Unmanned Aerial Vehicles - Routing and Path Planning – Challenges and Trends

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- **Expertise:** telecommunications and computer networks architectures, technologies and services: network architectures and services, management/control/data plane, protocols, routing, 5G,6G, SDN, NFV, virtualization, QoS assurance, multimedia services over IP networks
- **Our UPB team:**
  - **Recent research interest :** Software Defined Networking (SDN), Network Function Virtualization (NFV), MEC/edge computing, 5G networking and slicing, vehicular communications, UAV, AI in 5G, 6G - management and control
  - **Partners in many research European** and bilateral projects in the above domains

- **Acknowledgement**

- This **overview text** and analysis is compiled and structured, based on several public documents, conferences material, studies, research papers, standards, projects, surveys, tutorials, etc. (see specific references in the text and Reference list).

  - The selection and structuring of the material belong to the author.

  - Given the extension of the topics, this **presentation is limited to a *high- level view only*. The list of topics discussed is also limited.**

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Unmanned Aerial Vehicles- Routing and Path Planning – Challenges and Trends

- **Motivation of this talk**
  - **UAV(drones)** - popular for many applications and services (civilian, military)
  - **Multiple UAVs** are **wirelessly interconnected** in ad hoc manner, composing UAV networks (**UAVNET**)
    - **FANET** acronym is also used for **Flying Adhoc Networks -** able to forward packets, gather, and share information

  - **UAVNETs** - **characteristics and needs different from traditional mobile ad hoc networks (MANET) and vehicular ad hoc networks (VANET)**
    - **large variety of applications and operational contexts**
    - **dynamic behavior, rapid mobility and topology changes (both: physical and logical)**
    - cooperation needed **: UAV-ground stations (GS), UAV-UAV, UAV- satellites,**
    - **3D Work space/ environment**, including space communications
      - Obstacle-avoiding trajectories
      - Real-time problems during flight
    - In some cases - **delay tolerant network (DTN)** – dedicated solutions to accommodate high delays and intermittent connectivity

  - **Need of new specific methods and technologies** for Data Plane and Management & Control (M&C) at different layers
    - Physical layer, MAC layer, **routing**, **path planning,** tracking, traffic engineering, cooperation, security, etc.
    - **UAV Routing and Path Planning– crucial topics in UAV area**

CONTENTS

1. Introduction

1.1 Unmanned Aerial Vehicles (UAV) (**drones**)

- **UAVs- popular solutions** for many applications (civilian, military domains)
  - objectives
    - surveillance, delivery, transportation in different fields, agriculture, forestry, environmental protection
    - **mission critical operations -** rescue/emergency, military domains, security

- **UAVs are wirelessly interconnected** in ad hoc manner → **UAVNET**

- The **communication technologies in** UAVNETs depend on applications
  - **Examples:**
    - **Outdoor** - a simple line of sight 1-to-1 link with continuous signal transmission E.g., Surveillance–UAVs can communicate through satellite communication links
    - **Satellite communication** - preferable solution - for security, defense, or more extensive outreach operations
    - **Civil and personal applications** - cellular communication technologies are preferred
    - **Indoor communication** - e.g. in mesh network and Wireless Sensor Network (WSN) - Bluetooth or point-to-point (P2P) protocols
    - **Communication to a multi-layered network** – complex process in UAV context

1. Introduction

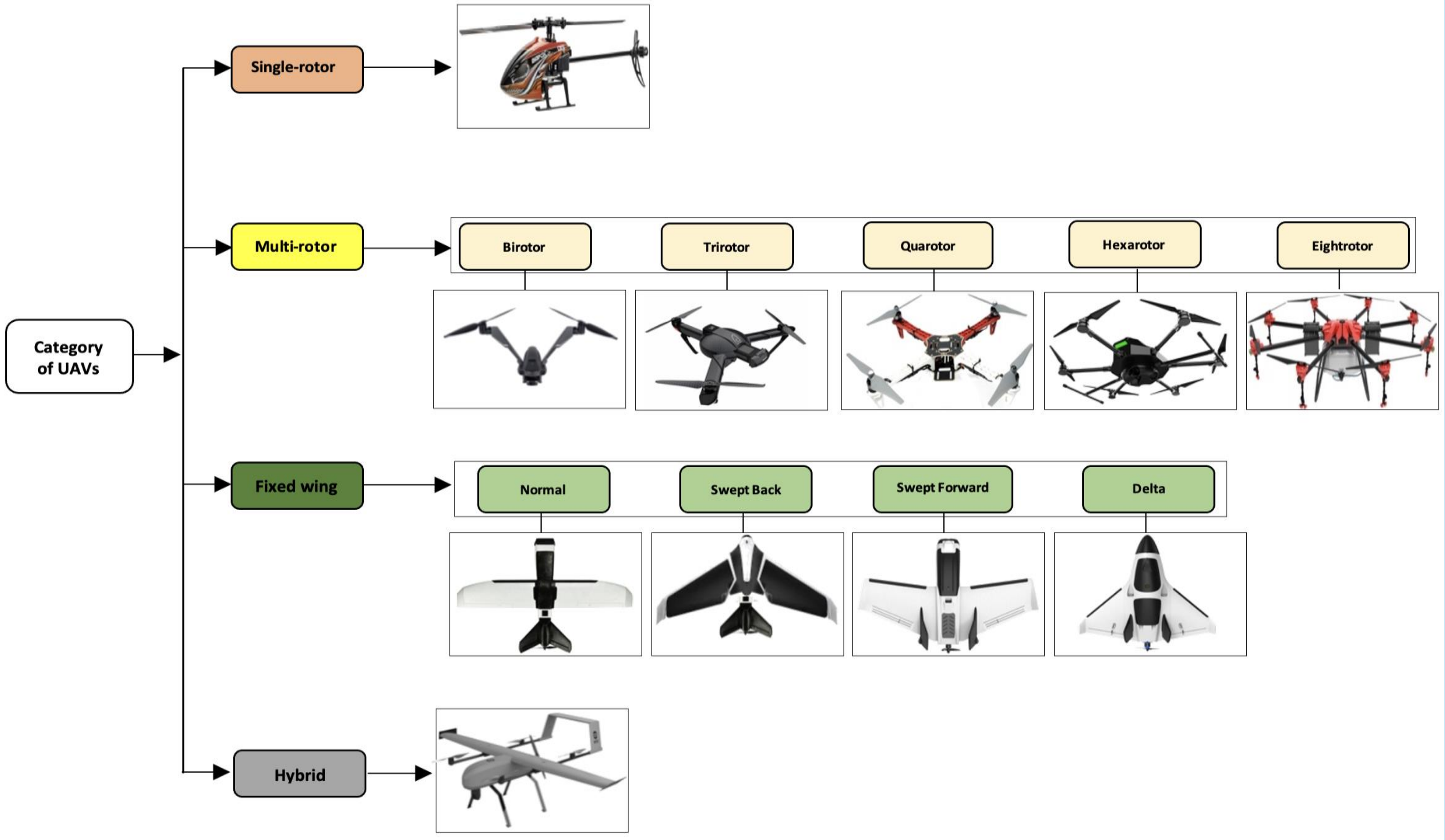
1.1 Unmanned Aerial Vehicles (UAV)

- **UAV Classification**- based on **different criteria** depending on UAV missions and distinguishing parameters
  - **Missions and applications**: civil and commercial UAVs - in agriculture, aerial photography, logistics, data collection, military missions
  - **Performance-related** characteristics: range, maximum altitude, aircraft weight, wingspan, wing loading, speed, endurance, cost design, and size
- **Engine type**: fuel engines and electric motors
- **Mechanical/physical characteristics**:
  - **weight** - *Micro*, *Light, Medium*, *Heavy*, and *Super Heavy* classes, spanning a range from under 5 kilograms to over 2 metric tons
  - **landing and takeoff capabilities**
    - VTOL (*Vertical Takeoff and Landing*) – no external support to takeoff and landing
    - HTOL (*Horizontal Takeoff and Landing*)- longer flight ranges, can carry larger payloads, but need external support
    - *Hybrid*- combines the capability of both VTOL and HTOL types
  - **flight range:** close, short, medium, and large endurance categories, spanning a range from under 10 to 1500 kms

