Chapter 1

Introduction

1.1. Motivation

Multiple spacecraft/aircraft flight formation and coordination control are topics that have received a lot of attention over the past decades. Also, the new developments powered by technological advances have spurred a broad interest in autonomous vehicles. The explosion in computation and communication capabilities as well as the advent of miniaturization technologies has increased the interest in a wide variety of research communities, including robotics, communications, automatic control, etc. On the one hand, cooperative and coordinated behavior of a group of unmanned aerial vehicles can cover a larger operational area than a single autonomous vehicle. On the other hand, the lifting of heavy and/or large structures, underway replenishment (fuel, munitions, goods, and personal transfer from one ship to another while under way) and aerial refueling are operations in which coordination is highly required. Thus, the main motivation of this work can be found in the wide variety of applications of multiautonomous vehicle systems such as in the following examples:

Formation flying have been used in survey operations, homeland security, etc. During World War II the groups of B-17 bombers used to fly in a close formation and be escorted by P-51 Mustang fighters also flying in formation to gain better protection as a group. Piloting for many hours in a close formation and under the enemy fire has been proven to be tiring and stressful. Current fighters and bombers fly much faster than those during WWII which may increase the stress and induce nerve-racking

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experiences on pilots. In Figure 1.1 a group of nine aircraft is shown doing a fly pass during the French Bastille Day Military Parade.

Figure 1.1. *Aircraft formation flying*

Heavy and/or large load transportation vehicles such as the Helistat and the Skyhook projects that combine features of a blimp and a quadrotor helicopter. The Helistat was planned to be capable of carrying big loads for the US Forest Service. It consisted of a blimp and four Sikorsky Helicopters joined by a metallic structure. All the four helicopters were controlled by a human pilot. The Skyhook is planned to carry up to a 40 ton load with an operational range of 320 km without refueling. Figure 1.2 shows a virtual scene of a Skyhook carrying a heavy load in remote zone.

Figure 1.2. *SkyHook heavy lifter vehicle. Courtesy of SkyHook Intl. Inc.*

Aerial refueling is a task in which an aircraft (tanker) transfers fuel to another aircraft (receiver). This operation is used when an aircraft needs to take off with a greater payload of weapons, cargo, or personnel. It requires a good coordination between the tanker and the receiver. It is a fact of history that a rescue mission helicopter – UH-60L has made more than 20 attempts to make contact with a tanker with no success. This gives an insight into the difficulty and importance of this type of operation. Figure 1.3 shows a USAF KC-135R Stratotanker, two F-15s and two F-16s, on an aerial refueling operation.

Figure 1.3. *Aerial refueling of an F-15 Aircraft. Courtesy of the U.S. Air Force*

Spacecraft formation flying is an important project of the National Aeronautics and Space Administration (NASA) in its search for Earth-like planets. Figure 1.4 shows a virtual image of a scheme of multiple spacecraft formation. A spacecraft formation requires a tighter level of precision, slower displacements, and automated control rather than human control.

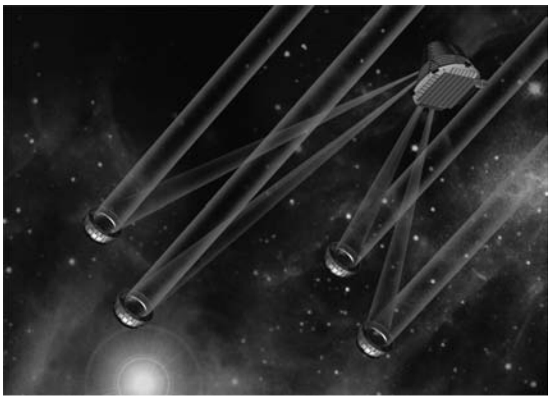

Figure 1.4. *NASA's formation flying for which the levels of precision are much tighter. Courtesy of NASA*

1.2. Historical background

Man's dream of flying can be traced back to ancient times and illustrated by Daedalus' wings made of feathers and wax in Greek mythology. However, the idea of a device capable of horizontal and/or vertical flight was first developed in China. They made the first steps toward flight around 400 BC with the Chinese "tops", a toy made of feathers at the end of a stick which may be considered as one of the first unmanned aerial vehicles (UAV). A UAV can be defined as an aircraft with no onboard human pilot that can be reused and capable of controlled flight, carrying a payload, etc. The UAV has been a feature of aviation history for many years. The origin of the UAV is closely related to cruise missiles; the main difference is that a UAV has been designed to be used in multiple missions and a cruise missile has been designed to destroy itself along with its target. Therefore, a cruise missile cannot be considered as a UAV, while a UAV can be considered as an evolved form of an almost autonomous aircraft.

