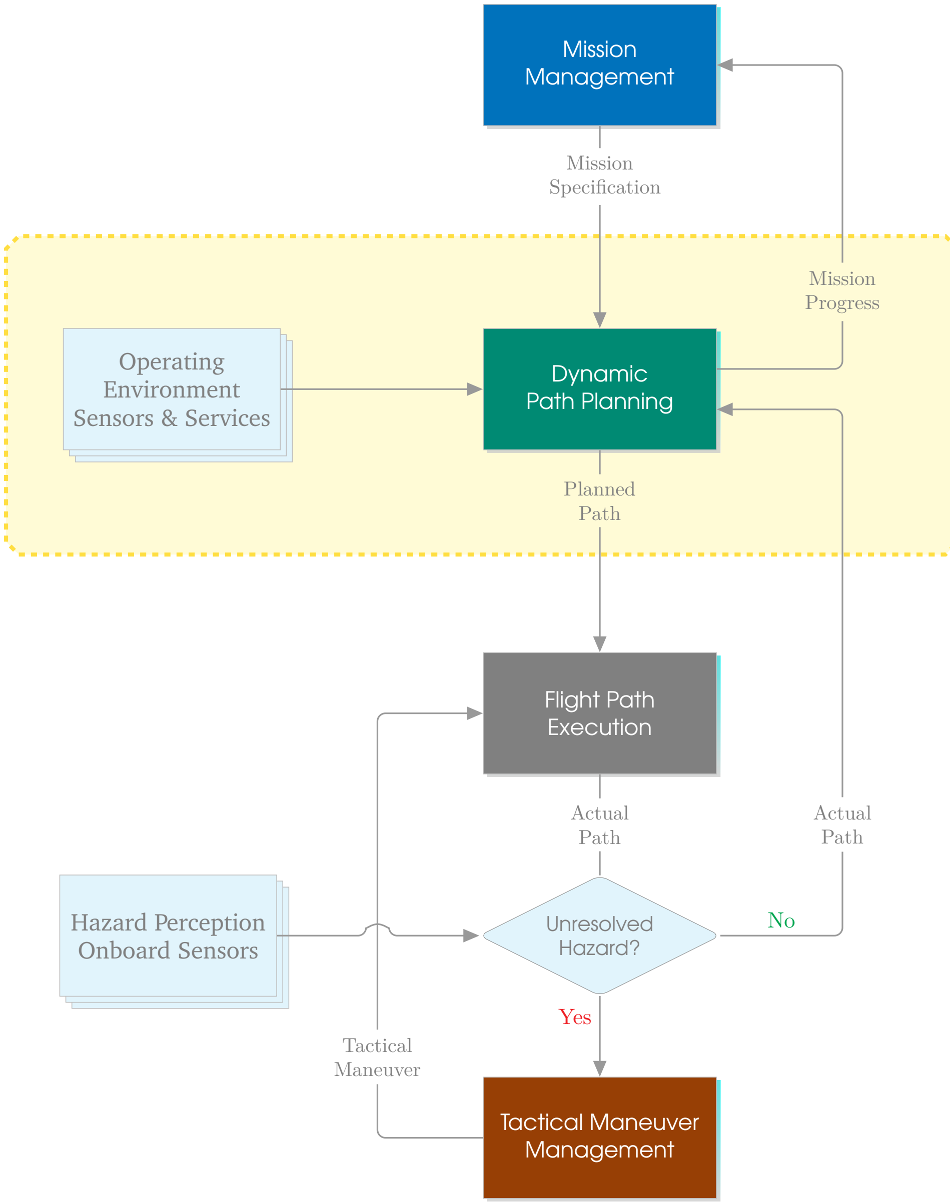

Figure 1. A schematic of the scope of dynamic path planning function.

Afterward, DPP may be invoked to reestablish the aircraft on a flight path that recovers mission objectives.

Flight Path Execution addresses the execution of the planned flight path but not its generation or modification. Its primary role relative to DPP is to achieve the expected navigation precision as may be required for certain encounters. Changes to vehicle performance that preclude the expected precision would be communicated to DPP functions to assess the continued feasibility, and to account for the altered performance envelope.

2.4 Operating Environment Services

A key attribute of the DPP automation is its ability to respond automatically to sensed and informed changes to the operating environment. A common theme among various AAM operational concepts is a reliance on dedicated services as sources of dynamic information about the operating environment. Specifically, the following types of services support the DPP automation system operation.

1. An *airspace service* provides real-time information about the activity of restrictive airspace structures of significance to the flight. This service complements the static information about the airspace structure, rules, regulations, and constraints stored in the automation system.

2. A *terrain and obstacle service* provides terrain and obstacle data relevant to the flight. This service complements the static terrain and obstacle data stored in the automation system.

3. A *traffic intent service* provides available intent of traffic aircraft currently flying, as well as the intent of those projected to be flying in the relevant airspace, during the period of interest. This service complements the onboard surveillance systems which sense state data of the traffic aircraft in the vicinity.

4. An *atmospheric data service* provides current and forecast winds, temperatures, and weather hazard information of relevance to the flight. This service complements the onboard sensors which sense proximate weather, temperature, pressure, and winds data.

5. An *aerodrome service* provides real-time information on active departure and arrival procedures, takeoff and landing slots and assignments, aerodrome emergency status, and refueling and maintenance infrastructure. This service complements the static information about the aerodrome schedules, configuration, and infrastructure stored in the automation system.

6. An *airspace coordination service*, if specified by an AAM operational concept, may assist with flight path coordination, such as cross-checking the intended flight path against the flight paths of other aircraft expected to be in the airspace.

> Some operating environment services may be acquired from third-party providers, while others may be available in-house to an AAM operator. Examples of entities offering these services include the FAA, the PSU (Provider of Services to UAM), the SDSP (Supplemental Data Service Provider), the VAS (Vertiport Automation System), and the USS (UAS Service Supplier), depending on the context and operational concept.

3 System Overview

This section presents a *static view* of the DPP automation system. The static view describes the system goals, objectives and tasks (WHAT), the rationale behind the selected concept (WHY), and the system usage (WHO, WHEN, WHERE).

3.1 System Goals, Objectives, and Tasks

The goal of a DPP automation system is to ensure that a safe and operationally acceptable flight path is available to the users and the flight path execution system throughout the flight.

The objectives of the DPP automation system are to construct and maintain a flight path with five principal qualities: *feasibility*, *deconfliction*, *harmonization*, *flexibility*, and *optimality*.

- A *feasible* path is one that conforms to the aircraft performance and range capabilities; complies with the airspace structure, rules, and constraints; avoids the terrain and charted obstacles; and meets the arrival constraints.
- A *deconflicted* path is one that avoids unsafe proximity to known aircraft, dynamic obstacles, inclement weather, and other emergent airspace hazards.
- A *harmonized* path is one that follows cooperative rules and procedures to ensure that the use of the airspace is coordinated with other airspace users.
- A *flexible* path is one that provides adequate maneuverability to ensure future flight path changes, if needed, are available and feasible.
- An *optimal* path is one that best achieves the operator's business objectives for the specific flight.

The primary tasks of the DPP automation system to manage a flight path are:

- to **create** the flight path;
- to **monitor** the flight path and the factors which may impact it;
- to **evaluate** ongoing acceptability of the flight path and proposed changes;
- to **revise** the flight path, as needed, to sustain the desired qualities; and
- to **coordinate** the flight path with other airspace users and service providers.

3.2 System Rationale

The rationale behind the DPP automation system definition lies in the derivation of system objectives from the system goal by asking two questions:

1. what constitutes a *safe and operationally acceptable* flight path, and
2. how does the system ensure that such a path is *available throughout the flight*?

The answer to the first question lies in the selection of the flight path qualities: *feasibility*, *deconfliction*, *harmonization*, *flexibility*, and *optimality* of the flight path. The answer to the second question lies in the selection of the system tasks: to **create**, **monitor**, **evaluate**, **revise**, and **coordinate** a flight path with these qualities. The rationale behind these selections is as follows.

Flight Path Qualities

- The flight paths must be *feasible*, meaning that the aircraft must be able to fly them safely without violating performance envelope and available energy, airspace restrictions, fixed terrain and obstacles, and aerodrome procedures. The consequence of an infeasible flight path may be rejection by the pilot, the flight path execution system, or the airspace authorities.
- The flight paths must be *deconflicted* up to a predefined time horizon against known traffic, restricted airspace, dynamic obstacles, and weather hazards, in order to ensure safety. Flight paths that remain conflicted are unsafe and may violate the operating rules of the flight.
- The flight paths should be *harmonized* with other airspace users and service providers, in order to enhance operational safety, capacity, efficiency, and equity. Unharmonized flight path changes may compromise these attributes and also violate the operating rules.
- The flight paths should offer *flexibility* by sustaining adequate maneuverability and anticipating typical contingencies with proactive flight path adjustments. A failure to sustain adequate flexibility and anticipate contingencies may occasionally compromise the ability to complete the intended mission.
- The flight paths should be *optimal* with respect to the operator's business goals and preferences. The absence of optimality may compromise the operator's business objectives and, for AAM aircraft with limited energy reserves, may impact the mission by cutting into the margins of already limited operational range. The optimal flight path is constructed with respect to the optimization criteria and operational constraints assigned to the specific flight by the mission manager, taking system-level optimization into consideration.

System Tasks

- **Create:** A mission specification may not specify a flight path to be flown. The DPP automation system, therefore, must create a flight path with the desired qualities that satisfies the mission objectives.
- **Monitor:** Safe and efficient flight operations in an increasingly complex and dynamic AAM operational environment means that a static flight path planned prior to departure is not sufficient to ensure that it remains acceptable throughout the flight. The system, therefore, must monitor continually the aircraft state, the dynamic operating environment, and other unplanned events during the flight.
- **Evaluate:** As a result of monitoring the progress of the flight through the dynamic operating environment, the system may identify factors that impact the qualities of the planned flight path. The system must evaluate the impact of such events to

the planned flight path for its continued safety and operational acceptability. The system must also be able to evaluate a candidate flight path proposed by a user.

- **Revise:** If the flight path evaluation reveals a degradation in desired flight path qualities, the system must revise the flight path to ensure that it remains feasible, deconflicted, harmonized, flexible, and optimal throughout the flight. If necessary, the DPP automation system must ensure that the qualities of the flight path related to safety are prioritized over the others. Depending on the operational concept employing DPP automation, the feasibility, deconfliction, and harmonization qualities may generally be considered more safety-critical than the flexibility and optimality qualities [3].
- **Coordinate:** Since flights operate in an airspace with other users, it is paramount that all computed flight paths—initial as well as revised—be in harmony with the operations of other users. The system, therefore, must coordinate the planned flight paths with applicable airspace and aerodrome users according to the procedures of the AAM operational concept.

3.3 System Usage

The DPP automation system usage begins with preflight path planning, and continues through the duration of the flight. Based on an operator's usage model, certain components of the system may be deployed onboard the aircraft while others at the operator's ground facility, with complementary capabilities. The DPP automation system supports *interactive* users and also responds to *automated* triggers. Interactive users include flight planners, pilots, airspace coordinators, and system administrators. Automated triggers include change event and temporal event triggers. Figure 2 summarizes typical usage of the DPP automation system.