1. Introduction

1.1 Unmanned Aerial Vehicles (UAV)

- **Different types of UAVs**

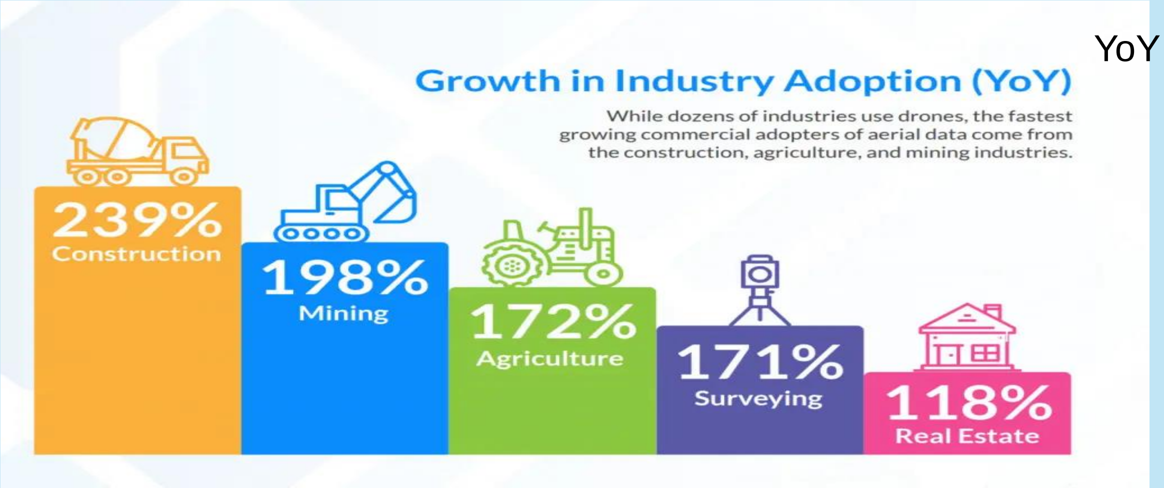


Source: W.Y.H. Adoni, S.Lorenz, J.S.Fareedh, R.Gloaguen and M.Bussmann, Investigation of Autonomous Multi-UAV Systems for Target Detection in Distributed Environment: Current Developments and Open Challenges, 2023, https://doi.org/10.3390/drones7040263

1. **Introduction**

1.2 UAV Applications examples

- **Individual, Business and Governments**
  - Express shipping and delivery, Unmanned cargo transport
  - Aerial photography for journalism and film
  - Disaster management: gathering information or supplying essentials
  - Storm tracking and forecasting hurricanes and tornadoes
  - Thermal sensor drones for search and rescue operations
  - Geographic mapping of inaccessible terrain and locations
  - Building safety inspections, Precision crop monitoring
  - Law enforcement and border control surveillance
  - **In progress: development of many other use cases**



YoY = Year-over-Year

Source: https://www.aonic.com/my/blogs-drone-technology/top-10-applications-of-drone-technology/

1. Introduction

1.2 UAV Applications examples

- **Delivery** Drones Technology
  - known as “last mile” delivery drones; deliveries from nearby retailers or warehouses
- **Emergency Public Rescue**
  - E.g., Disaster areas, Autonomous Underwater Vehicle (AUV)
- **Military domain**: thermal imaging, laser range finders, airstrike, surveillance, etc.

- **Agriculture:** field surveys, sowing across fields, tracking livestock, and predicting crop yields easier while saving workers’ important time
- UAV for **Outer Space**
- UAV for **Wildlife and Historical Conservation**
- **Medicine**
  - to transport/deliver medical supplies and goods in remote areas
  - to transport transplant organs to surgery locations
- **Drone for 3D Modeling creation**
  - LiDAR drones can be equipped with LiDAR sensors, which survey landscapes and collect detailed data that can be used to create 3D models
    - **Light Detection and Ranging** (LiDAR - a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth)
- Drone for **Photography**

Source: https://www.aonic.com/my/blogs-drone-technology/top-10-applications-of-drone-technology/

1. Introduction

1.3 UAV Networks

- **Single UAVs** frameworks have been utilized for quite a long time in many apps.
  - The UAVs are connected to either *ground base station (GS)* or connected with a satellite station for communication in star topology manners
- **Multi UAVs** systems actually, are **UAV networks**; no need to connect every UAV to GS

- **Multi UAV systems vs. single UAV**
  - **Advantages**
    - Scalability: higher and dynamically extensible coverage area (transmission range of a UAV -in meter units)
    - Stability, reliability: No single point of failure
    - Timewise efficient: faster response in completing a complex task
    - Sustainability: more sustainable than single UAV systems
    - Possibility to dynamically allocate/re-allocate subtasks
  - **Issues/challenges**
    - Cost of the more complex hardware used for communication with either the ground station or satellite can be higher
    - Complex management and control
    - Dynamic physical and logical topologies – due to high mobility: suynchronization and coordination problems

1. Introduction

1.3 UAV Networks

- **Inter-UAV wireless communication** is necessary in **UAV communication networks (UAVCN) ,** a.k.a. **flying ad hoc network (FANET)**
  - **Notation**
    - **UAV network = FANET= UAVCN drone ad hoc network**

- **MANET** = Mobile Adhoc Network; **VANET**= Vehicular Adhoc Network
- **FANET ⊆ VANET ⊆ MANET**

- **UAV networks** – characteristics different w.r.t. MANETs and VANETs
  - **dynamic behavior -** rapid mobility and topology (physical, logical) changes
  - **new challenges** for communication at: PHY layer, MAC layer, management and control, **routing and path planning,** traffic management, cooperation, security

- **UAS = UA System** = the entire system that supports and controls the UAVs

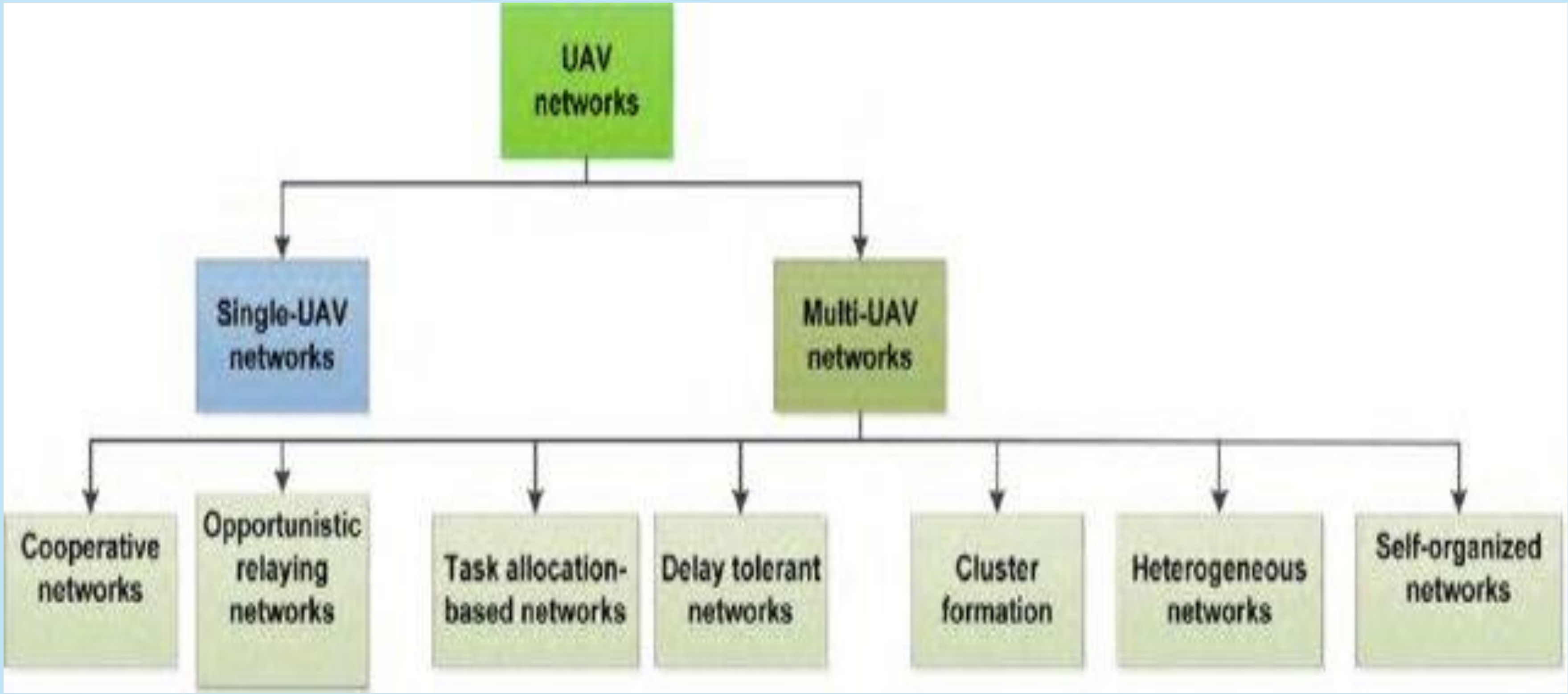
- Two **basic types** of UAVCN networks
  - **single-UAV network** - the UAV device is linked to a **ground base station (GS),** or to a satellite; each UAV acts as an *isolated node*
  - **multi-UAV network** – the UAV devices are linked
    - to each other (**U2U links**)
    - some of them are linked to the the **ground base station (U2G links), or satellite**