1.2.1. *Aviation history*

Throughout time, man-made flying machines have been evolving in many different ways such as balloons, dirigibles, autogyros, helicopters, airplanes, etc. [NEW 04, AIA 09]. A timeline documenting the evolution of aviation is shown in Table 1.1.

Early in 1754, Mikhail Lomonosov built a mechanical spring-based device, shown in Figure 1.5, capable of vertical takeoff and hover for few moments.

Although, man has been flying for centuries, perhaps the most important advances in aviation started in 1900s when the Wright brothers first successfully flew their glider in 1902 (see Figure 1.6). The Wright brothers' glider was based on the work of Sir George Cayley and other pioneers of 19th Century aviation. Other pioneers of aviation working in parallel were Gustave Whitehead, Samuel P. Langley, Lyman Gilmore, Richard Pearse, among others. Most of the airplanes developed during the 20th Century were based on the successful glider of the Wright brothers.

Another interesting moment in aviation history is the first flight of a manned helicopter, known to have risen from the ground in France in 1907. The Cornu helicopter, shown in Figure 1.7, was an experimental helicopter developed by Paul Cornu, and it was reported to have made several short hops, rising no more than 2 meters.

However, the first successful rotorcraft was not a true helicopter but an autogyro developed by Juan de la Cierva in 1919. Later, Sikorsky introduced several helicopter configurations from the early 1930s to the present (see Figure 1.8).

Year	Vehicle name	Designer	Type	Country
400 BC	Chinese “tops”		Helicopter	China
1483	Aerial screw	Leonardo Da Vinci	Helicopter	Italy
1670	Lighter than air	Francesco Lana de Terzi	Balloon	Italy
1709	Lighter than air	Bartolomeu de Gusmao	Balloon	Portugal
1754	Prototype	M. Lomonosov	Helicopter	Russia
1783	Lighter than air	Montgolfier brothers	Balloon	France
1843	Prototype	Sir G. Cayley	Helicopter	UK
1856	L’Albatros artificiel	Jean-Marie Le Bris	Airplane type	France
1861	Prototype	Bright	Helicopter	
1874	Monoplane	Felix du Temple	Airplane	France
1878	Prototype	Forlanini	Helicopter	Italy
1884	Monoplane type	A. Mozhaysky	Airplane	Russia
1890	Eole	Clément Ader	Airplane	France
1902–1905	Glider	Wright brothers	Glider	USA
1907	Hopper	P. Cornu	Helicopter	France
1913	Albatros		Airplane	
1915	MS type L	Morane-Saulnier	Airplane	France
1917	Dr I Triplane	Fokker	Airplane	Germany
1920–1924	Prototype	Pescara	Helicopter	
1923–1935	C1–C30	Juan de la Cierva	Autogyro	Spain
1926–present	Vega, Sirius, etc.	Lockheed	Airplanes	USA
1939–present	S-1, etc.	Sikorsky	Helicopters	Russia

