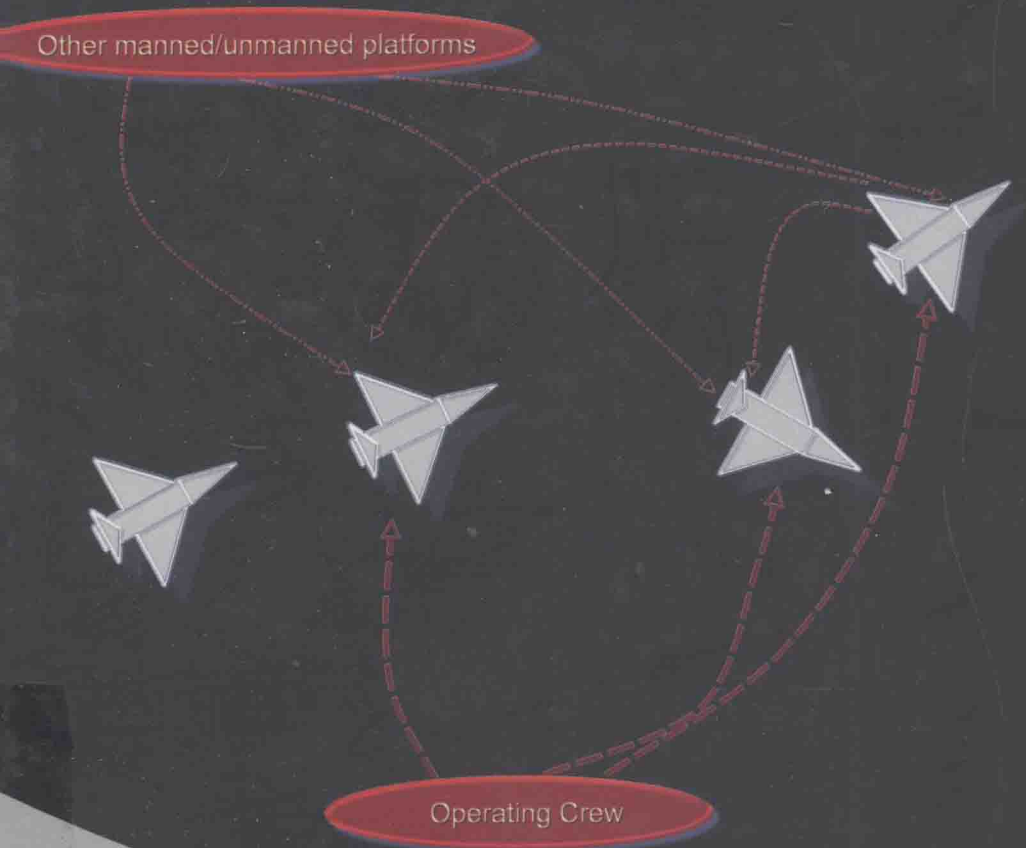
Safety and Reliability in Cooperating Unmanned Aerial Systems

C. A. Rabbath • N. Léchevin



World Scientific

Safety and Reliability in Cooperating Unmanned Aerial Systems

Camille Alain Rabbath
Nicolas Léchevin
Defence R&D Canada - Valcartier

World Scientific

NEW JERSEY • LONDON • SINGAPORE • BEIJING • SHANGHAI • HONG KONG • TAIPEI • CHENNAI

Published by

World Scientific Publishing Co. Pte. Ltd.
5 Toh Tuck Link, Singapore 596224
USA office: 27 Warren Street, Suite 401-402, Hackensack, NJ 07601
UK office: 57 Shelton Street, Covent Garden, London WC2H 9HE

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

SAFETY AND RELIABILITY IN COOPERATING UNMANNED AERIAL SYSTEMS

ISBN-13 978-981-283-699-1
ISBN-10 981-283-699-3

Printed in Singapore by Mainland Press Pte Ltd.