  - The network topologies are/can-be configured dynamically

1. Introduction

1.3 UAV Networks

- **Taxonomy of UAV networks**



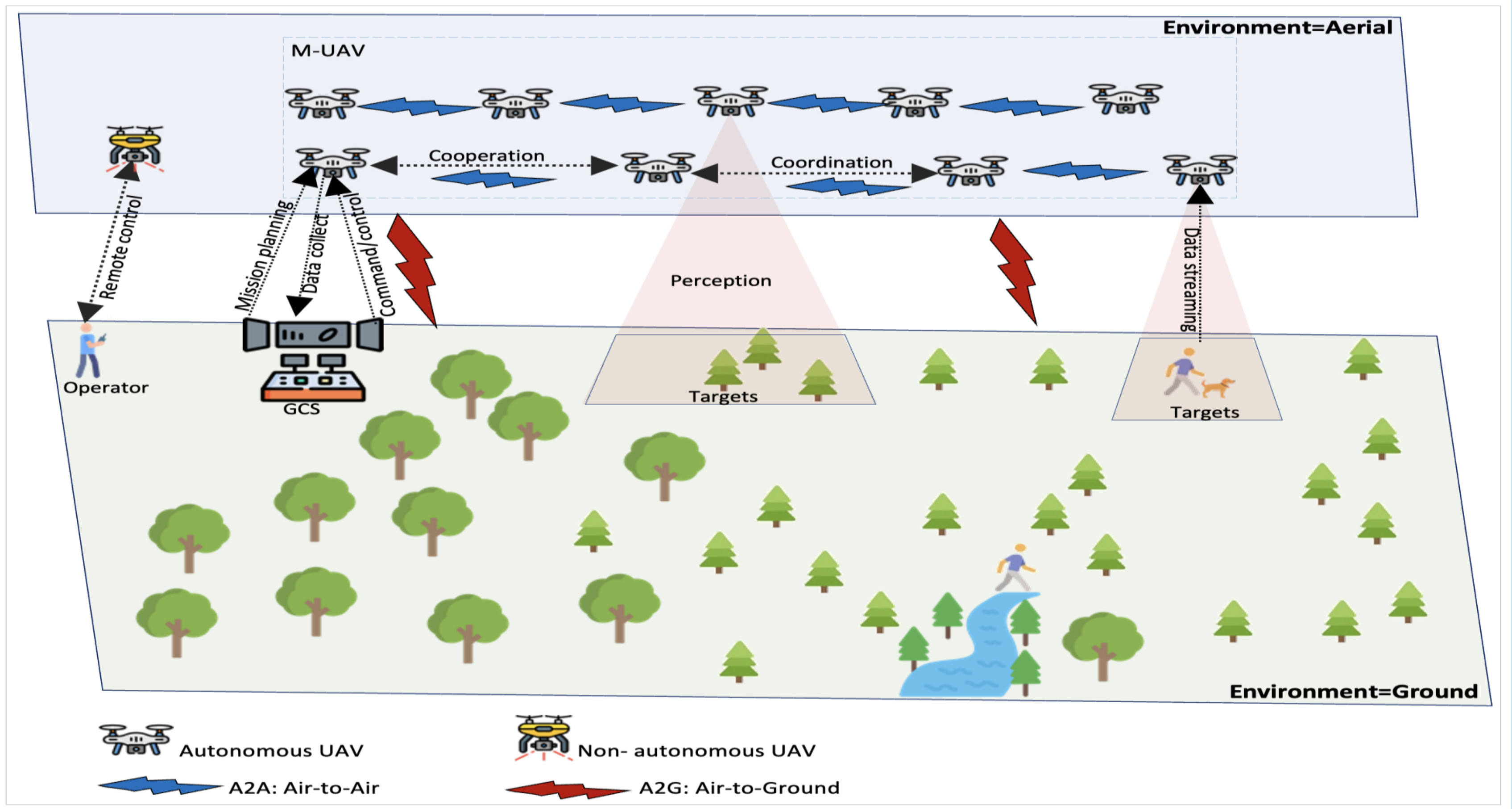
Source: M.Yeasir Arafat and S.Moh, Routing Protocols for Unmanned Aerial Vehicle Networks: A Survey, DOI 10.1109/ACCESS.2019.2930813, IEEE Access, 2019

1. Introduction

1.3 UAV Networks

- **Overview of a multi-UAV ecosystem**

GCS- Ground Control Station



Source: W.Y.H. Adoni, S.Lorenz, J.S.Fareedh, R.Gloaguen and M.Bussmann, Investigation of Autonomous Multi-UAV Systems for Target Detection in Distributed Environment: Current Developments and Open Challenges, 2023, https://doi.org/10.3390/drones7040263

1. **Introduction**

1.3 UAV Networks

- **Different views on UAV networks architectures**

- **Cooperative Multi-UAVs**

  - **Cooperative UAVs-based task achievement**
  - **(+)- advantages (-) -issues**

  - **Opportunistic relaying networks**
    - (+) Execute tasks based on **coordination**, support for dynamic network, **tolerant to link failures** (opportunistic transmissions), good utilization of network resources
    - (-) Use various estimations and approximations, **UAVs collision- problem**, **complex computations**, packet duplication, high energy consumption

  - **Delay-tolerant UAVs networks**
    - (+) Support **UAVs with limited power resources**, **store and forward** method can avoid the routing complexity
    - (-) **Low (intermittent) connectivity**, no E2E connectivity**, high latency**, issues with buffer and bandwidth capacity, security

Source: A.I.Hentati, L.C. Fourati, Comprehensive survey of UAVs communication networks, Computer Standards & Interfaces 72 (2020) 103451, www.elsevier.com/locate/csi

1. Introduction

1.3 UAV Networks

- **Different views on UAV networks architectures** (cont'd)

- **Multi-Layers UAV Networks**

  - **UAV swarms**
    - (+) Many UAVs in the large mission areas, few communications with GSs
      - They can cooperate to solve complex tasks
    - (-) UAV collisions, complex computations for coordination
  - **Ground WSN**
    - (+) Multiple/distributed data sources, available UAVs sensors, fast data collection
    - (-) Limited opportunities to communicate with sensors, limited trs. range
  - **Internet of Things (IoT)**
    - (+) Layered network architecture, fast aerial packets delivery, various applications and services, efficient traffic management
    - (-) Low UAVs energy, UAVs range limitations, UAVs landing restrictions, congestion in urban airspace
  - **Cooperation with Cloud Computing**
    - (+) UAVs offload heavy computations -> cloud data centers, remote computation and storage services
    - (-) Latency, UAVs range limitations, security issues

Source: A.I.Hentati, L.C. Fourati, Comprehensive survey of UAVs communication networks, Computer Standards & Interfaces 72 (2020) 103451, www.elsevier.com/locate/csi

1. Introduction

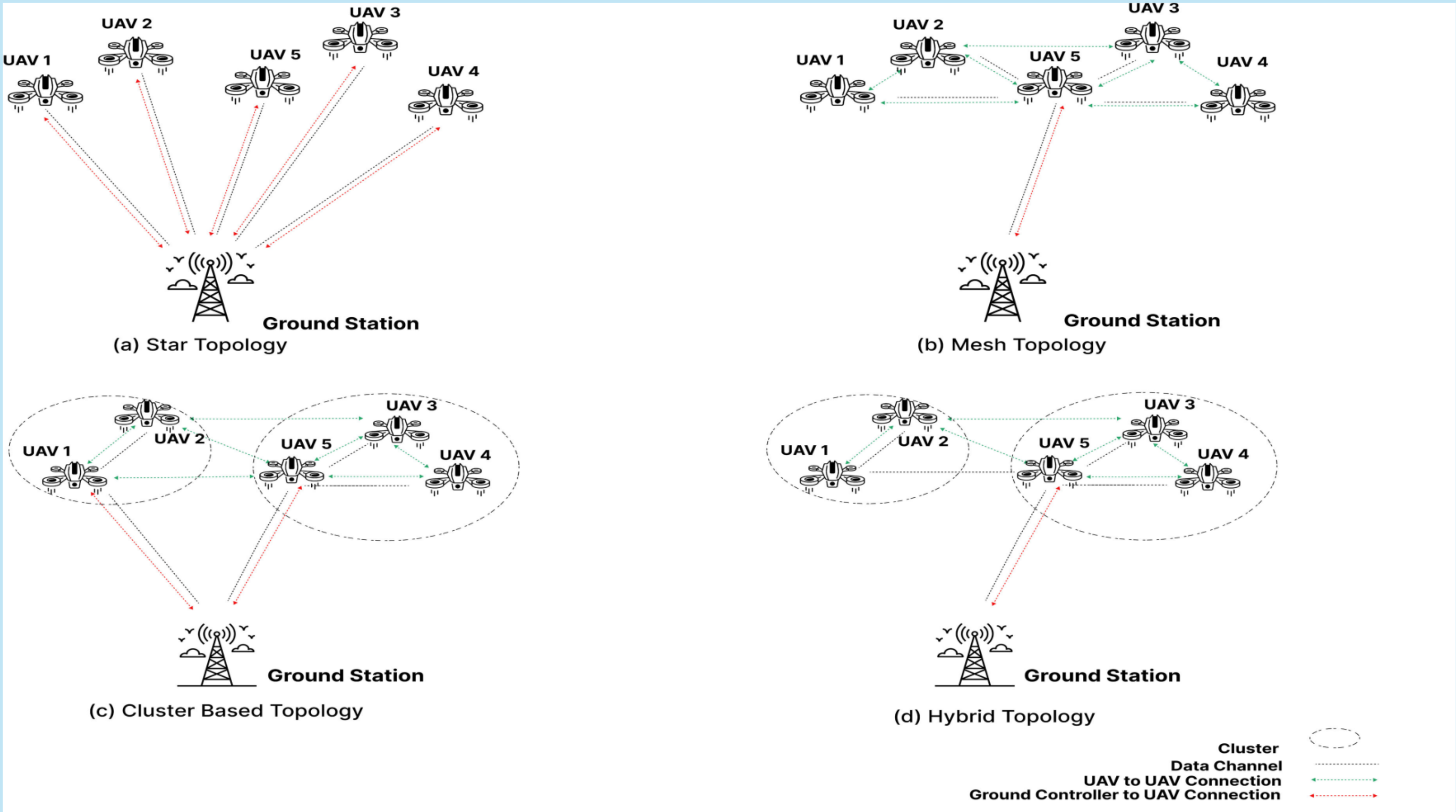
1.3 UAV Networks

- **Multi-UAV topologies- examples**
  - **(a) Star topology:** each UAV (node) is directly connected with GS node
  - **(b) Mesh topology**: the GS is only connected to a single node (**cluster head** of the UAV group- playing a role of Gateway)
    - The cluster head passes the data packets from the GS to the other member nodes and vice-versa
  - **(c) Cluster-based network topology**
    - The UAVs are grouped in clusters; each cluster has a head
    - GS is connected to heads UAVs of clusters
    - The heads collect data packets from the member UAVs and forward them to the GS and vice versa
  - **(d) Hybrid mesh network**- one cluster head UAV is connected to the GS
    - The head can pass the information to the UAVs of its group but also pass information to other nearby cluster heads
    - The head can pass information from the GS to other connected nodes and vice-versa
    - The GS can be connected also to single UAVs or group cluster heads
    - The cluster heads can share information within their groups or the head UAVs of another group
  - **Inter-UAV communication topologies: star, ring, mesh**