> The DPP automation system is normally configured and started before the flight, and it is stopped at the completion of the flight. The dynamic planning of the flight path can, however, be paused and resumed during the flight, either by the pilot or by a designated aircraft system. A reason for pausing dynamic path planning is a potential hazard detected by an independent overriding tactical system dedicated to that type of hazard (e.g., collision avoidance system). The DPP automation system may be commanded to resume dynamic path planning after the hazard encounter has ended. During the suspension of dynamic path planning, the automation system continues to monitor the operating environment but inhibits display and transmission of all outgoing flight path solutions.

Flight Planner uses the ground-hosted system to build an acceptable baseline flight path during preflight planning. The flight planner's role ends with sending the flight path to the onboard system. Specifically, the flight planner uses the system to:

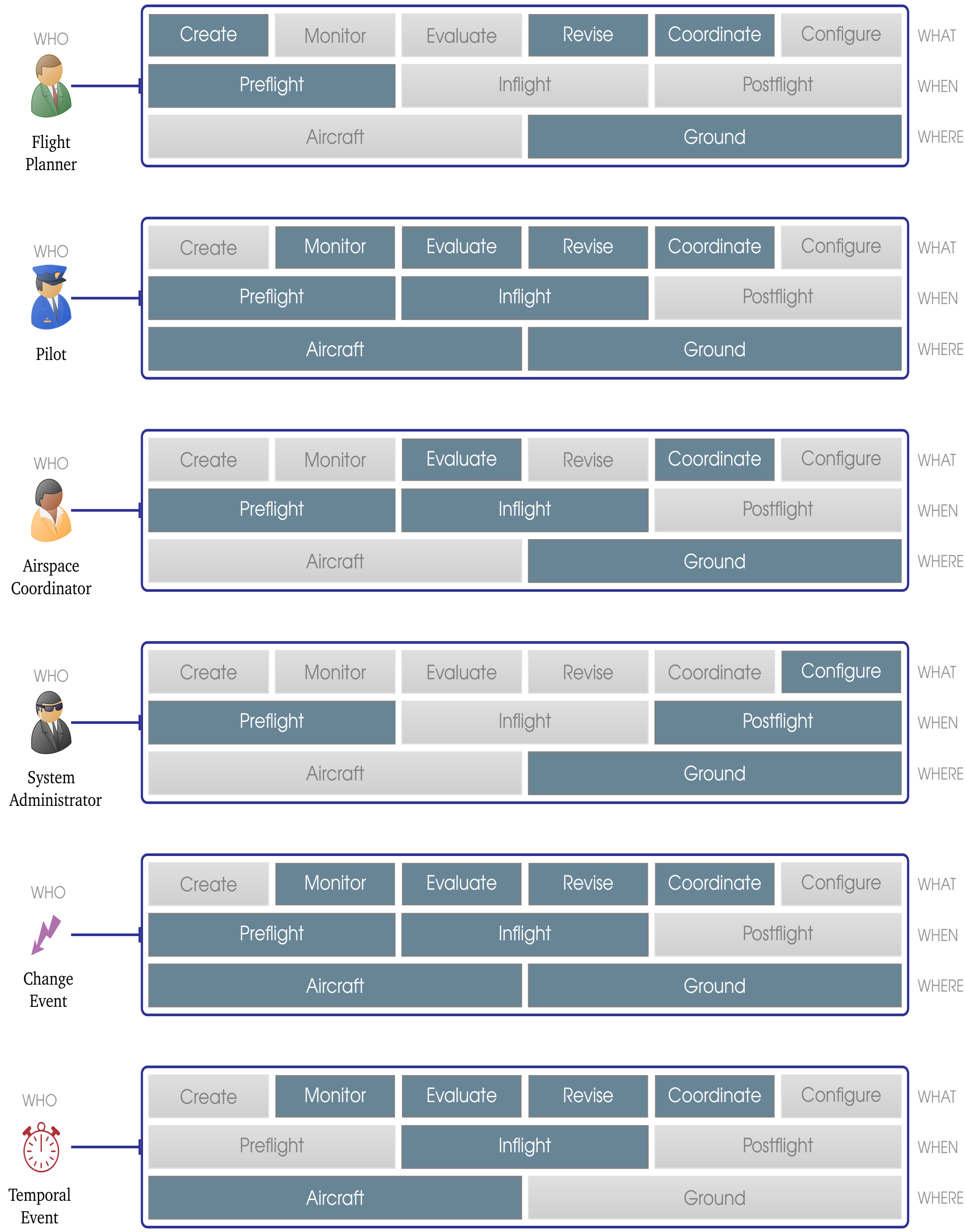

Figure 2. Typical usage of the DPP automation system.

F-1. create a feasible, flexible, and optimal flight path,

F-2. strategically deconflict a planned (feasible) flight path,

F-3. coordinate flight path with airspace users, and

F-4. revise the flight path in response to changes in planning inputs.

Pilot uses the onboard system to maintain acceptability of the flight path during the flight in response to observed changes. The pilot's task begins with accepting the baseline flight path computed by the flight planner. Specifically, the pilot uses the system to:

P-1. review the flight path in preparation for the flight,

P-2. respond to a change in mission objectives during flight,

P-3. revise the flight path due to observed or otherwise alerted hazards,

P-4. revise the flight path in response to an onboard system failure,

P-5. revise the flight path in response to a passenger emergency, and

P-6. evaluate a proposed/hypothetical flight path change.

Airspace Coordinator may use the ground-hosted system to evaluate and coordinate a flight path with the relevant airspace and aerodrome users. Specifically, the airspace coordinator may use the system to:

A-1. evaluate the flight path with respect to established rules and procedures, and

A-2. strategically deconflict the flight paths of client aircraft in the airspace.

> This concept assumes that an airspace coordinator assists in coordinating flight paths among multiple fleet operators as well as among fleet operators, aerodrome operators, and community stakeholders, as would be defined by the applicable AAM operational concept. The airspace coordinator role may be performed by a human, an automation system, or a human supported by an automation system. The DPP automation system may be part of a larger suite of tools that enables airspace coordination.

System Administrator is a secondary user who configures and maintains the DPP automation system. The system administrator performs these actions before a flight is planned. The system administrator may also review the system health logs after the flight, to aid with configuring the system for the following flights. Specifically, the system administrator uses the system to:

S-1. configure system usage parameters, features, and interfaces, and

S-2. review health of the system interfaces and modules.

Change Event Triggers detect changes in the operating environment (i.e., airspace, atmosphere, traffic and aerodromes), triggering the onboard system automatically to evaluate and revise, if necessary, the flight path during the flight. Specifically, change event triggers cause the system to:

C-1. respond to a change in the operating environment,

C-2. respond to a change in flight path constraints,

C-3. respond to a flight-specific trigger,

C-4. respond to an in-flight contingency event,

C-5. suspend dynamic path planning in deference to a higher-priority system, and

C-6. resume dynamic path planning.

Temporal Event Triggers invoke the onboard system to refresh the flight path and to monitor the system health periodically during the flight. Flight path refresh may be necessary if no other interactive or automated trigger has invoked system execution for a specified period of time. Specifically, temporal event triggers cause the system to:

T-1. compute a more optimal/flexible path than the current path,

T-2. plan a proactive response to anticipated contingency events,

T-3. monitor flight conformance against the intended flight path, and

T-4. report health of system interfaces and modules.

> As degrees of freedom diminish toward the end of the flight (as flight path flexibility is supplanted by fixed arrival structures, for instance), the DPP automation system has a correspondingly diminished role.

3.4 Design Considerations

Certain design considerations regarding hosting of the DPP automation system are offered.

1. **Onboard versus Ground:** The DPP concept supports hosting the system onboard the aircraft and/or hosting it at a ground facility, depending on the user. This document illustrates examples of onboard hosting for the onboard pilot, and ground hosting for the flight planner. Regardless of the user location, onboard hosting of DPP automation has inherent advantages. An automation system hosted onboard the aircraft benefits from direct access to the real-time data from onboard systems and sensors. It will have the most precisely known current position of the aircraft, and it will have access to the actual trajectory being commanded by the flight path execution system. Therefore, it will not be susceptible to errors in assumed position and active route that offboard systems must use. It will have direct access to the atmospheric sensing (e.g., wind, turbulence, convection) to validate or correct its

models, and it can directly receive the aircraft-to-aircraft surveillance information to manage conflicts. Being located onboard, the loop-closure time from flight-path decision to execution is minimized. Importantly, an onboard DPP automation system is robust to disruptions in air-ground data communication for time-critical decisions that will increasingly be the norm for AAM operations as they mature. It is advisable for the DPP automation system to be colocated with its human authority (i.e., the pilot) for mission decision-making, *and* also to be colocated with the flight execution system to ensure continuity of trajectory guidance. For remotely piloted or supervised flights, this may result in complementary instantiations of the DPP automation.

2. **Operator Facility versus Service Provider Facility:** The DPP concept supports hosting the ground automation system at a fleet operator's facility and at a service provider's facility for delegated dynamic path planning. The document illustrates the concept through the example of a flight planner performing DPP at the fleet operator's facility. It is possible for a fleet operator to delegate some of the DPP functionality to a service provider, while retaining sufficient functionality to meet its responsibility during the delegation. A system that is hosted at the fleet operator's facility may have better access to the operator's proprietary business preferences and aircraft models. As a result, it may be capable of computing flight paths with greater accuracy and tighter conformance than a system used by a commercial third party with restricted access to proprietary data. These attributes of computed flight paths could enable less conservative planning, potentially tighter separation standards, and improved responsiveness, all of which contribute to the increased system capacity and operator efficiency.

4 Conceptual Architecture

This section presents a conceptual architecture of the DPP automation system operating in an AAM environment. The conceptual architecture describes the system's functions, interfaces, data, and process. It ties together the system's static view (§3:WHAT, WHY, WHO, WHEN, WHERE) to its dynamic view (§5:HOW).

4.1 System Functions

The objectives of the DPP automation system to construct and maintain flight paths dynamically with the desired qualities can be achieved by five core functions. These functions are organized in terms of managing the flight paths with desired qualities, i.e., creating, monitoring, evaluating, revising, and coordinating flight paths which are feasible, deconflicted, harmonized, flexible, and optimal. The core functions of the system are supplemented by supporting functions: modeling the mission objectives; modeling the operating environment; processing incoming data required by the automation system; and processing outgoing data generated by the automation system. The system also needs the ability to configure its operational modes and interfaces in order to serve a potentially diverse array of AAM operations as well as to support variations in system hosting and user interactions. Finally, the system needs a mechanism to manage contingency events. Figure 3 shows these top-level functions of the DPP automation system, which are described below.