Safety and Reliability in Cooperating Unmanned Aerial Systems

Preface

The vision is clear: several unmanned aerial vehicles collaborate and coordinate their flight and actions to achieve a mission, while human operators, barely involved, monitor the progress of the vehicles. This vision is not yet a reality. Before multiple unmanned aerial vehicles are deployed in a coordinated fashion, novel systems must be devised. Among those, systems that ensure safe and reliable operations. Currently, a great many researchers are deploying every effort to design more effective multi-vehicle control concepts and algorithms. Furthermore, there exists a vast body of knowledge in fault-tolerant control, and in fault detection and fault recovery techniques for the individual aerial platform. Yet, very little has been said to date about how to perform reliable and safe autonomous multi-vehicle operations. Indeed, ensuring mission success despite off-nominal, or degraded, operations of mission-critical vehicle components is an open problem which has drawn attention only recently. Despite fault-tolerant control software and hardware embedded onboard air vehicles, overall fleet performance may still be degraded after the occurrence of anomalous events, such as systems malfunctions, damage and failures. As far as we are aware, this book is the first of its kind in presenting a set of basic principles and algorithms for the analysis and design of health management systems for cooperating unmanned aerial vehicles. Such systems rely upon monitoring and fault adaptation schemes. Cooperative health management systems seek to provide adaptation to the presence of faults, from a team perspective, by capitalizing on the availability of interconnected computing, sensing, and actuation resources. There is currently little literature on the safety and reliability for cooperating unmanned aerial systems, although the topic of cooperation for effective fleet monitoring and fault-adaptation purposes is emerging.

This monograph is the culmination of several years of research, and as such is biased with previous results obtained by the authors. We have our own view on the problem of health management, and have addressed a limited number of scenarios. This monograph presents the concepts in the form of theorems, lemmas, propositions, and step-by-step procedures. The health management concepts are illustrated by means of simple examples and numerical simulations of practical UAS operations. Cases of tight formation control and coordinated rendezvous for a network of formations are addressed in this book. Therefore, researchers, academics, graduate students and aerospace engineers, we hope, will appreciate the content.

We wish to thank Defence R&D Canada, and in particular Dr. Alexandre Jouan for his support of this initiative. The first author acknowledges the support of the Natural Sciences and Engineering Research Council of Canada (NSERC). The second author gratefully acknowledges the support of NSERC and the Department of National Defence of Canada in the form of a Visiting Fellowship. We would like to thank Quanser Inc. for providing experimental data to support the modeling of the ALTAV, in particular Drs Jacob Apkarian and Ernest Earon who have shown constant support of our ideas. We have indeed learned quite a lot from their vast knowledge of real-time control systems. We also had the pleasure of collaborating with several academic researchers in the areas of unmanned systems control and fault tolerance. In particular, we would like to thank Professor Youmin Zhang of Concordia University for the many discussions we had on the area of individual vehicle fault-tolerant control, thus improving our understanding of the issues and challenges in such field. We would like to thank Dr. Antonios Tsourdos and his team at Cranfield University (UK). We have had the honor of collaborating with Antonios for several years, which helped us learn more effective techniques of cooperative control, path planning, and guidance. The generous advices of Mr. Jean Bélanger, Dr. Dany Dionne and Professor Pierre Sicard of University of Québec at Trois-Rivières are also gratefully acknowledged. This book was written over a period of one year after working hours and during weekends. Hence, we would like to express our most sincere gratitude and warmful thanks to our families and friends for their support during this intense period of our lives.

C.A. Rabbath and N. Léchevin

Contents

Chapter 1

Introduction

To date, unmanned aerial vehicles, or UAVs, have been operated in real missions with various levels of autonomy [1, 2]. In the future, unmanned and joint manned-unmanned missions are likely to include cooperative sensor networks for search, rescue, and monitoring; collaborative indoor/outdoor surveillance and protection using small, miniature or micro UAVs [3, 4]; as well as cooperating networked unmanned combat aerial vehicles (UCAVs) and weapons for engaging mobile targets in adversarial environments. Furthermore, UAV applications are expected to include firefighting, some level of policing, first-responder support in case of natural disasters, remote sensing, scientific research, and geographical surveying, to name a few. It is commonly acknowledged that the development of UAVs has been partly motivated by the desire to accomplish missions that are too "dull, dirty, or dangerous" for humans. However, there are still some challenging barriers to overcome before the futuristic vision of multiple UAVs, UCAVs and weapons operating cooperatively with other manned vehicles can be realized.