1. Introduction

1.3 UAV Networks

- **Multi-UAV topologies: (a) Star b) Mesh (c) Cluster-based (d) Hybrid mesh**



Source: N. MANSOOR et al., A Fresh Look at Routing Protocols in Unmanned Aerial Vehicular Networks: A Survey, IEEE Access June 2023

CONTENTS

2. Routing in UAV Networks

2.1 UAV General Routing Requirements

- **Routing and forwarding**
  - **Classical network layer operations, to support data transport from source to destination**
  - **Extended algorithms and protocols for UAV, but meeting specific requirements in UAV domain**

- **Existing routing algorithms and protocols (MANET, VANET) cannot fully solve the UAV networks needs**
  - UAV - large sets of applications and routing criteria, varying levels of dynamicity, 3D work space, geographical different contexts, intermittent links, fluid topology, etc.

- **General requirements of UAVs routing protocols**
  - must select the most effective communication paths for reliable and stable data transmission
    - Various factors/requirements to consider
      - various criteria/metrics of routes finding
      - E2E delay, throughput, managing dynamic topology, network density, intermittent links, power constraints and changing link quality
      - Mobility; the lifespan of UAV nodes is limited -> seamless handovers are important
      - Energy efficiency requirements
      - Security guarantees, dependable, and reliable data transmission
      - Special QoS requirements in some use cases

    - **Architecture**: **centralized, distributed or hybrid**

2. Routing in UAV Networks

2.2 Basic routing principles - still valid for UAV case

- **Legacy routing principles: Hop-by-hop routing** or **Source routing**

General taxonomy of routing protocols

- **Static (**fixed) **routing protocols**
  - a routing table is calculated and uploaded to the UAVs before flight
    - (-) not possible to update or modify during UAV operation
    - (-) no dynamicity, not fault-tolerant

- **Proactive routing protocols (PRP)- classical/basic principle**
  - the routing/forwarding tables store all the routing information
  - tables are updated and shared periodically among the nodes (inter- node messages)
    - (+) always contains the latest information
    - (-) control traffic overhead; possible slow response to network changes (delays)
    - higher speed solution: event-triggered message exchanges between routers

- **Reactive (on-demand) routing protocols (RRP)**
  - a route is computed at the source node when a request happens and is stored for a limited time
    - (+) less control overhead than in PRP
    - (-) possible higher latency in finding the route
- **Hybrid routing protocols (HRP)**
  - combine PRP-RRP; good for large-scale networks that may have several sub-network areas; intra-zone routing can use PRP, and inter-zone use RRP

2. Routing in UAV Networks

2.2 Basic routing principles

- **Specific to UAV methods**
  - **Position based routing protocols** (using geographical information)
    - **Necessary: UAV position tracking**
    - UAVs use the GPS signal (RF signal transmitted by satellites) containing location and time information
      - or, other positioning systems, such as GLONASS, Galileo or BeiDou, for greater accuracy and better coverage in different regions of the world
  - **Hierarchical protocols** (for large networks)

- **High level view comparison** (summary)

Routing approach	Static/ Dynamic	Network size	Real time Overhead	Latency	Mobility	Computation Complexity
Static	Static	Small	No	Low	Fast	Low
Proactive	Dynamic	Small	Yes	Low	Slow	Medium
Reactive		Larger		High	Average	Average
Hybrid		Any		High	Average	Average
Position-based		Large		Low	Average	High
Hierarchical		Large		High	Average	High

2. Routing in UAV Networks

2.3 UAV delivery modes

- **Delivery schemes: unicast, multicast, broadcast**
  - **geocast** (from source **–** only to nodes located in a specific geographical area)

- Single path mode
  - to transmit data between two specific nodes; simple routing/forwarding tables
  - the routing table is predefined; no alternative paths exist

- **Multipath routing mode**
  - (+) several paths can be available
  - (+) better defence against jamming attack (e.g., disruption of wireless communication)
  - (+) efficient and reliable data transmission is possible
  - (-) higher cost to masintain the routing table (e.g., in case of many routing paths)
    - possibility of route loops if errors occur

2.4 Examples of UAV routing and forwarding related methods

- **Cooperative routing**
  - higher communication reliability; the **nodes helps each other** with information by exploiting broadcasting schemes
  - the neighboring nodes are considered as **relay nodes**
  - link types : cooperative trs. (CT) and direct transmission (DT)

2. Routing in UAV Networks

2.4 Examples of UAV routing and forwarding related methods (cont'd)

- **Path discovery**
  - **assumptions**
    - bi-directional paths
    - the geographical position of the target destination node is known by the source node
    - on-demand style of route finding
    - a **backward learning** method can be used
  - to reach the destination, a **route request (RREQ) message is sent**
    - (RREQ-similar method is used in also MANET AODV –Ad Hoc On Demand Distance Vector Routing Protocol)
      - using broadcast mode, i.e., on all-possible paths from source node to destination node
    - the packets travelling to the destination collect information about the path
      - if an intermediate node already knows the path requested, then it answers to the source node
  - the destination node receives several replicas of interrogation packets
    - it can select the best path on some conditions
    - the selected path is used for data transmission
  - a response (RREP) is returned to the source, indicating the best path
  - this path is stored for some life-time and can be used in the future by the source

2. Routing in UAV Networks

2.4 Examples of UAV routing and forwarding related methods (cont'd)

- **Store-carry-and-forward (SCF) routing technique**
- It can be used in several cases: intermittent connectivity; high mobility; long delays; when a direct E2E connection is not available

- **Main idea**: information can be sent to an *intermediate station* where it is stored and sent at a later time instant to the final destination, or to another intermediate station
  - the intermediate station/ node verifies the message integrity before forwarding it
  - in SCF the messages are forwarded among encountered mobile relay nodes (called SCF routers)
- SCF it is used when some network fault causes a disconnect from its next relay node
  - but forwarding data is still necessary
  - and it is also not possible to transmit data to next hop, as the node is out of transmission range
  - in this case the current packet holder node carries the data until it meets another node or the destination node
  - a decision is made at each relay node (SCF router) to store, replicate, or delete a message
- SCF is efficiently used in FANETs, if the UAV nodes are sparsely distributed
  - SCF can be exploited in **delay-tolerant networks (DTN)** with ferrying UAVs
    - ensures high throughput in delay-tolerant routing in UAV networks.
  - (-) high delay may happen

Source: M.Yeasir Arafat and S.Moh, Routing Protocols for Unmanned Aerial Vehicle Networks: A Survey, DOI 10.1109/ACCESS.2019.2930813, IEEE Access