Table 1.1. *Aircraft evolution*

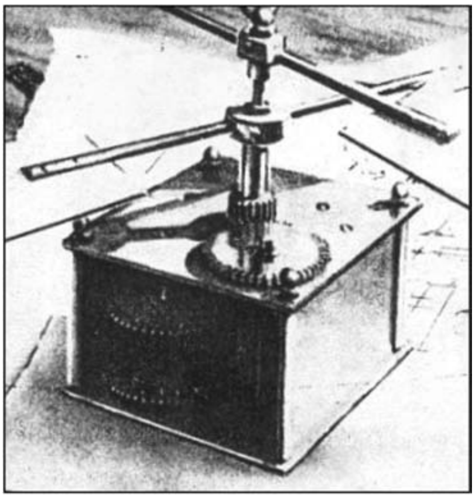

Figure 1.5. *Lomonosov’s helicopter. Courtesy of Aviastar [WOR 11]*

Figure 1.6. *Wright brothers first flight. Courtesy of Wikipedia [WIK 11c]*

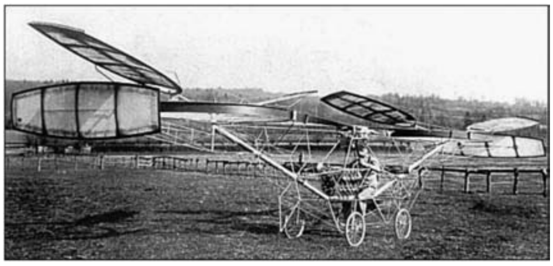

Figure 1.7. *Cornu's hopper*

Figure 1.8. *Sikorsky VS-300. Courtesy of Aviastar [WOR 11]*

During and after World War I (WWI) there was an explosion in helicopter and airplane development all around the world. A more recent type of aircraft is the tailsitter which is an aircraft capable of vertical takeoff and landing (VTOL) as well as being capable of flying as a classic airplane. After WWII, in 1951, Lockheed and Convair were awarded the contract by the US Army and the US Navy to build the XFV (also referred as "Salmon") and the XFY (also known as "Pogo"), tailsitters. Figure 1.9 shows a Convair XFY-1 tailsitter. This concept of VTOL was abandoned due to many design and operational problems, e.g. the pilot had to look over his shoulder to properly stabilize the aircraft for landing. Also, it is considered that the XFV and the XFY VTOLs did not contribute to the development of modern VTOLs. Nowadays, there are many efforts to improve actual designs of helicopters and airplanes, to make them more stable, more reliable, more comfortable, etc.

Figure 1.9. *Convair XFY "Pogo". Courtesy of Aviastar [WOR 11]*

The advent of new technologies and miniaturization have spurred the design and development of manned and unmanned aerial vehicles. Military and civil aviation stepped up the development and production of aircraft and helicopters. In civil applications, man-piloted aircraft systems have been used to transport people and cargo; unmanned aerial vehicles have been used mainly for surveillance. In military applications, UAVs have been used in a wide variety of missions such as target and decoy, reconnaissance, surveillance, etc.

1.2.2. *Evolution of UAVs*

The history of unmanned aerial vehicles began around 1849. On August 22, the Austrians attacked the Italian city of Venice using unmanned balloons loaded with explosives. The next important advance in this domain happened during and after WWI. In November 1917, the US Army started the project to build the Kettering Bug that first flew in 1918 (see Figure 1.10). This unmanned aircraft was intended to be used as an aerial torpedo against Zeppelins.

The first French UAV was designed, built and tested in 1923. In the 1930s, the UK and the US developed the Radioplane OQ-2, a small teleoperated airplane. The German army, in 1938, started the development of a radio-controlled antiship flying bomb. The German V1 unmanned airplanes, shown in Figure 1.11, and the V2 missiles were flying bombs rather than UAVs. However, the V1 wing has been a base model for target drones.

Figure 1.10. *Kettetring Bug. Courtesy of the National Museum of the US Air Force*

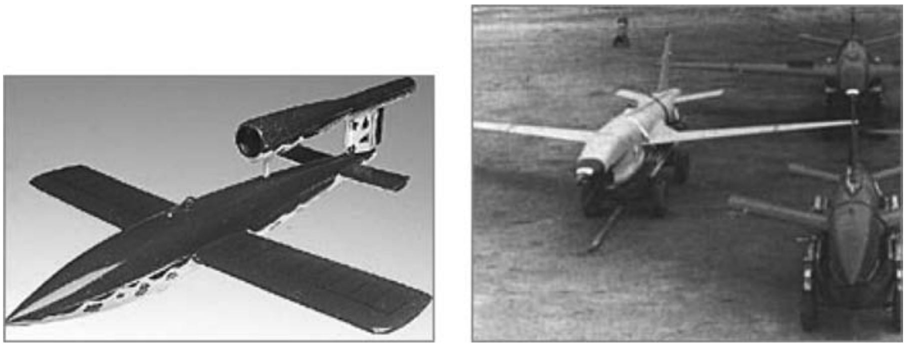

Figure 1.11. *German V1. Courtesy of Wikipedia [WIK 11b]*

During the Korean and Vietnam wars, the development of UAVs made important advances. The Ryan Firebee was a well-proven platform for a target drone that led to other missions such as reconnaissance UAV. A modified version of the Ryan Firebee, called the Ryan Model 147 Lightning Bug, was used as a reconnaissance UAV to spy on Vietnam, China, and North Korea in the late 1960s and early 1970s. During the late 1970s and throughout the 1980s, the Israeli Air Force, an aggressive UAV developer, pioneered several important new UAVs that have been integrated into the UAV fleets of many other countries.