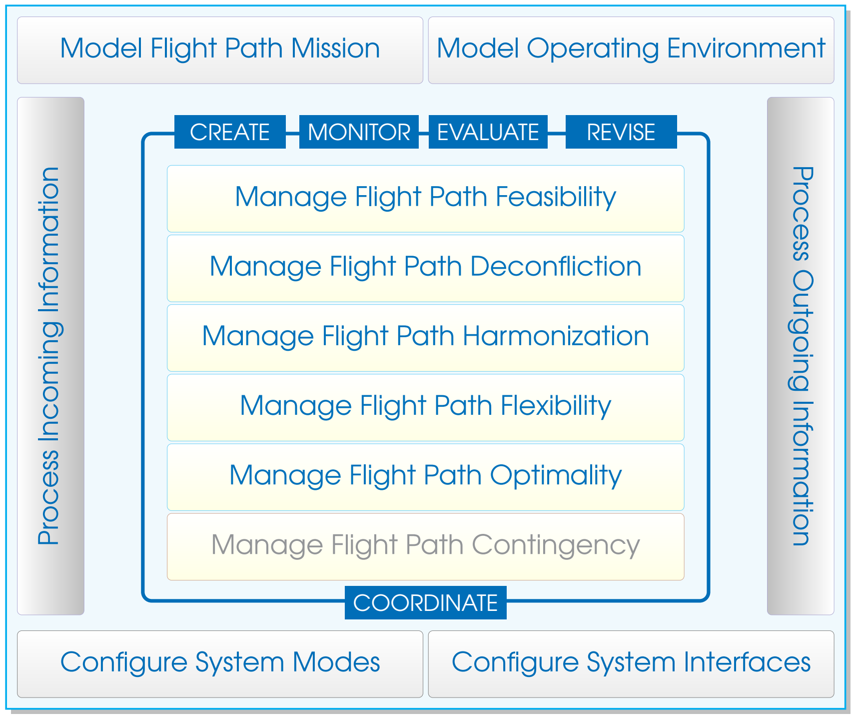

Figure 3. Top-level functions and tasks of DPP automation system.

Model Flight Path Mission models an operator's mission objectives, defined in terms of mission specification and mission parameters. Mission specification includes the origin, the destination, the desired departure and/or arrival times, and the selected aircraft type. Mission parameters include elements that affect flight path generation, such as operator and passenger preferences, flight optimization criteria, flight path constraints, guidelines to address potential diversion contingencies, and available degrees of freedom for flight path planning.

Model Operating Environment models the environment in which the flight path will be executed. The model is defined in terms of the current and predicted data related to airspace, atmosphere, aerodromes, traffic and hazards. Airspace information includes the applicable rules, structure, constraints, and community restrictions. Atmospheric data includes winds, temperature, visibility, and atmospheric hazards to flight such as turbulence, convective weather, and icing. Aerodrome information may include operational configuration, arrival structure, terminal area restrictions and guidelines, schedule constraints, surface conditions, and refueling infrastructure status. Traffic information includes, for each aircraft in vicinity, its state, intent, conformance to intent, operational mode (e.g., applicable flight rules) and emergency status. Hazards (in addition to atmospheric hazards noted above) include terrain, obstacles, special activity airspace, temporary flight restrictions, and any other known static and dynamic restricted areas.

Manage Flight Path Feasibility is responsible for planning and maintaining a flight path that conforms to the aircraft performance and range, complies with the airspace structure, rules, and constraints, and avoids the terrain and fixed, charted obstacles. This function alerts the user of potential infeasibility due to changes in operating environment, aircraft systems, or airspace constraints. It also notifies the user of constraints which needed to be relaxed by the DPP automation system in order to maintain feasibility.

Manage Flight Path Deconfliction is responsible for planning and maintaining a flight path that does not, within an applicable time horizon, conflict with known traffic and other known, dynamic hazards. This function alerts the user of the detected conflicts, presents relevant contextual information, and supplies available resolution options.

Manage Flight Path Harmonization is responsible for planning and maintaining a flight path that follows cooperative rules and procedures to ensure that use of the airspace is harmonized with other airspace users.

Manage Flight Path Flexibility is responsible for planning and maintaining a flight path which preserves adequate maneuverability to make future flight path changes, when necessary. This function uses configurable rules to define the factors that affect flexibility, such as robustness or adaptability to potential disturbances, and applicable thresholds for replanning. This function alerts the user of a degradation in predicted flight path flexibility that may signal added risk to mission completion.

Manage Flight Path Optimality is responsible for planning and maintaining a flight path which is optimal with respect to the criteria and constraints set by the fleet operator. This function alerts the user of a degradation in optimality and violation of optimization constraints.

Manage Flight Path Contingency is responsible for identifying and responding to contingency events. It includes proactive responses to anticipated contingencies and reactive responses to those observed during the flight. This function alerts the user of the contingencies, and the methods used to mitigate their impact (e.g., relaxing a constraint, revising an optimization criterion). It also alerts the user of unresolved contingencies which may require user intervention.

Process Incoming Information is responsible for transforming the incoming data into useful information. The function applies rules for data security, data decoding, data source selection, data loss, data latency, and data disposition. The function alerts the user of known instances of missing data, data parsing errors, and erroneous data.

Process Outgoing Information is responsible for organizing and making available the system output to the users and external systems. The output data includes the planned flight path and its qualities, the predicted energy consumption profiles, and the contextual airspace, aerodrome and aircraft data. The function also reports the system health and other operational alerts to the users.

Configure System Modes is responsible for managing the modes of system operation, for monitoring health of system modules and databases, and for customizing rules for planning and maintaining acceptable flight paths.

Configure System Interfaces is responsible for managing interactive interfaces to the system users and automated interfaces to the operating environment.

4.2 System Interfaces

Given the broad diversity of factors that influence the goals of flight path safety and operational acceptability for any given flight, the DPP automation system is necessarily dependent on an extensive and diverse array of static and dynamic inputs. These inputs specify the mission, user preferences, aircraft capabilities, the operating environment, and constraints posed by the shared use of that environment. The outputs of DPP automation are less diverse than the inputs. The primary outputs are the computed flight path solution(s) and sufficient information to assist the stakeholders in verifying flight path acceptability, maintaining situation awareness, and preparing for flight path execution. Figure 4 depicts the inputs and outputs of the DPP automation system, which are described below.

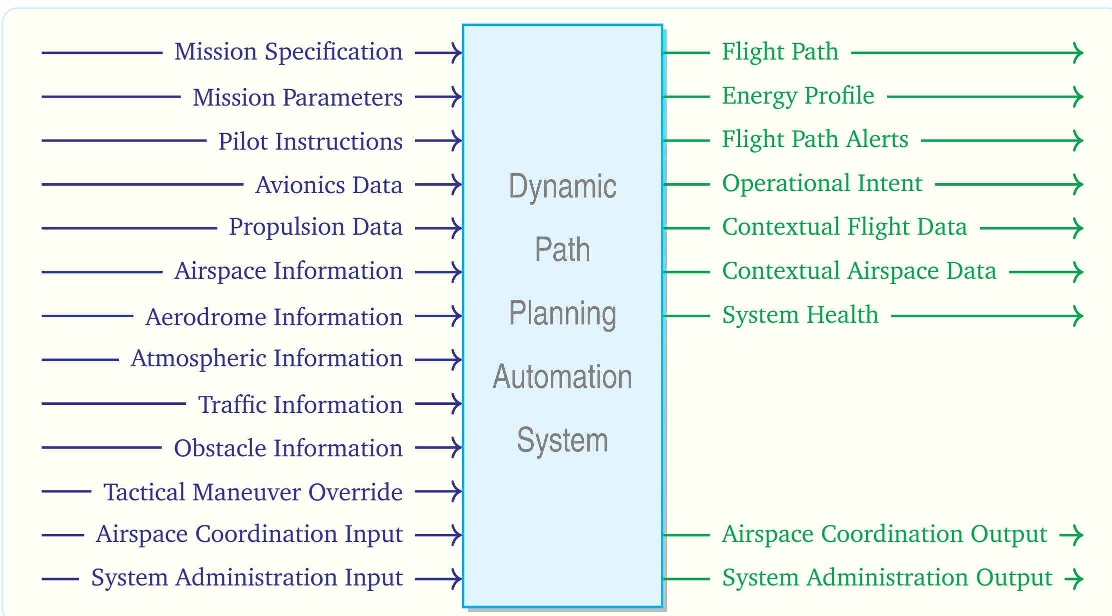

Figure 4. Key inputs and outputs of the DPP automation system.

4.2.1 Inputs

The DPP automation system requires the following information to accomplish its objectives.

- **Mission Specification** includes the origin, the destination, the desired departure and/or arrival times, mission type (passenger and/or cargo), and the selected aircraft type. This information is generally fixed and supplied to the DPP automation system by the flight planner; however, the pilot has the ability to change certain elements of the mission specification during the flight (e.g., a new destination).

Mission Parameters include elements that affect flight path generation, such as operator and passenger preferences, flight optimization criteria, path constraints, rules to address potential diversion contingencies, and available degrees of freedom for flight path planning. This information is supplied to the DPP automation system initially by the flight planner; the pilot may make changes to the mission parameters during the flight, if needed.

Pilot Instructions include changes to mission specification and mission parameters, flight path change inquiries, and decisions based on computed results (e.g., selection among multiple presented flight path options). An onboard pilot interacts with the system via a pilot interface, while a remote pilot may communicate instructions to the system via datalink.

Avionics Data includes the current time; aircraft state data; aircraft navigation performance data; sensed weather, winds, and turbulence data; proximate traffic state and intent data; datalink messages from the ground systems; and the aircraft health data. The DPP automation system receives these data automatically from respective aircraft sensors.

Propulsion Data includes the current propulsive energy available and the energy consumption rate. The data may also include propulsion specific parameters, e.g., the current or expected lift mode for eVTOL aircraft. An onboard DPP automation system receives this data automatically from the relevant propulsion system interface, while an offboard DPP system relies on an air-ground datalink to receive the data.

Airspace Information includes airspace rules, the airspace structure in effect, and real-time status of special-activity and temporarily restricted airspace of relevance to the flight. The DPP automation system relies on published airspace data and airspace information services for real-time updates to the data.

Aerodrome Information may include operational configuration, departure and arrival structure, takeoff and landing slot identification and availability, terminal area restrictions and guidelines, schedule constraints, surface conditions, and refueling, charging and maintenance infrastructure status. The DPP automation system relies on an aerodrome service for this information.

Atmospheric Information includes the current and forecast winds, temperatures, visibility, turbulence and other weather hazards of relevance to the flight. The DPP automation system relies on atmospheric data services for this information.

Traffic Information includes the available intent of the aircraft currently flying or projected to be flying in the relevant airspace during the period of interest. Their conformance to the shared intent is also provided, if available. These data complement the sensed data of the proximate traffic aircraft gathered by the onboard aircraft surveillance sensors in order to develop a complete and coherent picture of the expected traffic in the local airspace. The DPP automation system relies on a traffic intent service for this information.

- **Obstacle Information** includes the terrain map and real-time, dynamic obstacle data of relevance to the flight. The DPP automation system relies on a terrain and obstacle identification services for this information.