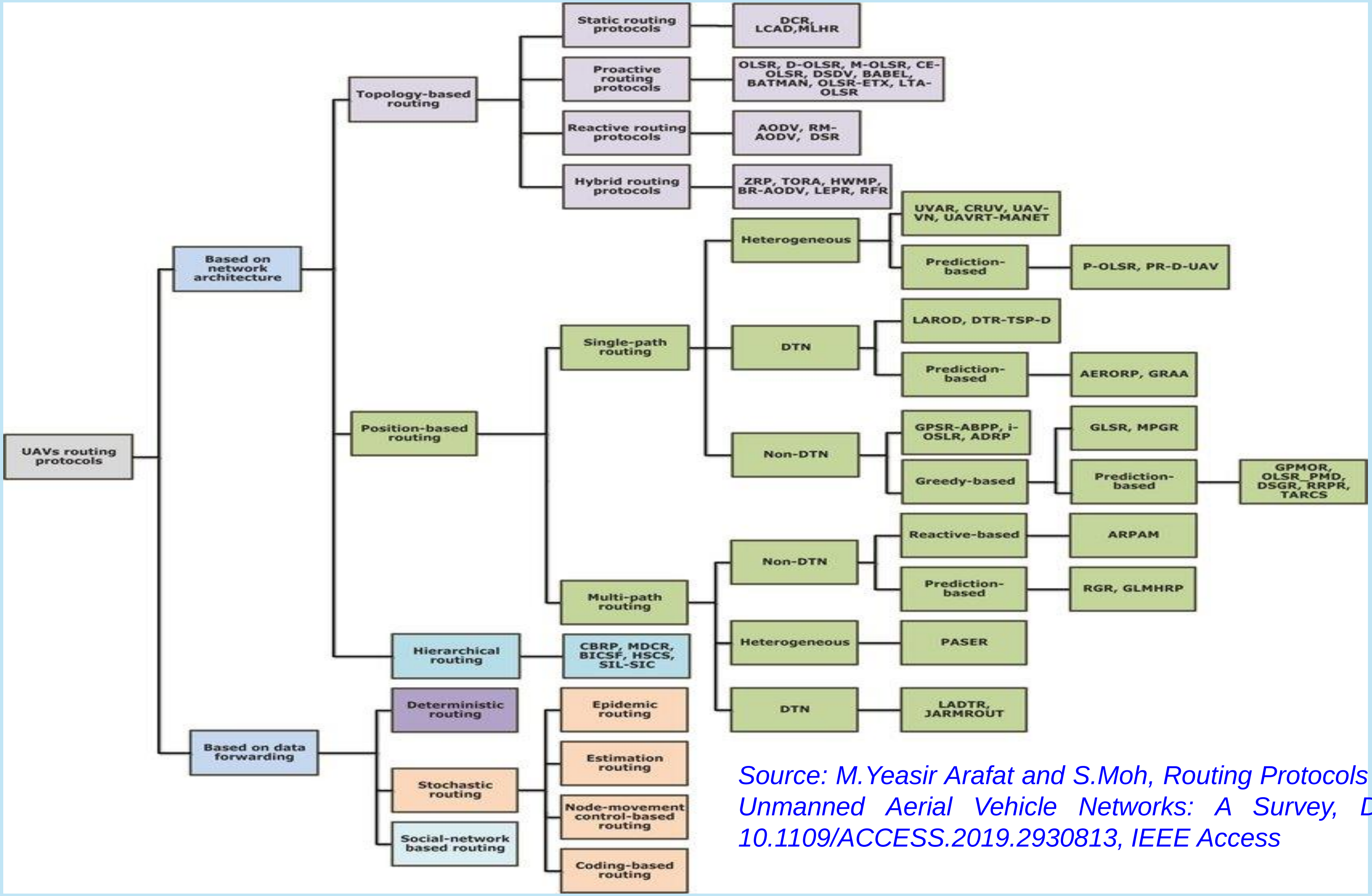
2. Routing in UAV Networks

2.4 Examples of UAV routing and forwarding related methods (cont'd)

- **Prediction methods**
  - based on the direction, geo location, and speed of the UAVs used by the source node to transmit data to the next node
    - the parameters usually provide enough good approximations about the next relay node in communication network
  - Predicting geo location is used to find the next relay node (UAVs positions evolution in time)
  - SCF method could be used to avoid packet loss in the network; path discovery can find active paths between nodes
- **Greedy forwarding (GF)**
  - GF - **distance-based (location-based) greedy routing algorithm** for UAV networks solely based on UAVs' local observations of their surrounding subnetwork
  - **Objective:** to **minimize the number of hops** in the transmission path
  - Approach: to choose a relay node that is *geographically* nearest to the destination node
  - GF is a progress-based forwarding strategy
    - At each step the current node passes the packet to a neighbour node which is closest to the destination
    - If there is no neighbour node closer to the destination node, the algorithm fails and the node keeping the packet is called local minimum
  - **Drawbacks**
    - local optimum problem (it may not find the best relay node to reach its destination)
    - high overhead

2. Routing in UAV Networks

2.5 UAV routing protocols Taxonomy – criterion**: based on network arch. or on data fwd.**



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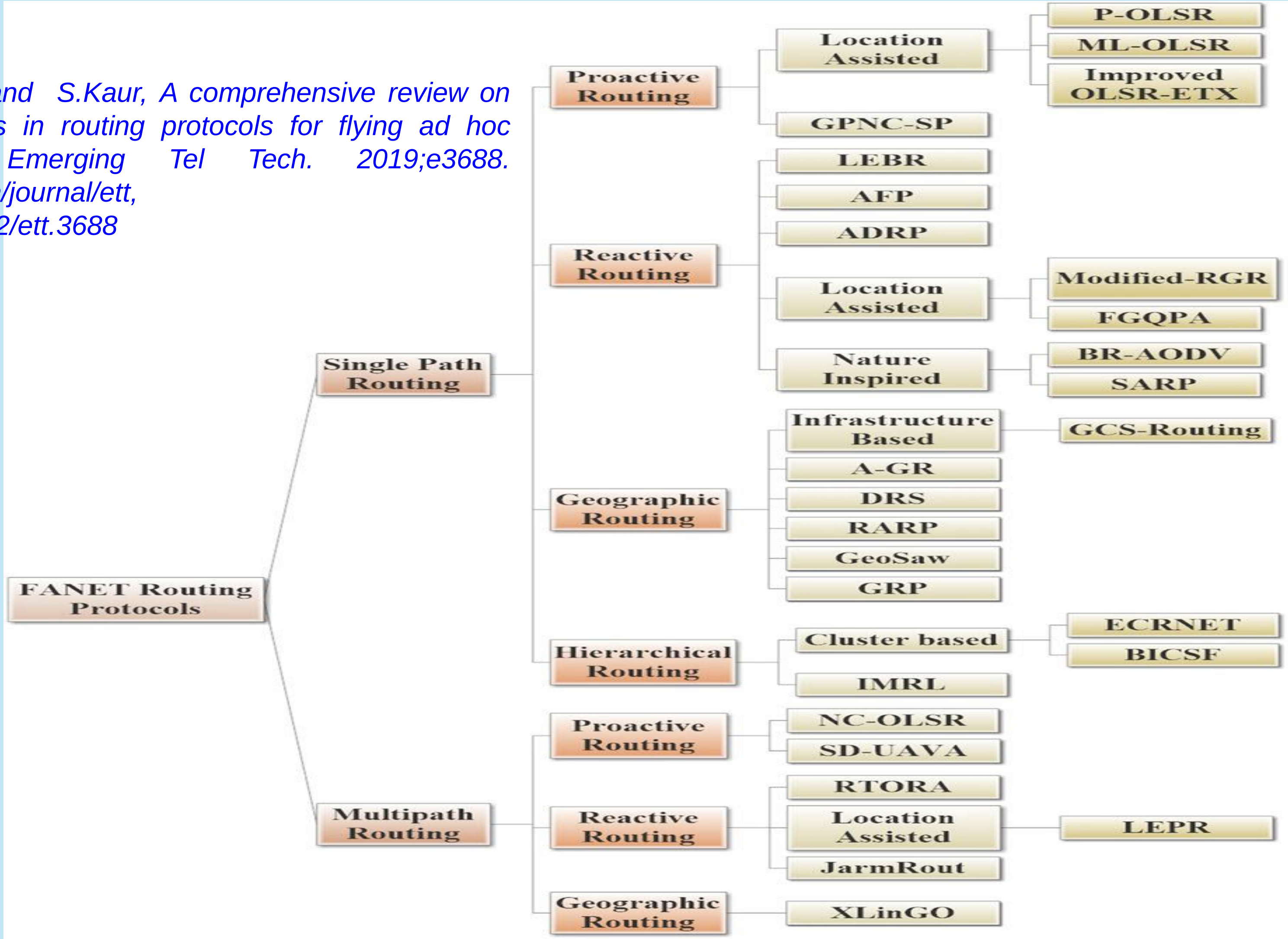
2. Routing in UAV Networks

2.5 UAV routing protocols Taxonomy – notations

- ADRP Adaptive Density-based Routing Protocol
- AODV Ad-hoc On-Demand Distance Vector
- BATMAN Better Approach to Mobile Ad hoc Network
- BICSF Bio Inspired Clustering Scheme for FANET
- CBRP Cluster-based Routing Protocol
- DCR Data Centric Routing
- DSGR Distance-based Greedy Routing
- DTP-TSP-D Deadline Triggered Pigeon with Travelling Salesman Problem
- DSR Dynamic Source Routing
- DOLSR Directional Optimized Link State Routing
- DEQPSO Differential Evolution and Quantum-Behaved Particle Swarm Optimization
- DSDV Destination Sequence Distance Vector
- DTN Delay Tolerant Network
- GLSR Geographic Load Share Routing
- GPMOR Geographic Position Mobility-Oriented Routing Protocol
- GLMHRP Geolocation-based Multi-hop Routing Protocol
- GPSR Greedy Perimeter Stateless Routing
- GPSR-ABPP GPSR-Adaptive Beacon and Position Prediction
- HSCS Hybrid Self-organized Clustering Scheme
- HWMRP Hybrid Wireless Mesh Routing Protocol
- HWMP HRC Hybrid Routing based on Clustering
- JARMROUT Jamming -Resilient Multipath Routing
- LADTR Location Aided Delay Tolerant Routing
- LCAD Load-Carry-and-Deliver
- LEPR Link Estimation Preemptive Routing
- MDCR Modularity-based Dynamic Clustering Relay
- MPCA Mobility Prediction Clustering Algorithm
- ML-OLSR Mobility and Load aware OLSR
- MLHR Multi Level Hierarchical Routing
- OLRS Optimized Link State Routing
- OLSR-PMD OLSR with Mobility and Delay Prediction
- POLSR Predictive-OLSR
- PASER Position Aware Secure and Efficient Mesh Routing
- RGR Reactive-Greedy-Reactive
- RM AODV Radiometric AODV
- RRPR Robust and Reliable Predictive Routing
- RTORA Rapid-reestablish Temporally Ordered Routing Algorithm
- RSGFF Recovery Strategy Greedy Forwarding Failure
- SIL-SIC Swarm Intelligence-based Localization and Clustering
- TARCS Topology-Aware Routing Choosing Scheme
- TORA Temporally Ordered Routing Algorithm
- TBRPF Topology Broadcast based on Reverse-Path Forwarding
- UVAR UAV-Assisted Routing
- ZRP Zone Routing Protocol