Over the past few years, there has been significant interest in the design of systems that use multiple autonomous agents to cooperatively execute a mission [5–8]. One of the scientific and technological challenges of multi-vehicle control is ensuring efficiency and safety in a context in which the conditions of the vehicles, network and environment are changing, and are potentially abnormal. Under adverse conditions the capabilities of the vehicles may be reduced, compromising mission success and risking the safety of nearby civilian populations.

This book provides basic principles and algorithms for the design and the analysis of health management systems for missions involving cooperating unmanned systems, with the objective of addressing the realistic contingencies encountered in complex or hostile environments. The theory is complemented by case studies and examples of applications featuring small-scale unmanned vehicles, with emphasis on the modeling of realistic dynamics, implementation of algorithms and systems integration. Motivating this book is the fact that overall fleet performance can be degraded by anomalous events even when fault-tolerant control software and redundant (duplicate) hardware have been installed in air vehicles to increase reliability. For example, when severe body damage or actuator faults occur, a large difference between post-fault and pre-fault system dynamics may result in a significant reduction of control authority. The faulty vehicle is then no longer capable of performing its assigned task with the expected level of efficiency, and its role in the mission may need to be re-planned. Designed to enable teams to adapt to degraded operating conditions, cooperative health management (CHM) systems capitalize on the availability of various interconnected resources and on the sharing of key information among the networked entities with minimal involvement of the operating crew.

1.1 Unmanned Aerial Systems

There are several flight-critical components and systems for the UAVs: actuators, control surfaces, engines, sensors, flight computers, and communication devices. Together the platform with its systems and components form an unmanned aircraft system (UAS) [2]. Fig. 1.1 is a conceptual schematic of a typical UAS control system. The platform represents the vehicle body or UAV. The actuators usually consist of motors that drive control surfaces (ailerons, elevators, rudders, fins, canards), which in turn alter the aerodynamic characteristics of the platform. Servomotors are typically used with commercial-off-the-shelf (COTS) small-scale vehicles and radio-controlled aircraft. The actuation block in Fig. 1.1 can also include the propulsion system, which consists of engines and propellers. Sensors consist of inertial measurement unit (IMU) and inertial navigation system (INS) components, including rate gyros for roll, pitch and yaw motion, multi-axis accelerometers, digital compasses for directional information, pressure transducers for airspeed and altitude, ultrasonic range finders for measuring the distance to nearby objects, and electro-optical (EO) and infrared (IR) cameras. The guidance, navigation and control (GNC) system, the estimation/filtering system, and the health management (HM) scheme run on the flight computers. The transmitters and receivers (Tx/Rx) are

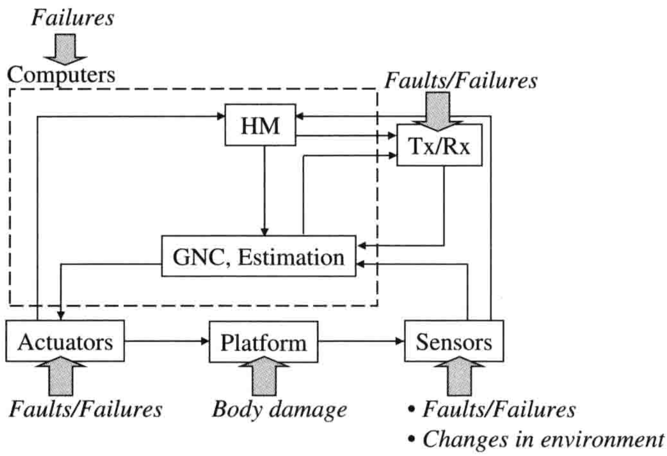


Fig. 1.1 Simplified schematics of UAS control system.

connected to the flight computers. Data obtained from Rx and the sensors are processed by the flight computers, which drive the actuators and the Tx to steer the vehicle accordingly and to transmit relevant information to the rest of the team and the operating crew.