- **Airspace Coordination Input** is either a response from an airspace coordinator to the shared operational intent, or a request by an airspace coordinator and/or the fleet operator to consider a change to the flight path. The AAM operational concept has yet to determine the roles, responsibilities, and communication mechanism between an aircraft and an airspace coordinator; the DPP automation system conceptual architecture, therefore, includes a placeholder interface to an automated airspace coordination service.

- **Tactical Maneuver Override** includes commands to pause and resume dynamic path planning, as dictated by an aircraft tactical maneuver management system (see Figure 1) with presumed higher priority than the DPP automation system. The interoperability of dynamic path planning and tactical maneuver management has yet to be defined; the DPP automation system, therefore, allows for an automated interface to receive an 'override command' from a tactical maneuver management system.

- **System Administration Input** includes configuration parameters related to the system capabilities, external interfaces, and user interactions. The DPP automation system allows an administrator to interact remotely via a dedicated access-controlled administrative user interface.

> Airspace information, aerodrome information, atmospheric information, traffic information, and obstacle and terrain information collectively constitute the operating environment of the DPP automation system.

4.2.2 Outputs

The DPP automation system provides the following information to its users and systems.

- **Flight Path** is defined in terms of the aircraft latitude, longitude and altitude as functions of time. It may also include the derived information such as the ground speed, vertical speed, and indications of flight path constraints on speed, time and altitude. The system provides the flight path to the users and the aircraft flight path execution system.

- **Energy Profile** is defined in term of the predicted energy usage required to meet the remainder of the mission as a function of time. It may also include the derived information like the energy available, rate of energy usage, and predicted reserves as functions of time. The system provides the energy profile to the users and the aircraft flight path execution system.

- **Flight Path Alerts** include information designed to elicit the user's attention. These include conflicts and other problems with the flight path detected during the process of path planning, as well as the anticipated and observed contingencies. The alerts may also offer the system's resolution of the identified issues and contingencies. The system provides flight path alerts to the user displays. The system may also transmit any unresolved issues and contingencies to the fleet operator and/or the airspace coordinator.

- **Operational Intent** is generally an abridged version of the detailed flight path that may vary in content depending on its intended use. The system informs the pilot of the operational intent, and may share it with an airspace coordinator and the fleet operator.

- **Contextual Flight Data** includes information about the mission, the aircraft, and the user preferences which were used in generating the flight path. It may also include the aircraft's current and predicted conformance to the intended flight path, energy profile, and constraints. The system provides the contextual flight data to the pilot, and a relevant subset to the flight planner.

- **Contextual Airspace Data** includes the airspace elements which influence the computed flight path, such as the airspace structure and rules, airspace hazards, atmospheric conditions, obstacles, aerodrome constraints, and traffic aircraft. The system provides the contextual airspace data to the pilot, and a relevant subset to the flight planner.

- **System Health** includes the health of the components and interfaces of the system. The system provides this information to its users, and may also inform the fleet operator and the administrator.

- **Airspace Coordination Output** of the system depends on the services available from an airspace coordinator, as defined by the AAM operational concept. It may be a request to an airspace coordinator to coordinate the operational intent with other airspace users, or a response to a proposed flight path change from an airspace coordinator or fleet operator. The AAM operational concept has yet to determine the roles, responsibilities, and communication mechanism between an aircraft and an airspace coordinator; the DPP automation system, therefore, includes a placeholder interface to an automated airspace coordination service.

- **System Administration Output** includes the system health and response to the system administrator's commands. The DPP automation system allows an administrator to interact remotely via a dedicated access-controlled administrative user interface.

Depending on the AAM operational concept, the airspace coordination input and output data may be used by an airspace coordinator to perform flight path negotiation with other users in the airspace.

4.2.3 Interfaces

The DPP automation system is at the center of a significant influx of data and outflow of processed flight path solutions and supporting information. Figure 5 illustrates this extensive interchange, showing representative inputs in blue, outputs in green, and the suite of data source systems and users that interact with the DPP automation system.

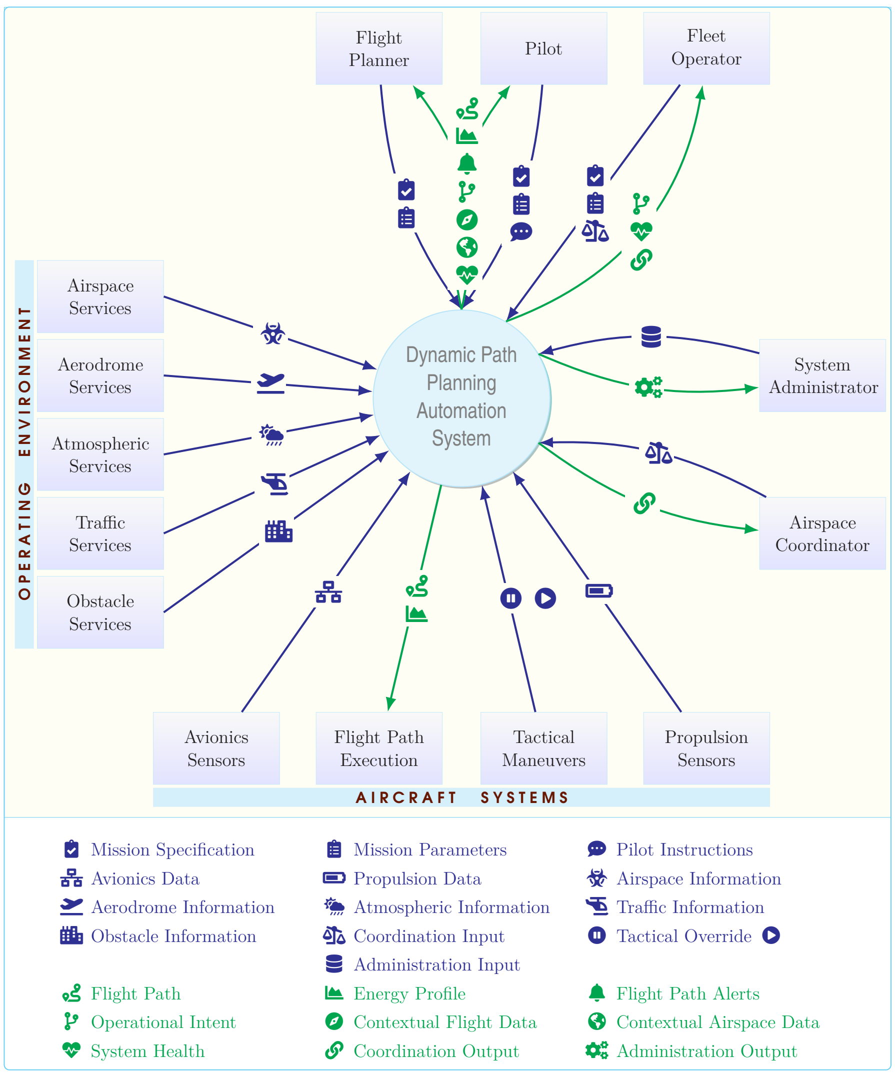

Figure 5. Inputs, outputs, connected systems, and users of the DPP automation system.

4.3 System Data

The DPP automation system needs three types of data in order to accomplish its objectives.

Dynamic Data includes information about the operating environment, the mission, and progress of the flight relative to the planned path, as described in §4.2.

Static Data includes information which does not change for a specified period of time, and is generally independent of the specific mission. The static data ranges from a fleet operator's proprietary business model and aircraft models to a navigation service provider's published data about airspace and aerodromes. Figure 6 lists the typical static data elements, categorized by fleet operator, aircraft, airspace, aerodrome, and system configuration. These data elements are stored internally, and may be refreshed by a system administrator on a periodic basis (e.g., navigation data update cycle).

Transitory Data includes information which does not change for a specific flight but will likely change from one flight to another. This includes mission specific data elements such as the aircraft tail number, flight identification, flight origin, and flight loading. These elements are specified by a flight planner at the time of initial flight path construction.

The **static data**, **transitory data** and the latest available **dynamic data** must be sufficient for a DPP automation system to perform its mission of maintaining a safe and operationally acceptable flight path throughout the flight. This ensures that the system continues to operate, albeit at the expense of optimum flight path qualities, in the event of a failure of one or more of the **dynamic data** interfaces.

4.4 Top-Level System Process

A top-level view of the DPP automation system reveals five integrated tasks needed to manage the flight path dynamically. Recall that the system **creates** an acceptable flight path, **monitors** the progress of the flight and the dynamic environment in which it operates, **evaluates** acceptability of the current and candidate flight paths, **revises** the flight path to restore or increase acceptability, and **coordinates** the flight path with other airspace users, possibly aided by an airspace coordinator. These tasks are performed in support of interactive users and in response to change events. Figure 7 depicts the top-level process to accomplish these dynamic path planning tasks automatically.

System Static Data	
Fleet Operator Information	
Business Model	Contains parameters related to the fleet operator's business objectives
Preferred Routes	Contains a list of preferred routes between aerodromes
Service Providers	Contains a list of preferred service providers (see §2.4)
Contingency Guidelines	Contains company rules for flight path contingency events
Aircraft Information	
Performance Models	Contains aircraft performance parameters
Propulsion Models	Contains propulsion system parameters
Off-nominal Aircraft Health	Contains fleet operator guidelines for handling off-nominal configuration
Airspace Information	
Navigation Data	Contains the latest navigation maps and charts
Airspace Structure	Contains a specification of airspace structures, e.g., corridors
Airspace Regulations	Contains rules, algorithms and parameters that define airspace regulations
Special Activity Airspace	Contains locations and default schedules of special activity airspace
Aerodrome Information	
Aerodrome Schedules	Contains aerodrome arrival and departure schedules and delay status
Takeoff and Landing Pads	Contains aerodrome pad configuration and availability
Charging Infrastructure	Contains aerodrome charging infrastructure availability and schedule
System Configuration	
Path Feasibility	Contains parameters that determine feasibility of a flight path
Path Deconfliction	Contains parameters related to conflict detection and resolution
Path Harmonization	Contains parameters related to cooperative practices and information sharing
Path Flexibility	Contains parameters related to ensuring adequate future maneuverability
Path Optimality	Contains parameters related to optimization performance index and constraints
Quality Prioritization	Contains parameters that determine relative priority of flight path qualities
System Health	Contains parameters related to system health and operational modes
System Interfaces	Contains parameters related to available external interfaces to the system
Users Management	Contains profiles of authorized users and their access permissions

Figure 6. A representative set of static data elements of a DPP automation system.