2.6 UAV routing protocols taxonomy 1 – criterion: **routing method used**

Source:A. Malhotra and S.Kaur, A comprehensive review on recent advancements in routing protocols for flying ad hoc networks, Trans Emerging Tel Tech. 2019;e3688. wileyonlinelibrary.com/journal/ett, https://doi.org/10.1002/ett.3688



2. Routing in UAV Networks

2.6 UAV routing protocols Taxonomy 1-– notations

- ADRP Adaptive Density-based Routing Protocol
- AFP Adaptive Forwarding Protocol
- A-GR: Geographical Routing Protocol
- AODV Ad-hoc On-Demand Distance Vector
- BICSF bioinspired clustering scheme for FANETs
- DRS Directional Routing Scheme
- DSGR Distance-based Greedy Routing
- DSR Dynamic Source Routing
- DSDV Destination Sequence Distance Vector
- DTN Delay Tolerant Network
- ECRNET Energy aware Cluster-based Routing in flying ad-hoc Networks
- ETX Expected Transmission Count
- FSR Fisheye State Routing
- GPSR Greedy Perimeter Stateless Routing
- GPNC-SP Shortest Path Routing based on Grid Position.
- LEPR Link Estimation Preemptive Routing
- OLRS Optimized Link State Routing
- OLSR-PMD OLSR with Mobility and Delay Prediction
- POLSR Predictive-OLSR
- RGR Reactive-Greedy-Reactive
- RTORA Rapid-reestablish Temporally Ordered Routing Algorithm
- SARP Stable Ant-based Routing Protocol

2. Routing in UAV Networks

- **2.7 Challenges open research issues and trends– summary**
  - Mobility- and low UAV density - problems
  - Energy efficient routing
  - Routing security, privacy and intrusion detection
  - Dynamic route selection
  - Collision awareness, Link disconnection, DTN issues
  - P2P UAV Communications
  - Prediction capable algorithms and protocols
  - Cognitive radio (CR) enabled protocols
  - UAV Cross-Layer Routing
  - UAVs control through cloud-based system
  - Mobility models and simulation tools
  - Data-centric routing
  - Quality of Services
  - Airspace regulations aware network model
  - AI/ML-based novel routing algorithms and protocols
  - Integration in 5G, 6G networks

2. Routing in UAV Networks

- **2.7 Challenges, open research issues and trends**
  - **Mobility- and low UAV density - problems**
    - High mobility can lead to link disconnections
    - UAVs can leave and join the network (various reasons)
    - Network can be partitioned for a long duration (malfunction or battery exhaustion).
    - Possible low density of UAVs in 3D space
    - Environmental obstacles, weather and geo conditions can lead to topological changes
  - **Potential solutions**
    - enhanced/new protocols designed to solve link disconnection
    - various localization techniques for the position estimation of UAV nodes
    - adaptive routing protocols - to provide a high delivery ratio, minimum delay
    - dynamic topology management, quick recovery, reliability, low control and processing overheads
    - opportunistic routing schemes

  - **Energy efficient routing**
    - UAVs flight range is inherently limited (battery)
    - More energy-efficient routing protocols are necessary
    - **Potential solutions**
      - hybrid metrics – to design energy-efficient, energy conservation routing and high-performance routing protocols and clustering algorithms

2. Routing in UAV Networks

- **2.7 Challenges, open research issues and trends**

- **Routing security, privacy and intrusion detection**
  - Different attacks have the routing operation as a target
  - The secure routing techniques including the jamming-resilient routing should be more addressed for trusted UAVNETs
  - M&C critical messages require protection, especially in hostile environments
  - The MANET security solutions may not be suitable for UAV/FANETs, due to specific characteristics of the UAV environment
  - Threats against UAV/FANETs can be flooding, fraudulent data, and manipulation
  - The lack of a central coordination mechanism in ad hoc wireless networks and the shared wireless medium introduces more vulnerabilities
  - Traditional PKI-based asymmetric solutions may not be suitable for structure-less UAV networks due to the absence of a central entity for issuing digital signatures
  - High computational overhead and delay in encryption and decryption- not appropriate for resource constrained and dynamic networks

2. Routing in UAV Networks

- **2.7 Challenges, open research issues and trends**
  - **Routing security, privacy and intrusion detection** (cont'd)
    - **Potential solutions**
      - enhanced secure protocols better adapted to UAV/FANETs are required
      - security mechanisms : cryptography, link identification, proof of identity, etc.
      - HW-driven security keys can be utilized to enable non-repudiation
      - alternative localization methods can be employed to mitigate the impact of jamming attacks on GPS positioning
      - secure handover mechanisms should be designed
      - development of secure routing schemes, including the detection and avoidance of malicious nodes through behavioral mechanisms
  - **Dynamic route selection**
    - Optimization of both path selection and flight duration are necessary while ensuring accurate information transmission across the UAV nodes
    - **Potential solutions**
      - objectives: to minimize energy consumption and E2E latency while ensuring efficient and reliable data transmission
      - metrics: link quality, traffic congestion, network topology and conditions changes
      - advanced dynamic route selection mechanisms
      - enhanced methods to identify the destination node and achieve optimal movement and path planning

2. Routing in UAV Networks

- **2.7 Challenges, open research issues and trends**
  - **P2P UAV Communications**
    - Development of new P2P routing protocols to support the traffic exchange (for data and file sharing) between UAVs
    - **Potential solutions:** proposals exist for modified data centric routing protocols
  - **Collision awareness**
    - Problem: practical collision avoidance is increasingly challenging
    - **Potential solutions**
      - *Store-Carry-Forward (SCF)* mechanism can enable latency-tolerant transmission and is a reliable mechanism for message delivery in disrupted environments
      - the UAV nodes can periodically broadcast their position and other relevant information for coordination and preventing collisions
        - this information can be used to dynamically adjust the UAVs' trajectories to avoid obstacles and optimize data collection
      - performance awareness can be exploited to develop a self-organizing network to avoid collision between UAVs
      - ML can predict the movements of UAVs and obstacles in real time, enabling more efficient and safe coordination

2. Routing in UAV Networks

- **2.7 Challenges, open research issues and trends**
  - **Cognitive radio (CR) enabled protocols**
    - Efficient and reliable spectrum sensing is important for identifying available frequency bands for communication
    - Effective spectrum management is essential for optimizing system performance
    - Integrating CR-enabled UAVs with existing wireless networks and infrastructure – additional challenges due to differences in communication protocols and technologies

    - **Potential solutions**
      - New protocols for communication between UAVs and other wireless devices to facilitate seamless integration
      - Managing both primary and secondary users - to prevent interference with other users sharing the same frequency band
      - New algorithms to handle interference and maximize spectrum utilization
      - Robust and reliable algorithms - for spectrum management, interference avoidance, and seamless integration with existing wireless networks

2. Routing in UAV Networks

- **2.7 Challenges, open research issues and trends**
  - **UAV Cross-Layer Routing**
    - Cross-layer approaches involving in routing not only the network layer but also PHY and L2 layers is a challenge
    - Inaccurate link state information exists (due to the 3D mobility) and also limited network resources (e.g., processing power, memory, battery power, and network bandwidth)
    - **Potential solutions**
      - Cooperation between several architectural layers for finding an optimal route can produce higher quality solutions
      - A cross-layer design (involving L1, L2, L3 layers) is also of interest, to achieve the reliability requirement of certain applications of UAV/FANET

  - **UAVs control through cloud based system**
    - Integration of cloud computing paradigm with FANETs is necessary, in order to extend the resources capacity of UAVNETs
    - Changes in several management and control paradigms arise, including routing

2. Routing in UAV Networks

- **2.7 Challenges, open research issues and trends**
  - **Mobility models and simulation tools**
    - Still not enough powerful simulation tools for modelling real-world UAV systems.
    - Mobility models algorithms are necessary to represent the UAV movement patterns
    - Three-dimensional communications should be supported by simulation tools (e.g., OPNET and NSx).
    - **Potential solutions**
      - Better UAV-oriented realistic mobility models (UAV/FANET- specific) are needed in order to simulate UAV/FANET protocols in a realistic way
      - Improvement of the existing simulation tools (e.g., NS-2, Opnet, OMNeT) or development of new ones
      - Mobility models can provide insights into how UAVs move and interact with each other in a particular environment, allowing to develop more effective routing and communication strategies
  - **Quality of Service**
    - UAV/FANET routing protocols should support the service quality requirements for special applications (delay, bandwidth, jitter, and packet loss
    - **Potential solutions**
      - Including data on traffic characteristics, available network resources and QoS requirements of the apps., while designing routing scheme would contribute to achieve the specific QoS required