Unmanned aircraft systems can be found in several sizes and exhibit various degrees of autonomy. A radio-controlled aircraft has the simplest level of autonomy, while an autonomous swarm exhibits the highest level of autonomy [9]. Increasing the autonomy of unmanned platforms could reduce the number of operators per vehicle, thus simplifying the task of the operating crew controlling vehicles involved in complex missions and potentially reducing costs. This book focuses on small-scale and miniature or micro UAVs, referred to respectively as SUAVs and MAVs [3, 9–16]. The acronyms UAV and UAS as used here refer to small-scale, miniature or micro unmanned aerial platforms with onboard and offboard systems dedicated to flight control and to accomplishing a mission. Briefly, these UAVs can fly close to the ground in confined areas and vary in size from a few meters to a few centimeters.

1.2 Cooperative Control

"Cooperative control" refers to a group of dynamic entities exchanging information to accomplish a common objective [17]. Cooperative control entails planning, coordination, and execution of a mission by two or more UAVs. A classical example of UAV cooperative control is formation flight. A typical formation includes a leader and a number of followers. Control schemes are usually designed to maintain the geometry of the formation. Followers try to maintain constant relative distances from neighboring vehicles, while the leader is responsible for trajectory tracking [18].

Why are safety and reliability of cooperating UAVs issues that need addressing? Removing the human from some of the flight control tasks and replacing him or her by software systems is a challenge that cannot be addressed without considering safety implications. When a number of UAVs are flying in formation, for example, their onboard systems establish their relative positions, speeds, and attitude by exchanging the necessary information via the communication network. Alternatively, they may use onboard proximity sensors. The onboard computers, namely the control systems, then use this information to produce a cohesive flight. Suppose one of the actuators of a UAV in the formation develops a fault. If the control system of the faulty UAV is not equipped with some form of robustness to fault or fault tolerance, or if the fault-tolerant control system is not capable of providing sufficient recovery to the fault, the vehicle may lose stability and exhibit an unpredictable pattern. As the control systems of the UAVs flying in formation aim at maintaining certain relative distances, velocities, and attitude at prescribed values under nominal conditions, the stability and cohesiveness of the formation may be lost. If their control systems are designed for nominal operating conditions, when the leader vehicle is at fault the follower vehicles will simply follow in its tracks without compensating for its erratic trajectory. Unless some sort of fault tolerance is embedded in the individual UAV GNC system and in the multi-UAV cooperative control system, the mission may be lost. Faulty aerial vehicles, and those naively following them, become inefficient in terms of energy consumption, fail to fulfil mission objectives, and represent a danger to humans.

Figures 1.2 and 1.3 illustrate two examples of cooperative control. In Fig. 1.2, a group of UAVs fly in a string-like formation. Cohesive group flight is ensured as follows: the control system of follower vehicle 1 (F1) acts to maintain a relative separation from the leader (L), and the control system of follower 2 (F2) does the same with respect to F1. Information flows from L to F1, and from F1 to F2. Information consists of d_L and v_L, representing relative distance and velocity between the leader and follower F1. This information is obtained through a communication network or from onboard proximity sensors and processing. The feedback control system onboard each vehicle uses inter-vehicle information exchange to compare relative distances and velocities and takes corrective action to maintain them at prescribed values. The bottom of Fig. 1.2 is a block diagram of the feedback loops showing the interdependence among the feedback control systems. The formation flight problem is discussed in more details in Chapter 3.