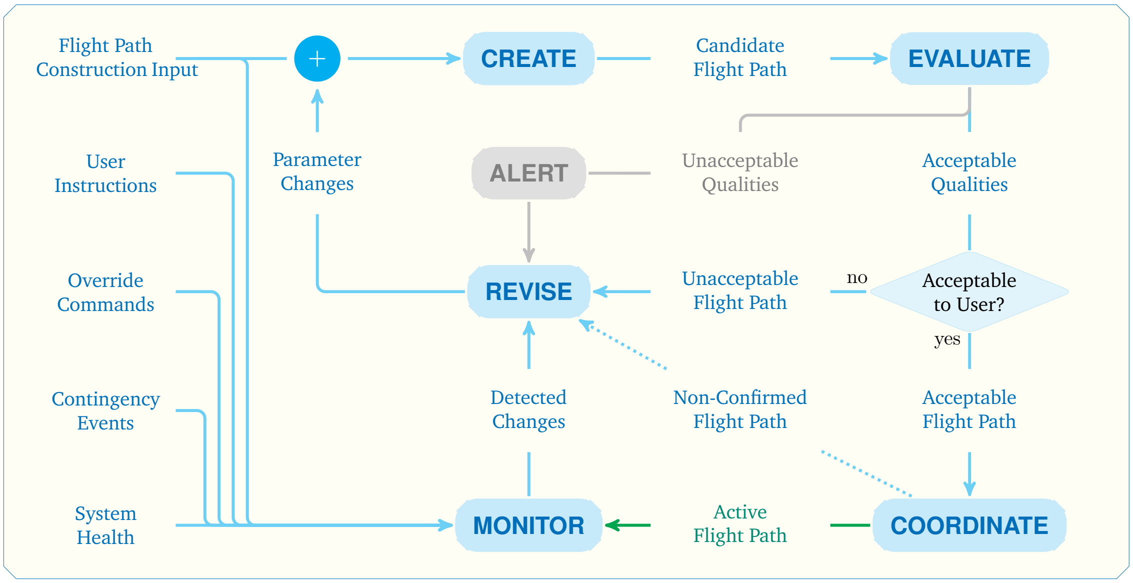

Figure 7. Top-level process to accomplish dynamic path planning.

4.4.1 Flight Path Creation

The system uses flight path construction inputs to create a flight path. The flight path construction inputs contain the complete set of information needed to construct a flight path, including such elements as the mission specification and parameters, the aircraft performance and energy models, the user preferences, the operating environment, and the aircraft state, intent, energy and health. The outcome of this task is the computed flight path, specified in terms of the lateral route, altitude profile, speed profile, and energy consumption profile as functions of time.

4.4.2 Flight Path Monitoring

The system monitors the progress of the flight and the dynamic environment in which it operates. In particular, the system continually monitors the path construction inputs, conformance of the flight to its planned path and expected energy usage, system health, user instructions, override commands, and potential contingency events. Since certain parameters, most notably the system time, aircraft state, and a majority of the operating environment data, are changing continuously, a change in such parameters is defined in terms of predefined threshold values. The outcome of this task is the discovery of changes to flight path construction input parameters.

4.4.3 Flight Path Evaluation

The system evaluates the flight path to compute flight path qualities, namely the flight path feasibility, deconfliction, harmonization, flexibility, and optimality. The outcome of this task is a determination of how a candidate flight path compares to the acceptable values, defined by the user or by community standards. If the flight path qualities are acceptable, then the system responds to the user and may coordinate the flight path with airspace users as a precursor to execution. If the flight path qualities are deemed unacceptable, then the system selects applicable rules and algorithms to be applied for revising the flight path. The system may, in addition, alert the user of potential contingencies as a result of degraded system health and/or operating environment anomalies.

> Flight paths created by the system are always *feasible* within established constraints; are mostly *deconflicted* against known hazards; and generally exhibit some level of *harmonization*, *flexibility*, and *optimality*.

4.4.4 Flight Path Revision

The system revises the flight path according to the specific reason for the revision, e.g., unacceptable flight path qualities, a non-confirmed flight path, a mission change, a change in the operating environment, a user-proposed flight path change, or a periodic refresh. Flight path revision rules enable the system to revise the *controllable* flight path construction input parameters. These parameters, in a typical order of consideration, are: the user preferences, the mission parameters, the relaxable constraints, and the mission specification. The aircraft model, the operating environment, the aircraft state, and available propulsive energy are examples of non-controllable flight path construction input data. The outcome of this task is a revised set of flight path construction input data to be used for the creation of a revised path.

4.4.5 Flight Path Coordination

The system coordinates the planned flight path with relevant stakeholders, which may include the proximate traffic aircraft, the airspace and aerodrome users, the airspace coordinator, and the fleet operator. The objectives of flight path coordination with respective stakeholders are:

- to share the current state and intent of the aircraft with proximate traffic, coordinating actions to ensure conflicts are resolved consistent with cooperative practices, and coordinating maneuver direction for encounters in close proximity;
- to share the operational intent with airspace users in order to enhance the aircraft's predictability in the airspace;
- to share operational intent with aerodrome operators and automation to ensure landing slot availability;
- to evaluate an airspace coordinator's request to change the flight path; and

- to share flight path changes, conformance status, system health, potential to change the flight path with revised mission parameters, and other information with the fleet operator.

The outcome of this task is the availability of a successfully coordinated flight path to the pilot for execution. Depending on the AAM concept, a candidate flight path which could not be coordinated successfully with other airspace users may trigger a negotiation between the DPP automation system and the airspace coordinator.

5 Operational Scenarios

This section presents the *dynamic view* of the DPP automation system. The dynamic view represents how the users, human and automated, use the system to accomplish their mission objectives. It includes a set of operational scenarios from the viewpoint of system users. These operational scenario examples are designed to provide the reader an overview of the process. The scenario description is representative and not comprehensive.

Each operational scenario is described in terms of its motivation (labeled as TRIGGER), any necessary preconditions (PRE), a typical flow of events (FLOW), and possible post-conditions (POST). The operational flows, in the form of sequence diagrams, depict high level interactions between the system and other entities: the flight planner, the pilot, the airspace coordinator, the aircraft, and the supporting services. Figure 8 relates the interactive users and the automated triggers identified in §3.3 to the operational scenarios described in §5.1–§5.5.

The DPP automation system may be configured, possibly per trigger, to:

a) require a user's acceptance prior to coordinating a flight path,

b) present the user a successfully coordinated flight path†, or

c) not require a user to be in the loop (*autonomous* operational mode).

†*Viable only if the coordination of flight paths is an automated process.*

5.1 Flight Planner Scenarios

TRIGGER The mission manager, generally the fleet operator, receives a flight request. The request may be in the form of either an automated reminder in the case of a scheduled flight, or a message in the case of an on-demand flight. The mission manager tasks a flight planner with creating the initial flight path.

PRE The mission manager has defined mission specification and initial mission parameters, based on the requested flight, the applicable fleet policy, and the customer preferences. The fleet operator has selected an aircraft, based on the number of passengers and typical energy needed for the origin-destination pair.

The fleet operator has also selected a pilot, based on availability, training, and fleet guidelines. The DPP system administrator has configured the system with the necessary preloaded static data, established connections to the relevant information services for dynamic data exchange, and ensured that the system is in acceptable health. If needed, the flight planner has access to an airspace coordinator, either a person or an automated system, responsible for coordinating airspace resource utilization and operations among operators.

FLOW Figure 9 shows a sequence of activities outlining a flight planner's use of the system. A flight planner begins by specifying a mission to the DPP automation system. The system collects the necessary information about the operating environment from the supporting services, and about the aircraft health and propulsive energy status from the aircraft. The system compiles the set of flight path construction parameters and creates a candidate flight path. It evaluates the flight path qualities and compares them to the acceptable values established by regulation or company policy, as appropriate. If the qualities are acceptable, then the system conveys a successful status to the flight planner. If the qualities are not acceptable, then the system informs the flight planner of the unacceptable flight path qualities. It is up to the flight planner to revise the mission parameters and request a new flight path. If the qualities are acceptable, then the flight path is communicated with an airspace coordinator for confirmation. Once confirmed, the flight path is transmitted to the onboard DPP automation system.

Once an acceptable flight path has been created, a flight planner is able to update it should the mission objectives change. The DPP automation system is continually monitoring the input interfaces, including the flight planner user interface. Upon receiving an update to the mission, the system revises the flight path construction parameters, re-creates a flight path, and evaluates the qualities of the revised flight path. If the qualities are unacceptable, then the system may (if so configured) iterate on the flight path construction parameters until the flight path achieves acceptable qualities. If the qualities are acceptable, then the flight path is communicated with an airspace coordinator for confirmation. Once confirmed, the flight path is transmitted to the onboard DPP automation system.

POST The ground DPP automation system and the onboard DPP automation system are synchronized with the intended flight path that has been accepted by the flight planner and coordinated with the other airspace users.

System Usage		Scenario
Flight Planner uses the system, during preflight planning on the ground, to:		
F-1	create a feasible, flexible, and optimal flight path	Figure 9
F-2	strategically deconflict a planned (feasible) flight path	
F-3	coordinate flight path with airspace users, possibly via an airspace coordinator	
F-4	revise the flight path in response to changes in planning inputs	
Pilot uses the system, either onboard or remotely, to:		
P-1	review the flight path in preparation for the flight	Figure 10
P-2	respond to a change in mission objectives during flight	
P-3	revise the flight path due to observed, or otherwise alerted, hazard during flight	
P-4	revise the flight path in response to a passenger emergency during flight	
P-5	revise the flight path in response to an onboard system failure during flight	
P-6	evaluate a proposed/hypothetical flight path change during flight	
Airspace Coordinator may use the system to:		
O-1	evaluate the flight path with respect to established rules and procedures	Figure 11
O-2	strategically deconflict the flight paths of client aircraft in the airspace	
Change events during flight cause the system to:		
E-1	respond to a discovered change in the operating environment	Figure 12
E-2	respond to a change in flight path constraint	
E-3	respond to a flight-specific trigger	
E-4	respond to an in-flight contingency event	
E-5	suspend dynamic path planning in deference to a higher-priority system	Not shown
E-6	resume dynamic path planning	
Temporal events during flight cause the system to:		
T-1	compute a more optimal/flexible path than the current path	Figure 13
T-2	plan a proactive response to anticipated contingency events	
T-3	monitor conformance of the flight against the intended flight path	
T-4	report health of system interfaces and modules	
DPP System Administrator uses the system to:		
A-1	configure system usage parameters, features, and interfaces before flight planning	Not shown
A-2	review health of the system interfaces and modules after flight completion	

Figure 8. Interactive users and automated events trigger dynamic path planning.