2. Routing in UAV Networks

- **2.7 Challenges, open research issues and trends**
  - **Data-centric routing**
    - Many UAV applications are task-specific and do not always follow the host-centric communication Intenet model .
    - E.g.: the GS (in a surveillance app.) can be only interested in the data rather than the node hosting the data
    - Such data types have different service requirements and performance constraints and can be affected by the dynamic nature of UAV operations(mobility, node join/leave, varying network topology)
    - Novel data-centric routing protocols that prioritize the information rather than the host are of interest
    - Many current UAV/FANET routing protocols adopt the host-centric Internet communication model
    - **Potential solutions**
      - Data-centric routing protocols that prioritize information over the host

2. Routing in UAV Networks

- **2.7 Challenges, open research issues and trends**
  - **Airspace regulation-aware network model**
    - The UAV 3D movement must obey the airspace regulations and guidelines, which include restrictions and designated areas for UAV flights
    - Many countries created notification systems to mark off certain areas of airspace, with restrictions for all types of UAVs
      - These areas: Prohibited Areas, Restricted Areas, or Military Zones
      - Example: UAVs are not allowed to fly within the Flight Restriction Zone (FRZ) of a protected aerodrome without proper authorization (to prevent collisions with airplanes or helicopters).
    - Temporary restrictions may exist in special circumstances or contexts.
    - Route planning must know information about restricted or controlled airspace
    - The current routing methods for UAV networks have not enough accounted for the complex nature of flight regulations.

    - **Potential solutions?**
      - Further research is needed to incorporate the regulations into UAV network models to ensure safe and legal operations

2. Routing in UAV Networks

- **2.7 Challenges, open research issues and trends**
  - **References**

    - *O. Sami Oubati, et al., Routing in Flying Ad Hoc Networks: Survey, Constraints, and Future Challenge Perspectives, IEEE Access 2019, DOI 10.1109/ACCESS.2019.2923840*
    - *M.Yeasir Arafat and S.Moh, Routing Protocols for Unmanned Aerial Vehicle Networks: A Survey, DOI 10.1109/ACCESS.2019.2930813, IEEE Access, 2019*
    - *D.S.Lakew, U.Sa'ad, N.Dao, W.Na and S.Cho, Routing in Flying Ad Hoc Networks: A Comprehensive Survey, IEEE Communications Surveys&Tutorials, Vol.22, No.2, 2020*
    - *N.Mansoor, MD.I.Hossain , A.Rozario, M. Zareei, and A.R Arreola, A Fresh Look at Routing Protocols in UAV Networks: A Survey, Digital Object Identifier 10.1109/ACCESS.2023.3290871*

2. Routing in UAV Networks

2.8 Recent trend: Artificial intelligence in UAV routing

AI algorithms are recently proposed, to enhance various UAV functions and in particular routing

- **Major idea:** to **integrate AI algorithms into control protocols** to assist UAVs in perceiving the networks and environment overall conditions based on limited observations.

- **Challenge: computational cost**
  - For each scenario one should analyze the benefits/drawbacks of using AI methods
  - Evaluation of real-time response capabilities of the AI-based solutions, for dynamic scenarios
- **New networking AI-based algorithms** (partially commercialized) are developed on top of the communication protocols
  - **Examples: AI enabled routing, compression, and task coordination** protocols

- **Machine Learning (ML) algorithms can help for optimal route path selection** (a more accurate topology perception, channel status, user behavior, traffic mobility, considering dynamicity, etc.)

2.8 AI-enabled routing protocols - Examples (selected list)

- ***1. Topology predictive routing protocols***
  - ML algorithms can
    - predict the node's motion trajectories (as an approximation of the network topology, provided that the communication range of nodes is known)
    - and include this information into the path selection
  - **Learning-based Adaptive Position MAC protocol**
    - Hybrid comm. protocol integrating a novel *Position-Prediction-based directional MAC protocol (PPMAC)* and a *Self-learning Routing Protocol* based on *Reinforcement Learning (RLSRP)*
  - **Predictive Dijkstra protocol**
    - Assumption: the locations of the intermediate nodes (when the packet is supposed to meet them) - are predicted enough well, by using ML methods
    - The predictive information is used for the path selection criterion
    - Performance: higher w.r.t. standard Dijkstra algorithm
    - **Issues**: its reliance on accurate trajectory prediction methods; need for global location information exchange.

Adapted from source: A.Rovira-Sugranes, A.Razi, F.Afghah, J.Chakareski , A review of AI-enabled routing protocols for UAV networks: Trends, challenges, and future outlook, Ad Hoc Networks 130 (2022) 102790, www.elsevier.com/locate/adhoc

2. Routing in UAV Networks

2.8 AI-enabled routing protocols - Examples (selected list)

- ***1. Topology predictive routing protocols*** *(cont'd)*

  - **Predictive greedy routing**
    - Adapted to highly dynamic network topologies
    - *Distance-based* greedy routing algorithm; it relies solely on the UAVs' local observations of their surrounding subnets
    - Each node estimates its neighbors' locations of (e.g., using *model-based object motion trajectory prediction*) and selects the next node that offers best progress toward the destination node
    - Low complexity and low overhead with no need for an initial route setup
    - Improvement, w.r.t. centralized shortest path routing algorithms

  - **Predictive Optimized Link State Routing (P-OLSR)**
    - Derived from OLSR
    - It exploits GPS information and calculates an *Expected Transmission (ETX)* count metric to estimate the link quality when finding the optimal path
    - It outperforms other algorithms such as OLSR and BABEL under dynamic network topology

2. Routing in UAV Networks

2.8 AI-enabled routing protocols - Examples (selected list)

- ***1. Topology predictive routing protocols*** *(cont'd)*

  - **Geographic Position Mobility Oriented Routing (GPMOR)**
    - *Geo-based* protocol using the Gauss–Markov mobility model to predict the movement of UAVs
    - It selects the next hop according to the mobility relationship in addition to the Euclidean distance, to make more accurate decisions
    - It provides effective and accurate data forwarding solutions
    - It decreases the impact of intermittent connectivity and achieves a better latency and packet delay rate than other position-based routing protocols

  - **Robust and Reliable Predictive (RARP)**
    - It combines *omni* and *directional* transmission with *dynamic angle adjustment*
    - It uses in a hybrid way unicasting and geo-casting routing protocols based on location and trajectory information
    - The intermediate node locations are predicted using 3-D estimation
    - Then, directional transmission is used toward the predicted location, enabling a longer transmission range and tracking topology changes

2. Routing in UAV Networks

2.8 AI-enabled routing protocols -Examples (selected list)

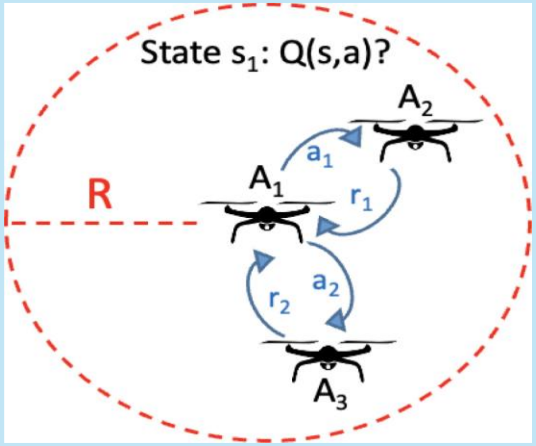
- ***1. Topology predictive routing protocols*** *(cont'd)*
  - **Q-learning-based Geographic ad-hoc routing protocol (QGeo)**
    - *ML-based geo-routing* scheme aiming to reduce network overhead in high-mobility scenarios
    - The nodes make geographic routing decisions in a distributive way, utilizing a RL method without knowing the entire network topology
    - It consists of location estimation, a neighbor table, and a *Q-learning module*
    - The location estimation module updates the current location information reported by the GPS or other localization methods
    - QGeo provides a higher packet delivery rate and a lower network overhead w.r.t. other geo-position-based protocols

- ***2. Self-adaptive learning-based routing protocols***
  - **Reinforcement Learning (RL)** is frequently used to make routing decisions
    - It applies continuous and online learning of the environment and their decision consequences on desired performance metrics such as delay, throughput, energy efficiency, and fairness
    - (+) abstract formulation which brings independence from topology prediction and channel estimation (this comes from the concept of learning from experience)

2. Routing in UAV Networks

2.8 AI-enabled routing protocols -Examples (selected list)

- ***2.Self-adaptive learning-based routing protocols*** *(cont'd)*
  - **Basic RL-based scenario- Example**
    - In state s**1**, node or agent A**1** has two candidate neighbors A**2** and A**3** to send its packet. It must select between action a**1** or a**2** based on the reward expected for each action a at state s, denoted as $Q(s, a)$.
    - Once A**1** selects the appropriate action, it obtains an immediate reward from the environment, r**1** or r**2**, respectively
    - Next, the same process is started in a new state s**2**; the decisions will be made based on the new environmental conditions and the learned policy in terms of actions-rewards relations
    - The end goal: to find an optimal policy in which the cumulative reward over time is maximized by assigning optimal actions to each state