In the late 1990s, the American UAV RQ-1A predator, shown in Figure 1.12, offered real-time video imagery without the danger of aircrew losses. The predator RQ-1L was used in the Balkans in 1995, Iraq in 1996, and it proved to be very effective. UAVs have been used especially in risky missions to collect intelligence information. More recently, the trend for battlefield UAVs had been emerging before the war in Afghanistan that began in 2001. An unmanned aerial system roadmap 2005–2030 has been published in [CAM 05].

Figure 1.12. *American RQ-1A Predator. Courtesy of Wikipedia [WIK 11a]*

1.2.3. *UAV classification*

UAV classification is usually determined by some criteria or features, e.g. use application, range, altitude, endurance, vehicle type, size, etc. We are interested in classifying UAVs due to their configuration as:

– fixed wing;

– rotary wing;

– free wing;

– tilt wing/rotor;

– tailsitter.

Based on this classification, we note that fixed wing conventional or hovering rotary-wing aircraft systems are the most commonly used vehicles. On the one hand, fixed wing conventional aircrafts have proven reliability, long flight time, and cruise efficiency, but they cannot hover or fly at low speeds. On the other hand, hovering platforms have the operational flexibility of being able to take off vertically, hover and land vertically, but they usually have limitations in forward flight, such as low speed and poor endurance. A relatively unexplored configuration is the tailsitter due to the awkward position of the pilot during takeoff, hover, and landing phases.

1.3. Flight control

Spacecrafts, aircrafts, and UAVs are dynamic systems that can be classified as underactuated mechanical systems. It is known that an underactuated mechanical system has fewer control inputs than degrees of freedom. Thus, the UAV represents an important challenge in automatic control. The UAV flight controller is designed to stabilize the altitude of an aircraft by holding a desired orientation and position. A flight controller also provides the means for an aircraft to navigate by tracking a desired trajectory. Different control techniques have been used to design flight controllers ranging from linear to nonlinear control algorithms.

In [HAU 92], an input–output linearization to stabilize a vertical/short takeoff and landing vehicle has been proposed. An extension and improvement of this work has been made in [MAR 96], in which the main idea was to find a flat output for the system.

In [BEN 96], a comparative analysis between different techniques has been presented. Here, the authors present techniques such as linearization, minimum phase, and sampled methods. Trajectory tracking for a Planar vertical takeoff and landing aircraft (PVTOL) has been also presented.

In [BOU 04], proportional-integral-derivative (PID) and linear-quadratic regulator (LQR) control schemes were used to control a mini rotorcraft with four rotors. A small experimental platform was developed and experimental results are provided. It is noted that the robustness of the control is not guaranteed against uncertainties and/or disturbances. In [BAR 07], a computer-vision-based algorithm is proposed and accomplished using several PID loops for altitude control.

In [MET 02], system identification modeling has been used to develop a parameterized model of a small helicopter. Unmodeled dynamics have been handled using an intuitive approach as in [GAV 01]. Also, robust control techniques have been used to stabilize small helicopters [LAC 03, MAR 02, LIN 99]. In [MET 02], a robust H_∞ loop-shaping controller has been developed and validated on an experimental helicopter platform performing a robust hover flight. In [MAR 02], an internal-model-based approach for autonomous landing of a VTOL vehicle on an oscillating landing platform on a ship has been presented. An internal-model-based error-feedback regulator has been developed ensuring the global convergence to the zero error manifold and the robustness against uncertainties affecting the system.

In the last decade, UAV altitude stabilization and autonomous hover using bounded input strategies were developed. Several nonlinear saturated flight controllers have been proposed in [FAN 02], [CAS 05], [LOZ 07], and [LOZ 03]. Nested saturations and saturated state techniques have been successfully implemented on real-time platforms to stabilize the PVTOL aircraft and mini rotorcrafts with four rotors.

Nonlinear methods such as sliding modes and backstepping have been proposed in [MAH 04], [OLF 01], [BOU 05], and [ISI 03]. In [ISI 03], a nonlinear adaptive output regulation and robust stabilization of system in feedforward form has been applied.