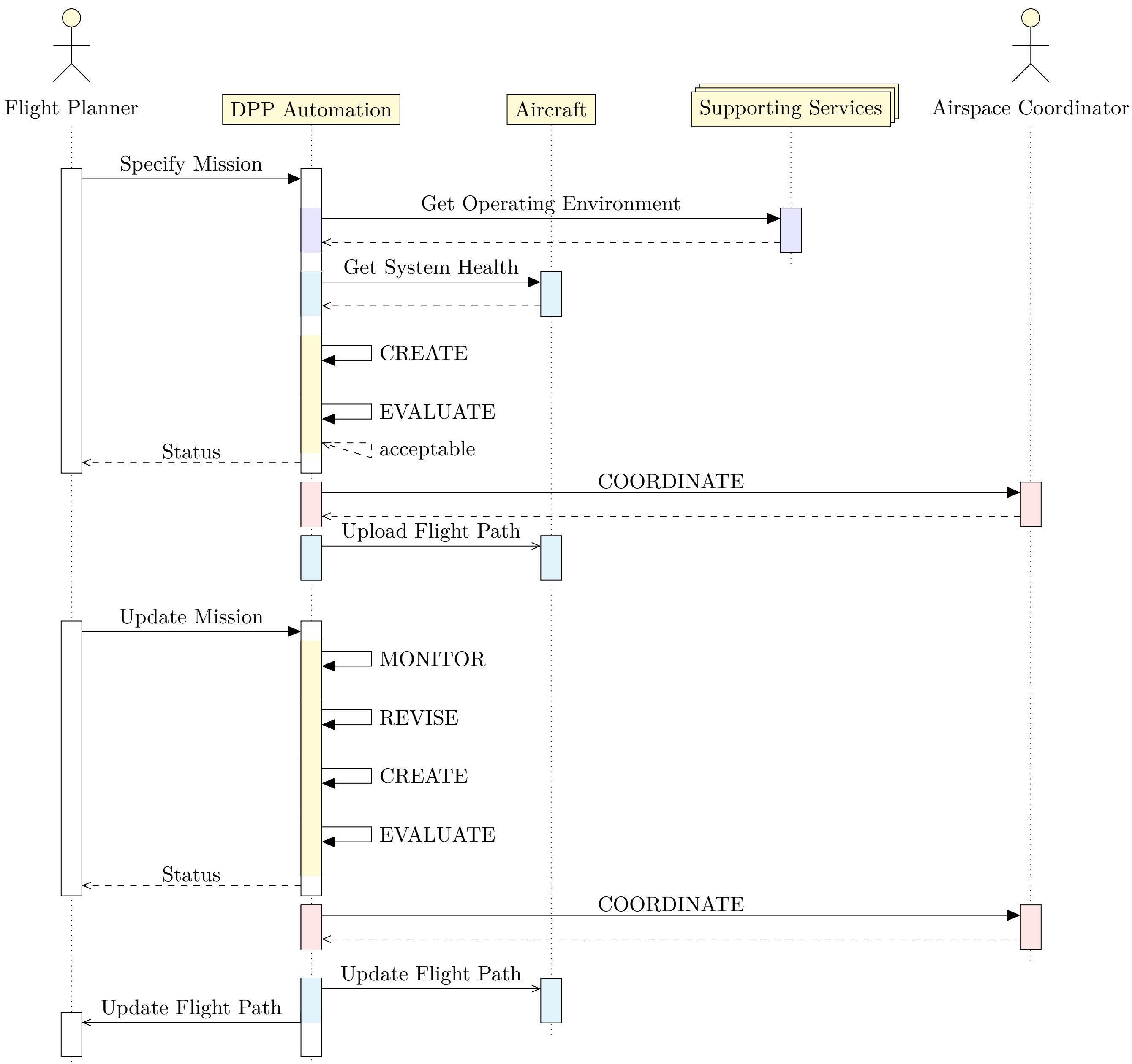

Figure 9. Flight planner plans (updates) a flight path to achieve a (revised) mission.

5.2 Pilot Scenarios

TRIGGER This scenario may be in response to one of several reasons. The pilot, when assuming the command of the flight, performs a sanity check to verify flight path acceptability. After departure, the pilot may inform the DPP automation system of a change to the mission, an observed hazard, or a potential emergency event due to aircraft and/or passenger health. The pilot may also want to use the system to evaluate the flight path qualities of a hypothetical flight path.

PRE The ground DPP automation system and the onboard DPP automation system are synchronized with the intended flight path that has been accepted by the flight planner and coordinated with the other airspace users. If needed, the DPP automation system has access to an airspace coordinator, either a person or an automated system, responsible for coordinating airspace resource utilization and operations among operators.

FLOW Figure 10 shows a sequence of activities outlining a pilot's use of the system. The pilot begins by performing a visual sanity check of the uploaded flight path based on experience. The system provides the contextual information to the pilot. Upon verification, the pilot activates the flight path in the system.

Once the system contains an active flight path, the pilot uses the system to manage the flight path. The DPP automation system is continually monitoring the input interfaces, including the pilot user interface. The pilot input may indicate a mission change, observance of an airspace hazard, or an onboard emergency due to a system failure or a distressed passenger. Based on the type of the detected change, the system revises the flight path construction parameters by applying the appropriate rules. The system then re-creates a candidate flight path, and evaluates its qualities. If the qualities are unacceptable, then the system iterates on the flight path construction parameters until a flight path achieves acceptable qualities. If the qualities are acceptable, then the flight path is communicated, upon pilot's approval, with an airspace coordinator for cross-check with other airspace and aerodrome users. Once confirmed, the system informs the pilot and updates the flight path in the automation system. Depending on the operational guidelines, a pilot may be required to confirm a request to coordinate with an airspace coordinator and also activate the new path manually for flight path execution.

The pilot may also instruct the system to evaluate a pilot-proposed change to the flight path. In that case, a candidate flight path is created and its qualities are evaluated as above. However, if the flight path qualities are unacceptable, then the flight path is not revised. Instead, the system alerts the pilot of the reasons for rejecting the proposed flight path change.

POST The pilot has accepted the planned flight path. The system has coordinated the flight path with an airspace coordinator. The flight is en route to its destination.

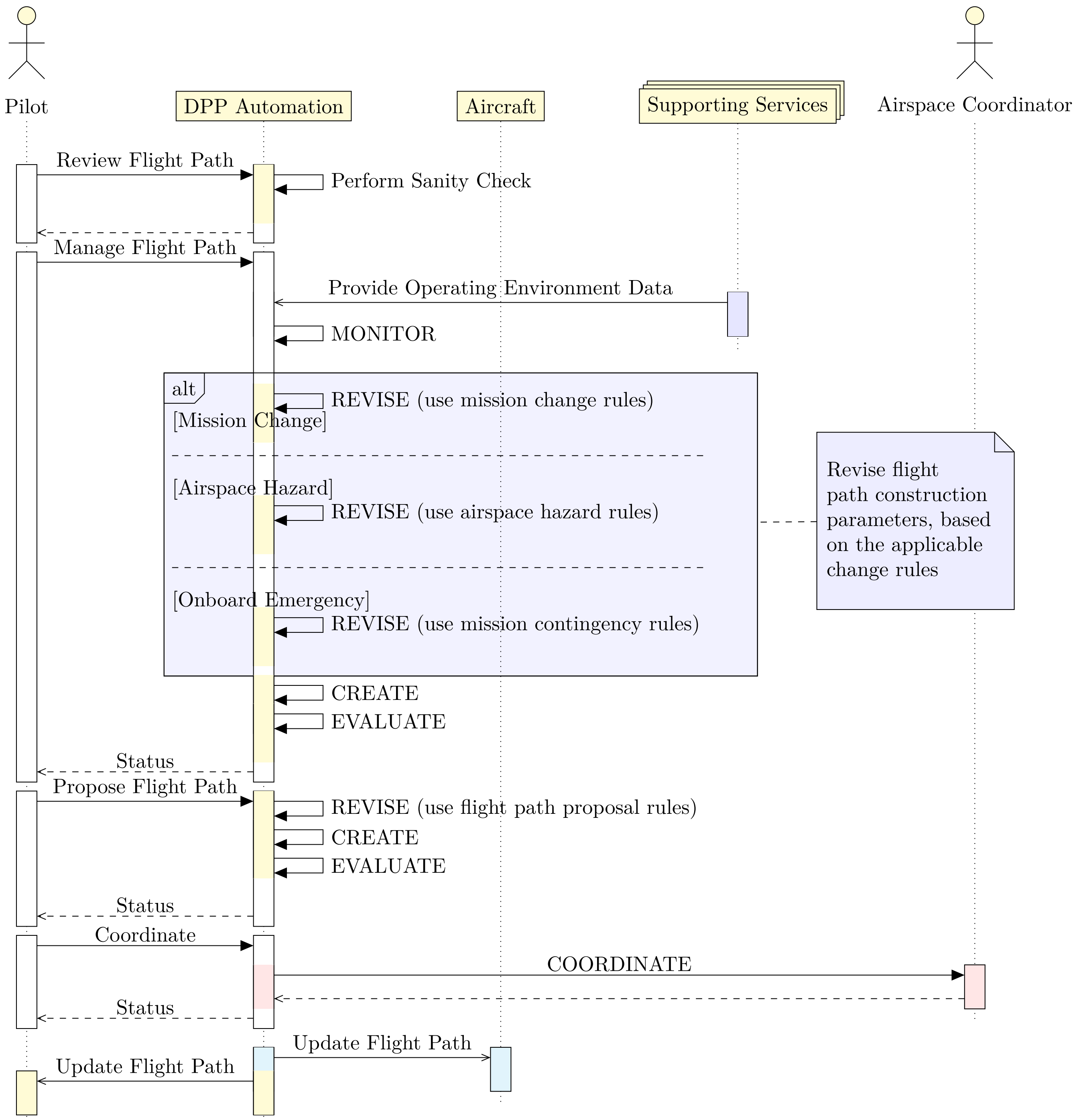

Figure 10. Pilot reviews, manages, and evaluates flight path and flight path changes.

5.3 Airspace Coordinator Scenarios

TRIGGER The airspace coordinator receives a request to coordinate an intended flight path with airspace users. The airspace coordinator decides to use the DPP automation system to determine if the requested flight path is deconflicted against expected traffic in the airspace and harmonized with respect to airspace rules and aerodrome procedures.

PRE The airspace coordinator has access to the operational intent of the current and predicted traffic in the airspace and the aerodromes of interest.

FLOW Figure 11 shows a sequence of activities outlining an airspace coordinator's use of the system. The airspace coordinator continually receives the state and flight path information of all relevant aircraft in the airspace from traffic intent services. The airspace coordinator also receives the intended flight paths of the flights that are planned to be in the airspace from respective flight operators. The airspace coordinator's use of the DPP automation system begins upon receipt of a request to coordinate a flight path. The system acknowledges the receipt to the transmitting aircraft. The airspace coordinator uses the system to perform strategic deconfliction and to verify adherence of the flight path to airspace rules and aerodrome procedures. The process includes creating a flight path from the shared state and intent information, and evaluating a flight path's *deconfliction* and *harmonization* qualities. If the system is unable to create a flight path, then it alerts the airspace coordinator of failure to process the request. If the system detects a conflict, then it alerts the airspace coordinator of failure to confirm due to the conflict. If the system finds that the flight path violates airspace rules and/or aerodrome procedures, then it alerts the airspace coordinator of failure to confirm due to the conformance violation. If the system finds the flight path to be sufficiently deconflicted and in conformance with the airspace rules and aerodrome procedures, then it confirms the flight path.

POST The requested flight path has either been confirmed or the system has alerted the airspace coordinator of reasons behind non-confirmation. The airspace coordinator may then inform the requesting aircraft of the outcome manually or automatically, based on the operational concept in effect.