Figure 1.3 presents an example of cooperative control and decision making. Three formations of small UAVs plan their paths to coordinate rendezvous on three targets in a constrained and hostile environment. The grid represents the streets of a city. Starting from the base, the UAVs fly at low altitude and are thus constrained by nearby structures. The formations are shown at three time instants, from time t_1 to time t_3. A square represents a threat in the sense that the safety of a UAV is at risk along a path leg

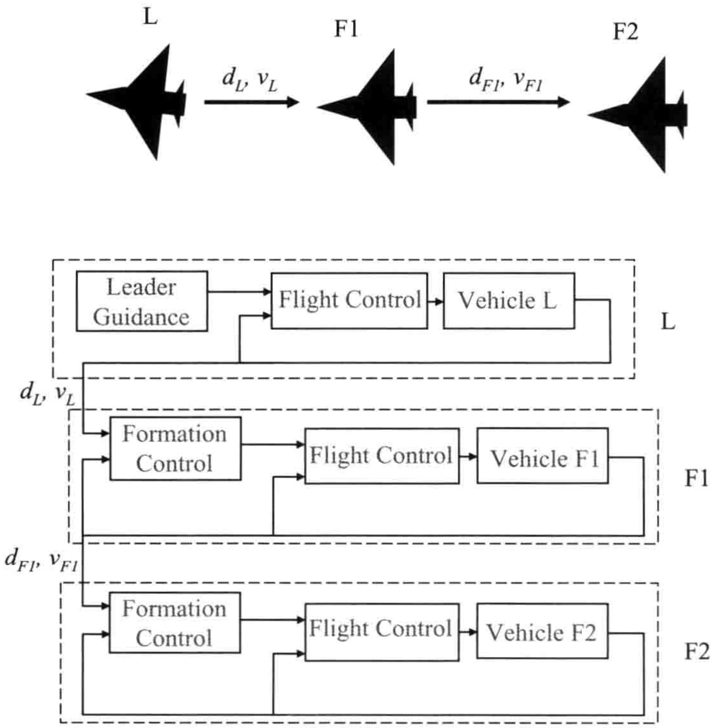


Fig. 1.2 Formation flight.

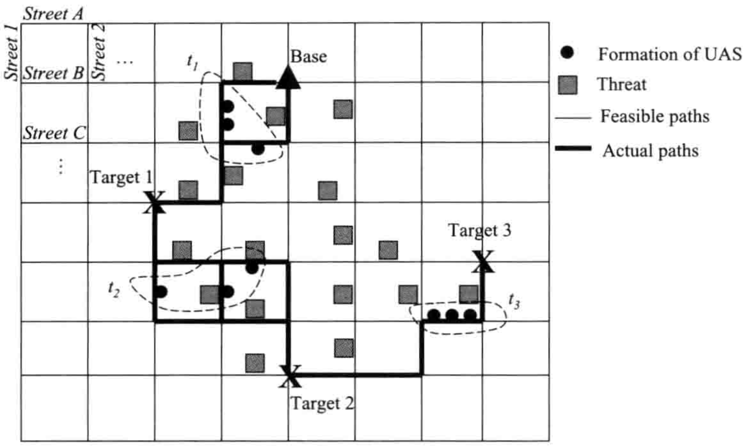


Fig. 1.3 Cooperative path planning and rendezvous.

comprising a square unit. These units may represent adverse environmental effects, danger zones, or obstacle-filled legs. At t_1, two formations follow the same path, at t_2, each formation follows a different path, and at t_3 all three formations follow the same path. At intersections, the formations have to decide which path leg to follow, taking into account the safety risks associated with each, the need to coordinate the rendezvous at each target, and the constraints on energy.

Decision making depends on solving the optimization problem of choosing routes that maximize the expected number of healthy vehicles at the targets and is based on the probabilities of loss associated with legs comprising threats. To do so, the cooperative control and decision making systems obtain information on the state of the formations via a communication network. The state includes the position of the formations, and the number of healthy vehicles remaining in the formations. The problem of cooperative control and decision making is discussed in Chapter 4.