1.4. Flight formation control

Cooperative control and multiple spacecraft formation control have been intensively investigated during the past decades. Multiple spacecraft formation flying has been identified by NASA as an enabling technology for 21st Century missions such as terrestrial planet finding and deep space exploration. Multiple aerial, ground, or underwater vehicles working cooperatively or in coordination have important applications. The applications of multiautonomous vehicles is currently progressing in multiple fields, e.g. industrial, military, and in the study of biological systems. Missions for these type of systems include exploration and map building, military operations, traffic control, entertainment, biological systems, transport of heavy or large loads, search and rescue operations, surveillance, and aerospace and ocean exploration. In this section, a discussion of the different approaches that have been proposed in the literature for coordinating multiple robot systems is presented. In Scharf's survey [SCH 04], five approaches have been identified for spacecraft formation flying: multiple-input and multiple-output (MIMO), leader/follower, virtual structure, cyclic, and behavioral. In following sections, a state-of-the-art on multiple spacecraft formation flying is discussed.

1.4.1. *Multiple-input and multiple-output*

In the MIMO architecture, the formation problem is treated as a MIMO system where a dynamic model of the formation was used to develop a formation controller. MIMO approaches are described in [LAW 00], [HAD 00], [SMI 02], and [DUN 02]. In [HAD 00], an LQR controller is designed using a minimal state realization of the relative error states. In [DUN 02], a model predictive control was derived to solve the nonlinear and constrained model predictive control (MPC) problem for multiple vehicle formation to a set of equilibria.

1.4.2. *Leader/follower*

In the leader/follower architecture, one agent is designated as leader, while the others are designated as followers that should track the orientation and position of the leader with some offset. Leader/follower approaches are described in [HAD 98], [DES 98], [CHE 06], and [KRI 06]. In [CHE 06], an input-to-state stability (ISS) concept has been used as a tool to develop a formation control. In this approach, saturated controls enforce ISS of the dynamics, thereby avoiding the problem of dealing with locally asymptotically stable zero dynamics. In [HAD 98], an adaptive control strategy was developed considering the presence of constant, but unknown disturbances.

1.4.3. *Virtual structure*

The virtual structure approach considers every agent as an element of a larger structure [LEO 01, BEA 99, LAW 99]. Usually, the motion of the virtual structure is done through controlling the individual spacecrafts by tracking their reference trajectories. In [BEA 99], a constellation template was proposed to solve the problem of the coordinated motion of space-based interferometers. A constellation template is a virtual structure that defines the desired position and orientation of each spacecraft within the constellation. In [LAW 99], an adaptive control approach was adopted to design a controller that includes saturation constraints.

1.4.4. *Behavior-based control*

The behavioral control in [BAL 98] and [ARR 06] is based on the decomposition of the main control goal into tasks or behaviors. This approach also deals with behaviors such as collision avoidance, flock centering, obstacle avoidance, and barycenter. In [BEA 01], [TAN 03a], [TAN 03b], and [OLF 06], the authors have used algebraic graph theory in order to model the information exchange between vehicles. By using this technique, several control strategies have been developed. In [OLF 06], a coordination control composed of a velocity consensus term, a gradient-based term was proposed. The gradient term helps the cohesion of the group, while the velocity consensus term synchronizes the velocities of the agents. An extension of this approach to include navigational feedback has also been presented in [OLF 06]. The navigational term is used to change the orientation of the group or to move the formation to a given reference position. Ren [REN 07a] presents a new strategy for consensus in multiagent systems with a time-varying reference. Several cases are presented, such as: all agents have access to the reference, several agents have access to the reference, etc. The analysis presented assumes that agent dynamics are represented by a first-order integrator. A state of the art in consensus algorithms can be found in [REN 07b].

1.4.5. *Passivity-based control*

In [LEE 03] and [LEE 06], an analysis of multiple agent coordination using a passivity approach to decompose the system into two passive subsystems is presented. The first subsystem, called “shape”, maintains the formation of the group of agents, while the second subsystem, called “lock”, represents the translational dynamics of the group. In [LEE 06], the convergence of velocity and relative position of the agents via passive decomposition is shown. A bilateral teleoperation approach has been used in [HOK 07] to teleoperate a group of agents. The authors provide results to achieve a bilateral teleoperation one-to-many (i.e. one master and many slaves in a leader/follower architecture). The center of mass is used as a virtual master robot which is used to coordinate the slave robots. Trajectory tracking is also considered using an input to state stability analysis. Consensus algorithms allow the coordination of velocities and/or positions of multiple agents. They have been the object of extensive analysis and development [BEA 01, REN 07b, TAN 03a, TAN 03b]. Trajectory tracking of flocks has recently been studied in [REN 07a] and [HOK 07].