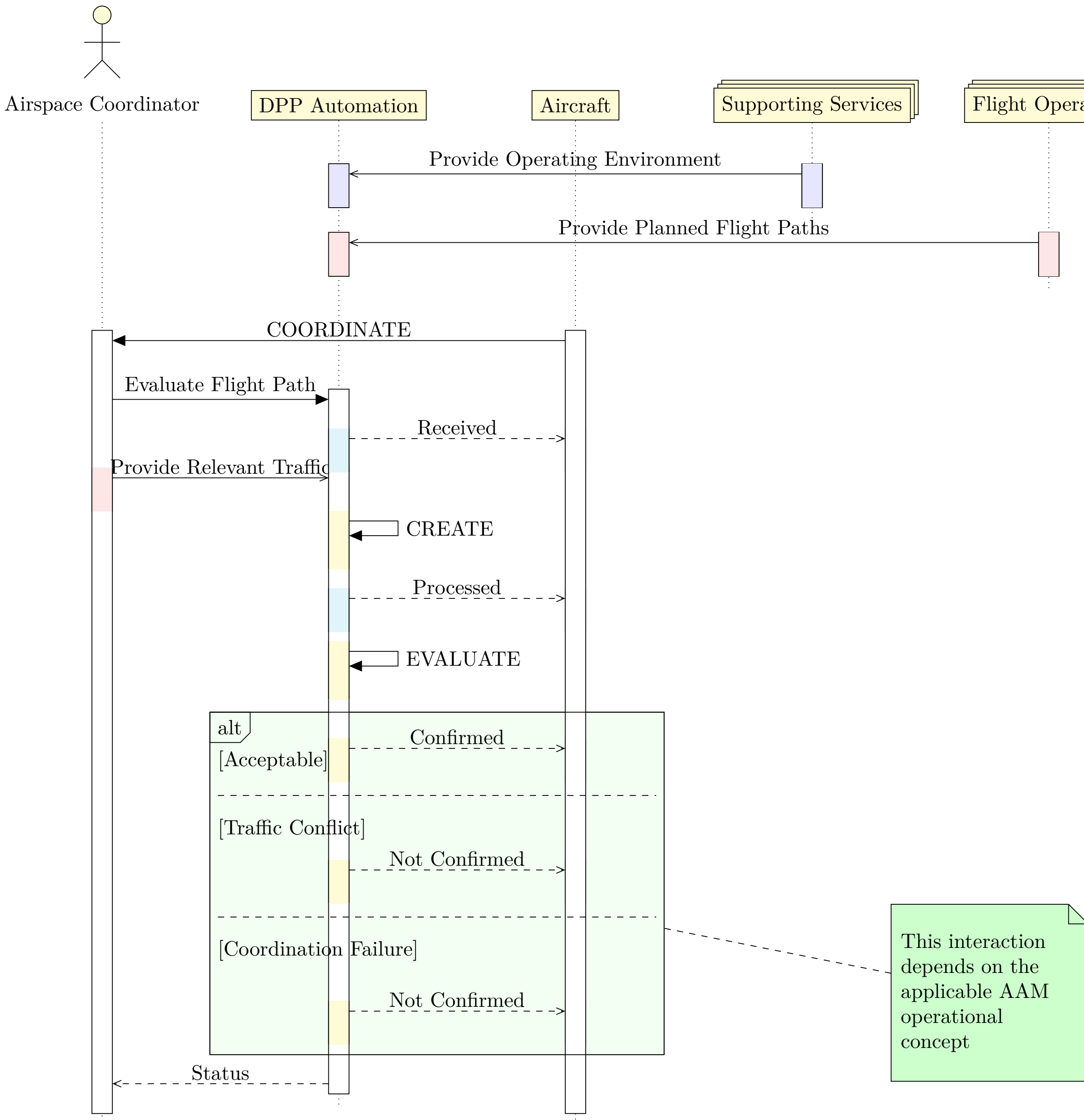

Figure 11. Airspace Coordinator coordinates flight path with airspace users.

5.4 Change Event Scenarios

TRIGGER One of several events such as changes to the operating environment, changes to mission constraints, flight-specific events, and in-flight contingencies, has occurred to cause the DPP automation system to execute automatically one or more of its functions.

PRE An acceptable flight path exists in the DPP automation system. If needed, the system has access to services which provide the operating environment information. The system also has access to an airspace coordinator, either a person or an automated system, responsible for coordinating airspace resource utilization and operations among operators.

FLOW Figure 12 shows a sequence of activities outlining events which trigger dynamic path planning automatically. Such events include changes to the operating environment, updated mission constraints, flight-specific events, and in-flight contingencies. The DPP automation system is continually monitoring its input interfaces for these events. The system may receive changes to the operating environment, i.e., traffic aircraft, atmospheric conditions, airspace restrictions, obstacles, and aerodrome conditions, from respective services. A fleet operator or a remote pilot may assign an updated mission constraint, e.g., a new required time of arrival (RTA), a different cruise speed, to the flight path. The aircraft may alert the system of a flight path contingency. The system is also monitoring the aircraft state to identify triggers related to a set of predefined flight conditions, e.g., reaching the initial cruise altitude, transitioning between propulsion modes.

Based on the type of the detected change, the system revises the flight path construction parameters by applying appropriate rules. The system then re-creates a candidate flight path, and evaluates its qualities. If the qualities are unacceptable, then the system iterates on the flight path construction parameters until the flight path achieves acceptable qualities. If the qualities are acceptable, then the flight path is communicated, upon pilot's approval, with an airspace coordinator for cross-check with other airspace and aerodrome users. Once confirmed, the system informs the pilot and updates the flight path in the automation system. Depending on the operational guidelines, a pilot may be required to confirm a request to coordinate with an airspace coordinator and also activate the new path manually for flight path execution.

The system provides the flight path constraint status to the fleet operator.

POST The aircraft flight path execution system has a new active flight path which has been accepted by the pilot and has been coordinated with other airspace users.

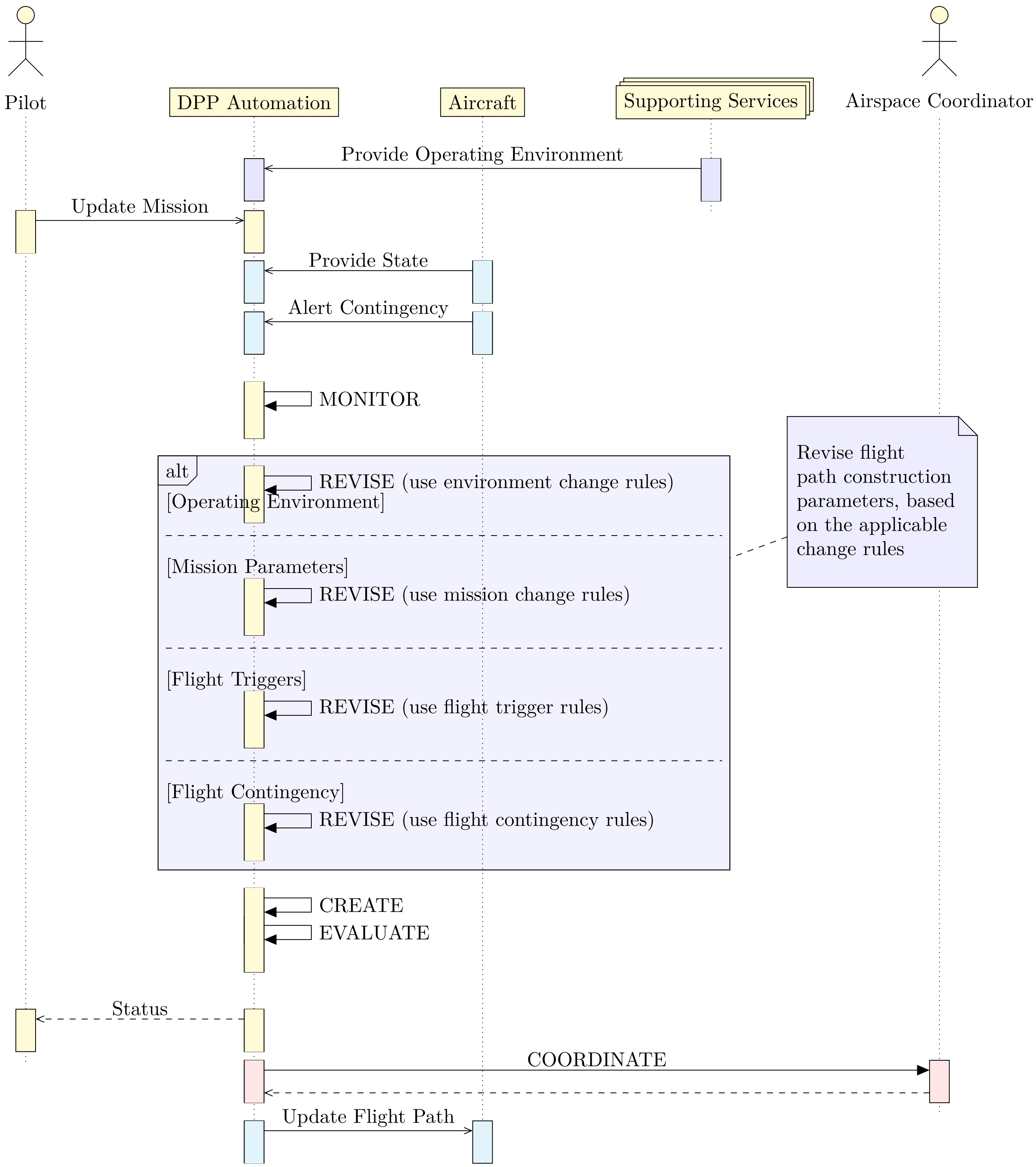

Figure 12. System responds automatically to external stimuli.

5.5 Temporal Event Scenarios

TRIGGER One of the user-defined intervals of time has elapsed since the last flight path evaluation.

PRE An acceptable flight path exists in the DPP automation system. If needed, the system has access to services which provide the operating environment information. The system also has access to an airspace coordinator, either a person or an automated system, responsible for coordinating airspace resource utilization and operations among operators.

FLOW Figure 13 shows a sequence of activities outlining periodic dynamic path planning. The DPP automation system refreshes the flight path periodically, in the process also reviewing proactively the best response to anticipated contingencies, e.g., unavailability of the planned destination aerodrome. The system reviews periodically the conformance of aircraft state and propulsive energy to the intended flight path and energy profile, respectively. The system reports the health of its components and interfaces to the user periodically. Note that the period of these periodic activities does not need to be the same. Periodic dynamic path planning is an important feature of the system in cases where none of the system users has interacted with the system and none of the event triggers has caused the system to review the active flight path for a certain period of time.

The process of periodic dynamic path planning begins when the system, monitoring the aircraft clock, determines that it is time to refresh the flight path. Note that the construction parameters may need to be revised if the aircraft is out of conformance with its intent. In that case, the system may be configured to alert the pilot, the airspace coordinator and the ground component of the DPP automation. The system creates a new flight path using the latest flight path construction parameters, and evaluates its qualities. If the flight path qualities show improvement and the pilot accepts, then the candidate flight path is communicated to an airspace coordinator for confirmation. Once confirmed, the system informs the pilot and updates the flight path in the automation system. Depending on the operational guidelines, a pilot may be required to confirm a request to coordinate with an airspace coordinator and also activate the new path manually for flight path execution.