1.3 Contingencies

During flight, a variety of events may affect the operation of UAVs. These include faults, or malfunctions, and failures, or complete breakdowns, in flight-critical components, platform damage, faults and failures in inter-vehicle information flow, anomalous behaviors or environmental occurrences such as bursts of wind, extreme weather, or icing on the airframe. Certain events are more likely to occur than others, depending on the context, and several different contingencies may be encountered concurrently. Furthermore, one contingency may lead to another. For example, cold weather may lead to control surfaces freezing and not responding as expected. Safe and reliable multi-UAV operations require systems that can handle such contingencies, as there are many off-nominal conditions that humans cannot handle in a timely and effective manner. It is not the purpose of this book to study ways of recovering from faults and failures affecting individual vehicle flight-critical components, software and systems. It is rather to present a number of UAV team cooperative monitoring and adaptation techniques and algorithms for a set of degraded conditions, building upon basic principles.

1.3.1 *Faults and failures of UAV components*

Faults and failures in UAV flight-critical components include those affecting sensors, actuators, flight computers, engine, and control surfaces. Faults in components in the control loop, as in Fig. 1.1, may compromise UAV flight. Such faults are known as component-level (CL) faults. This book considers actuator, control effector and sensor faults.

Common faults include the actuator or control effector getting stuck in a certain position and not responding to commands, the actuator having lost its authority, the actuator or control effector moving to its upper or lower limit, and the gain of the actuator becoming a fraction of its nominal value [19, 20]. For example, if the control surfaces of a fixed-wing UAV (such as the aileron, rudder or elevator) get stuck, they may stop responding to actuator commands or may only partially respond to commands. The consequence of a control surface fault is reduced performance and possibly instability, depending on the effectiveness of the health management system. A fault is distinct from a failure in that a fault is a malfunction, whereas a failure suggests complete breakdown of a system component or function [21].

Sensors in the UAV feedback loop in Fig. 1.1 are subject to both hard-over failures, which are catastrophic but relatively easy to detect, and soft failures, which are difficult to detect but nonetheless critical [22]. Hard-over failures are typically detected and identified by a sensor with built-in testing. Soft failures include a small bias in measurements, slow-drifting of measurements, a combination of the two, loss of accuracy, and freezing of the sensor to certain values [23]. For UAVs equipped with GPS receivers, examples of faults include jamming of GPS data (intentionally or not) and the multi-path effect of reflections causing delays. These in turn result in inaccurate positions, and can have important consequences in dense urban terrain [24]. Sensors used for vision feedback may also suffer from failures [25]. A fault in a sensor alters the measurements required by controllers, and depending on the severity of the fault, may degrade the closed-loop performance.

1.3.2 *Vehicle damage*

An environmental hazard may cause damage to a UAV in areas of high density. The impact of the damage on UAV performance depends on the severity of the damage and on the effectiveness of the health management system. The platform itself may be damaged as well as the flight-critical components and systems. The partial destruction of an actuator, sensor or flight computer during flight may be interpreted as a CL fault.

In the case of a fixed-wing UAV, for example, control surface damage can change the dynamics, translating in a modified control input-to-state matrix and as an additional nonlinear term representing asymmetrical postdamage dynamics [19, 26]. If the dynamics of the vehicle are radically changed, the control system may need to employ online system identification and adaptation techniques and re-allocate the control effort to the remaining control surfaces to preserve a certain level of performance. Reference [27] proposes to model the body damage of an airship-type UAV as a change in the buoyancy force.

1.3.3 *Information flow faults*

Inter-vehicle communications are needed in any collaborative effort. Mobile ad hoc networks enable wireless transmission of data in dynamic environments over radio waves. The topology of these computer networks may vary with time, with nodes joining and leaving the network depending on their distance from one another. IEEE 802.11 standards are widely used with off-the-shelf computer network technology. Each UAV can be viewed as a node equipped with wireless Tx/Rx capable of transmitting and receiving data packets to and from its neighbors. The wireless medium is, however, unreliable. Wireless communications are subject to environmental intrusions that interfere with the signals and block their paths, introducing