1.5. Outline of the book

Chapter 2: Theoretical Preliminaries

In this chapter, some useful results on passivity, graph theory, and robust control are presented. These results will be used through the first half of the book.

Chapter 3: Multiagent Coordination Strategies

In this chapter, a contribution to controllability and observability of multiagent systems is presented. Several approaches to velocity and position forced consensus are presented. It is shown that formation tracking to a time-varying reference can be achieved by using a feedback control based on the center of mass of the multiagent system.

Chapter 4: Robust Control Design for Multiagent Systems with Parametric Uncertainty

In this chapter, we develop an algorithm for robust control design for dynamical systems assuming parametric uncertainty and control input time delay. A robust absolute stability analysis is presented with application to multiagent systems.

Chapter 5: On Adaptive and Robust Controlled Synchronization of Networked Robotic Systems on Strongly Connected Graphs

In this chapter, a controlled synchronization of networked robotic systems communicating on strongly connected graphs is presented. Adaptive and robust tracking control algorithms are utilized to synchronize heterogeneous robotic systems (with dynamic uncertainty) while following a desired trajectory. The robustness of the control algorithms to constant delays in communication is also demonstrated.

Chapter 6: Modeling and Control of Mini UAV

In this chapter, we present the general dynamic model for mini UAVs considering the aerodynamic moments and forces. The dynamic model of two prototypes are developed, a bi-rotor tailsitter and a convertible quadrotor UAV are studied. The main contribution of this chapter is the modeling of two new designs of mini UAV, a tailsitter using variable pitch propellers and a convertible quadrotor using tilting rotors. The stabilization on vertical mode using linear and nonlinear control laws for stabilizing the attitude and position.

Chapter 7: Flight Formation Control Strategies for Mini UAVs

In this chapter, we introduce two approaches to flight formation control such as nested saturation based nonlinear control and high-order consensus nonlinear control.

Chapter 8: Formation Based on Potential Functions

In this chapter, we address a 2D formation control, using simple potential functions that generate the desired forces and a nested saturation controller to move the vehicles to their goal positions.

Chapter 9: Quadrotor Vision-Based Control

In this chapter, a vision-based control scheme for autonomous hovering and trajectory tracking of a miniature quadrotor is presented. Vanishing points techniques are used to estimate the rotation matrix and translation vector of the camera mounted on the quadrotor. These methods have been tested using real images. The analytic results are supported by experimental tests.

Chapter 10: Toward Vision-Based Coordination of Quadrotor Platoons

This chapter presents a vision-based scheme for position coordination of two camera-equipped quadrotors in hover flight. Applying a homography estimation technique, the aircrafts are capable of estimating their relative position with respect to their corresponding target. Simulations and real-time experiments illustrate the performance of this method.

Chapter 11: Optimal Guidance for Rotorcraft Platoon Formation Flying in Wind Fields

In this chapter, a time-optimal guidance for a platoon of rotorcraft flying in formation through a region of strong winds fields is presented. The main goal is to program the heading for the virtual center of mass in such way as to minimize the flight time between two-way points. The heading program is obtained by using a Zermelo navigation approach.

Chapter 12: Impact of Wireless Medium Access Protocol on the Quadrotor Formation Control

This chapter presents an overview of the medium access protocols' impact on the average consensus problem over wireless networks for a group of quadrotors. The analysis considers groups of quadrotors communicating over a wireless network considering both directed and undirected graphs of information flow.

Chapter 13: MAC Protocol for Wireless Communications

This chapter deals with the design of a wireless MAC protocol for UAV communication applications. A discussion on the protocols that define and control access to the wireless channel is provided. A new protocol based on carrier sense multiple access–code division multiple access (CSMA–CDMA) is presented.

Chapter 14: Optimization of a Scannable Pattern for Bidimensional Antenna Arrays to Provide Maximum Performance

This chapter presents an antenna array design for multirobot systems. The main objective of this chapter is to show the behavior of radiation for the design of antenna arrays in a uniform rectangular and concentric ring geometry, considering the optimization of a scannable pattern in a wide scanning range.

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