POST The aircraft flight path execution system has a new active flight path which has been accepted by the pilot and has been coordinated with other airspace users.

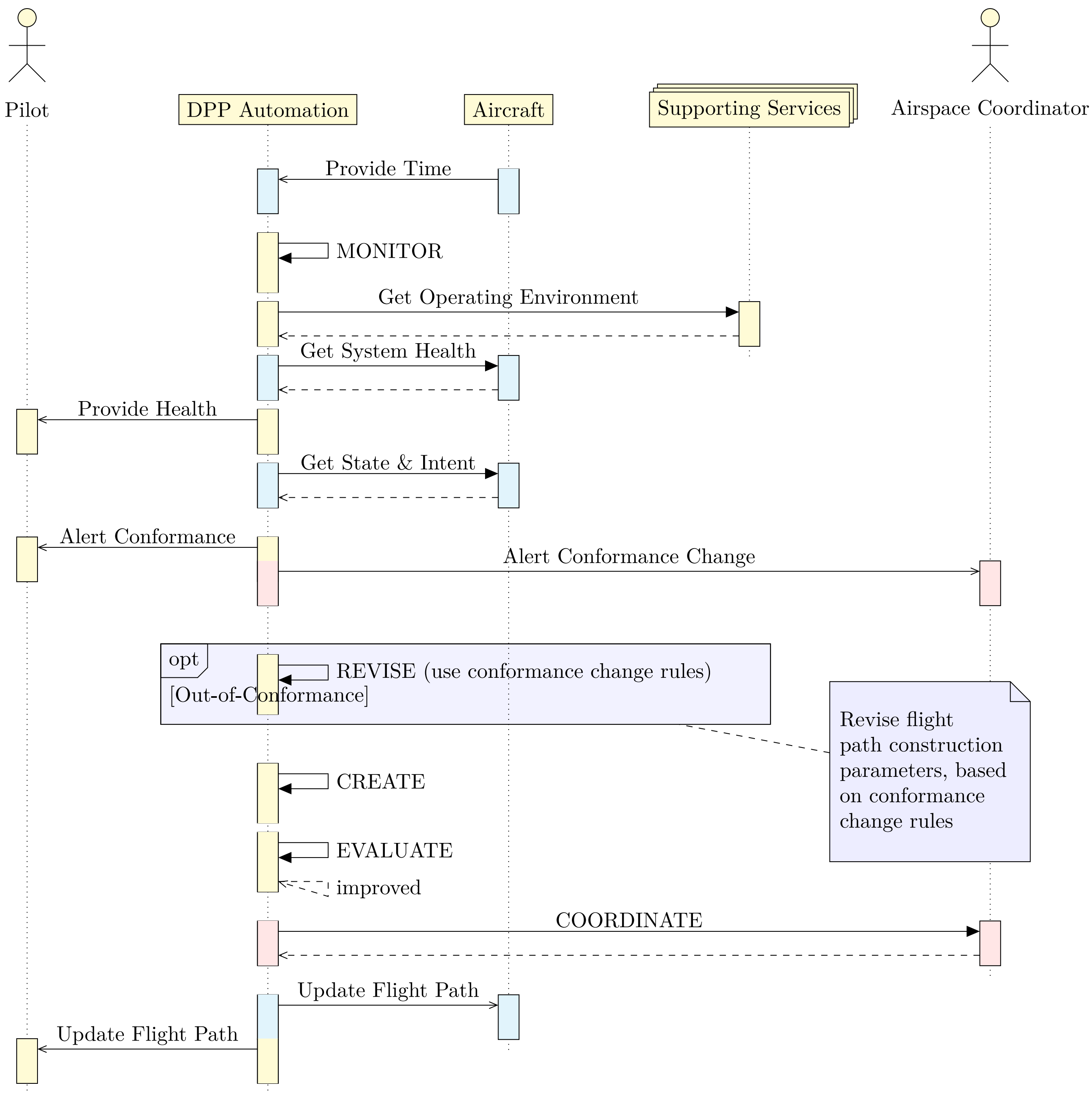

Figure 13. System refreshes flight path and provides health information periodically.

6 Conclusion

The concept of a dynamic path planning automation system is introduced in support of future Advanced Air Mobility flight operations. The DPP automation system provides the AAM users with the capability to create, monitor, evaluate, revise, and coordinate flight paths dynamically in response to the evolving operating environment throughout the flight. The system strives to ensure that these flight paths are feasible, deconflicted, harmonized, flexible, and optimal to best suit cooperative operations in the airspace. System users, external interfaces, key capabilities, and a high level process are described, which serve as the foundation for a conceptual architecture. A series of operational scenarios describe the various ways in which interactive users and automated triggers use the system to achieve the objectives of dynamic path planning. The concept allows for the DPP automation system to be installed onboard the aircraft as well as on the ground. The system ensures that a safe and operationally acceptable flight path is available throughout the flight.

In future work, NASA aims to leverage the proposed concept to architect and design a reference DPP automation system, in support of the verification and validation of AAM concepts related to flight path management. The system architecture will offer guidance to the industry, certification authorities, and service providers in establishing best design practices, community standards, and means of compliance recommendations. This concept document, as well as the ensuing architecture and design documents, will also further the AAM operators' understanding of the automation capabilities that will be required to operate safely, cooperatively, and efficiently in the increasingly complex AAM operating environment. The DPP concept will be used to study AAM contingency events, including their identification, classification, and resolution. The presented concept is applicable to flight operations both within and beyond the AAM operational environment, and will be used to study the impact of automation on such operations. NASA is also adapting DPP research capabilities developed originally for commercial transport operations to Urban Air Mobility operations.

References

[1] AIAA. *Guide to the Preparation of Operational Concept Documents*. Standard ISBN: 978-1-62410-548-7. American Institute of Aeronautics and Astronautics, Apr. 2018.

[2] FAA. *Urban Air Mobility and Advanced Air Mobility*. June 2021. URL: https://www.faa.gov/uas/advanced_operations/urban_air_mobility.

[3] Karr, David et al. "Initial Design Guidelines for Onboard Automation of Flight Path Management". AIAA-2021-2326. AIAA Aviation 2021 Forum. Aug. 2021.

[4] NASA. *Advanced Air Mobility Project*. Oct. 2021. URL: https://www.nasa.gov/aeroresearch/programs/iasp/aam/description/.

[5] National Academies of Sciences Engineering, and Medicine 2020. *Advancing Aerial Mobility: A National Blueprint*. ISBN 978-0-309-67026-5 | DOI 10.17226/25646. Washington, DC: The National Academies Press. URL: https://doi.org/10.17226/25646.

[6] Wing, David J and Levitt, Ian M. *New Flight Rules to Enable the Era of Aerial Mobility in the National Airspace System*. NASA/TM–20205008308, NASA Langley Research Center, Hampton, VA, Nov. 2020.

[7] Wing, David J et al. "Achieving resilient in-flight performance for advanced air mobility through simplified vehicle operations". AIAA-2020-2915. AIAA Aviation 2020 Forum. June 2020.

Appendix A

Abbreviations

AAM	Advanced Air Mobility
ATC	Air Traffic Control
DPP	Dynamic Path Planning
FAA	Federal Aviation Administration
IFR	Instrument Flight Rules
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
UAM	Urban Air Mobility
VFR	Visual Flight Rules

Appendix B

Glossary

Airspace Coordinator An entity, either human or an automated system, which provides coordination services among operators and aircraft in a geographic or otherwise operationally defined region. Services may include the exchange of intent information and cross-checking of submitted operational intents against those of other aircraft expected to be in the airspace. An airspace coordinator may also evaluate flight paths with respect to airspace and aerodrome rules and procedures.

Digital Flight A proposed mode of operations enabled by a set of cooperative procedures and digital technologies in which operators ensure flight path safety through highly-automated separation provision in lieu of visual procedures and Air Traffic Control separation services.

Dynamic Path Planning The process of building and maintaining a feasible, deconflicted, harmonized, flexible, and optimal flight path.

Fleet Operator The entity responsible for the flight planning and management of one or more aircraft in its fleet. When the meaning is clear from the context, the document uses the terms 'Fleet Operator' and 'AAM Operator' interchangeably, to refer to one or more of the flight planners, dispatchers, trackers, and mission managers.

Flight Path Qualities The *feasibility*, *deconfliction*, *harmonization*, *flexibility*, and *optimality* of a flight path.

- A *feasible* path is one that conforms to the aircraft performance and range capabilities; complies with the airspace structure, rules, and constraints; avoids the terrain and charted obstacles; and meets the arrival constraints.
- A *deconflicted* path is one that avoids unsafe proximity to known aircraft, dynamic obstacles, inclement weather, and other emergent airspace hazards.
- A *harmonized* path is one that follows cooperative rules and procedures to ensure that the use of the airspace is coordinated with other airspace users.
- A *flexible* path is one that provides adequate maneuverability to ensure future flight path changes, if needed, are available and feasible.
- An *optimal* path is one that best achieves the operator's business objectives for the specific flight.

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704–0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
01-09-2022	Technical Memorandum	

4. TITLE AND SUBTITLE
Dynamic Path Planning Automation Concept for Advanced Air Mobility

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Sharma, Vivek; Wing, David J.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, Virginia 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER
L–

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA/TM–20220009974

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category 64
Availability: NASA STI Program (757) 864-9658

13. SUPPLEMENTARY NOTES
An electronic version can be found at http://ntrs.nasa.gov.

14. ABSTRACT
Advanced Air Mobility (AAM) aims to develop an air transportation system for novel air vehicles between local, regional, intraregional, and urban places. Safety and efficiency of increasingly complex AAM operations are expected to require extensive use of automation, ranging from controlling the revolutionary new aircraft to managing flights dynamically in the high tempo airspace and aerodrome operations. Both onboard and ground automation will play central roles in assisting AAM operators with managing the flight paths of their fleet. This document presents a concept for dynamic path planning (DPP) automation applicable to AAM and other flight operations. The role of the DPP automation system is fivefold: (1) it creates a flight path with desired qualities of being feasible, deconflicted, harmonized, flexible, and optimal; (2) it monitors the progress of flight in a dynamic operating environment; (3) it supports the user in evaluating continued acceptability of the flight path in changing conditions; (4) it revises the flight path as needed to maintain the desired flight path qualities; and (5) it coordinates the flight path with airspace users and service providers. Key users of the DPP automation system include flight planners, pilots, and airspace service providers. The concept allows for the system to be installed onboard the aircraft as well as on the ground. The system responds automatically to the dynamic operating environment to ensure that a safe and operationally acceptable flight path is available throughout the flight.

15. SUBJECT TERMS
Advanced Air Mobility, AAM, UAM, Flight Planning, Dynamic Routes

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			STI Information Desk (help@sti.nasa.gov)
					19b. TELEPHONE NUMBER ***(Include area code)***
U	U	U	UU	47	(757) 864-9658