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2. Routing in UAV Networks

2.8 AI-enabled routing protocols -Examples (selected list)

- ***2. Self-adaptive learning-based routing protocols*** *(cont'd)*
  - **Q-Routing ideas:**
    - ***Exploration* phase** - evaluating the impact of routing strategies on performance metric by investigating different paths
    - ***Exploitation* phase**: to use the discovered best paths
    - **Issues**:
      - Exploration imposes a system overhead; however, it is critical for finding newly optimal paths (e.g., in a dynamic context of the topology)
      - Need to adaptively solve the *trade-off exploration/ exploitation* times to cope with topology dynamicity
  - **Q-Routing –Examples**
  - **Initial Q-Routing Protocol** (learning from experience)
    - Each node
      - stores the expected time to the destination through any of its neighbors as Q-values in a Q-table
      - selects the next node that minimizes the expected travel time to the destination
      - after a packet is received by a node, it sends back the real travel time to the previous node to updates its Q-values for the next round

2. Routing in UAV Networks

2.8 AI-enabled routing protocols -Examples (selected list)
- ***2. Self-adaptive learning-based routing protocols*** *(cont'd)*
  - **Q-Routing –Examples**
  - **Predictive Q-Routing (PQ-Routing)**
    - Extension of the conventional Q-Routing; Fine-tuning the routing policies to get an exploration–exploitation trade-off and
    - Learning and storing new optimal policies under decreasing load conditions and reusing the learned best experiences by predicting the traffic trend
    - Re-investigate the paths that remain unused for a while due to the congestion-related delays
    - PQ-Routing out-performes the Q-Routing w.r.t. learning speed and adaptability
    - **Issues:** It requires large memory for the recovery rate estimation
      - Not accurate in estimating the recovery rate under fast varying topology changes
  - **Full-echo Q-Routing**
    - It accelerates the learning speed of conventional Q-Routing
    - In conventional Q-Routing, each node only updates the Q-values for its selection (the best neighbor)
    - *Full-echo* routing: - a node gets each neighbor's estimate of the total time to the destination, which helps update the Q-values accordingly for each of the neighbors

2. Routing in UAV Networks

2.8 AI-enabled routing protocols -Examples (selected list)

- ***2. Self-adaptive learning-based routing protocols*** *(cont'd)*
  - **Q-Routing –Examples**

  - **Dual Reinforcement Q-Routing (DRQ-Routing)**
  - It uses *forward and backward explorations* by the sender and receiver of each comm. hop, by appending information to the packets they receive from their neighbors
  - It learns the optimal policy faster than the standard Q-Routing
  - Q-learning approach performs better than the traditional non-adaptive approach under scenarios with increasing traffic that causes node and link failures.
  - **Issues:**
    - Q-Routing does not always guarantee finding the shortest path
    - It does not explore multiple forwarding options in parallel

- Note: an extended list of routing protocols examples can be found, e.g., in :

Source: A.Rovira-Sugranes, A.Razi, F.Afghah, J.Chakareski , A review of AI-enabled routing protocols for UAV networks: Trends, challenges, and future outlook, Ad Hoc Networks 130 (2022) 102790, www.elsevier.com/locate/adhoc

CONTENTS

3. Path Planning in UAV Networks

3.1 Path planning (PP) problem in UAV

- **PP is related to the UAV routing**
  - **PP is dependent on geographical/environment information**

- **UAV PP main objectives**:
  - **To find for an UAV, the best (i.e., optimum) collision-free path between the start point and the destination point while addressing temporal, physical, and geometric constraints, or**
  - **Coverage Path Planning (CPP) – movement in a region** - for specific exploring UAV applications
- UAV PP (a.k.a. motion planning), is a branch of path-finding used in robotics
  - However, UAV specific differences exist, e.g.:
    - 3D space: UAVs can change their altitude level during the flight
    - Some UAVs (e.g., fixed-wing UAV), cannot hover; they must maintain a consistently high cruising speed, this determines more constraints
      - In contrast, a robot can decelerate and have a complete stop as needed
- **PP specific problems of interest:** environment modeling methods, path structures, optimality criteria, completeness criteria, UAV simulators

3. Path Planning in UAV Networks

3.1 Path planning (PP) problem in UAV

- **UAV Path Planning essential attributes**
  - **Security:** ensuring the safety of UAVs, particularly in environments where tasks are performed in potentially threatening conditions
    - Minimizing the probability of detection by hostile radars and other UAVs.
  - **Physical Viability:** refers to the physical constraints and limitations associated with the use of UAVs. (e.g., maximum path distance and the minimum path length)
  - **Mission performance**: relates to the ability of a path to satisfy the specific requirements of a given mission
    - Designing a path to complete a mission involves meeting various requirements, including maximal turning angles, maximum climbing/diving angles, and minimal flying heights
  - **Real-time implementation**: efficiency of the PP algorithm, particularly in the context of real-time implementation
    - The dynamic nature of UAV flight environments necessitates computationally efficient PP algorithms to respond fast to changing conditions

3. Path Planning in UAV Networks

3.1 Path planning problem in UAV

- **UAV PP targets**: low computational cost, full UAVs' maneuverability, dynamic flight control, optimality of trajectories while respecting dynamics constraints
- The PP problem has a non-linear nature and frequently has an exponential complexity
- **Classes of UAV PP problems (from applications point of view)**
  - ***Informative path planning (IPP) problem***: to plan paths for the robots/UAV as to maximize the utility of data collection
    - paths are planned such that the information gathered about an unknown environment is maximized, while satisfying the given budget constraint
  - ***Coverage path planning (CPP) problem*****:** to determine a path **that passes through all points of an area** or volume of interest while avoiding obstacles
  - ***Cooperative path planning***: to generate a coordinated mission through utilization of PP algorithms
    - **Example:**
      - a group of UAVs leave a base and should synchronously arrive at a designated rendezvous point
      - during their journey the UAVs might execute different tasks (e.g., area searches and detecting objects along)

Source: S.Ghambari, M.Golabi, L.Jourdan, J.Lepagnot and L.Idoumghar, UAV Path Planning Techniques: A Survey, RAIRO-Oper. Res. 58 (2024) 2951–2989 RAIRO Operations Research, https://doi.org/10.1051/ro/2024073 www.rairo-ro.org

3. Path Planning in UAV Networks

3.1 Path planning problem in UAV

• UAV considered as a (semi) autonomous vehicle, should move from one location to another one, while considering some defined criteria such as

- minimum values for: path length, flight time, fuel consumption, and danger exposure.

- Depending whether the environment is known or not, PP algorithms can be:
  - **Offline PP**
    - Assumption: all environmental information is known in advance
    - PP algorithms only depend on static environmental information
  - **Online PP**
    - The information on the environment is only partially known in advance
      - paths should be adjusted in real-time, based on real-time sensor information

- According to the employed cellular decomposition technology, CPP algorithms can be divided into three main types:
  - **no decomposition, exact cellular decomposition** and **approximate cellular decomposition**

Source: Cabreira TM, Brisolara LB, Ferreira PR (2019) Survey on coverage path planning with unmanned aerial vehicles. Drones 3(1):4. https:// doi. org/10. 3390/ drone s3010 004

3. Path Planning in UAV Networks

3.1 Path planning problem in UAV

- **General taxonomy of PP methods** : ***classical approaches***, ***soft-computing techniques***, **and *hybrid methods***
- ***Classical methods* (e.g.,** *graph search* algorithms)
  - A local path is generated based on the current information (spanning the operation area)
  - *The path is seen as partially planned but is not a global optimum*

- ***Soft-computing techniques*** are alternative methods
  - They have no assumption about the problem that is being optimized and adopt different learning strategies to perform an effective search towards the global path
  - They can be used in conjunction with pre-processed and stored cost maps, aiming to reduce the computational time
  - Recently: increasing attention is given on the application of soft-computing techniques
  - Limitation: they could be not convenient if computational resources are limited

- **Hybrid techniques:** combination of the two above

3. Path Planning in UAV Networks

3.2 Path planning model

- Consider a **3D workspace**
- Let it be ***w; it*** will often have obstacles; let $\boldsymbol{wo_i}$ be the $\boldsymbol{i_{th}}$ obstacle.
- The free workspace without obstacles is the overall area represented by $\boldsymbol{w_{free} = w \setminus \bigcup_i wo_i}$
- The initial point $\boldsymbol{x_{init}}$ and the goal region $\boldsymbol{x_{goal}}$ are elements in $\boldsymbol{w_{free}}$

- **The PP planning problem is defined by a triplet ($\boldsymbol{x_{init}}$, $\boldsymbol{x_{goal}}$, $\boldsymbol{w_{free}}$)**

- ***Definition 1-PP***: Given a function $\boldsymbol{\delta:[0,T] \to R^3}$ of bounded variation, where $\boldsymbol{\delta(0)= x_{init}}$ and $\boldsymbol{\delta(T)= x_{goal}}$,
  - if there exists a process $\boldsymbol{\Phi}$ which can guarantee $\boldsymbol{\delta(t) \in w_{free}}$, for all $\boldsymbol{t \in [0,T]}$, then $\boldsymbol{\Phi}$ is called **Path Planning**

- ***Definition 2-Optimal PP*****:**
  - Let Σ denote the set of all paths
  - Given a PP problem (-, -, -) and a cost function $\boldsymbol{c: \Sigma \to R \geq 0}$, if a process fulfils the *Definition 1* and if exists a feasible path having the minimum of cost, then the associated process $\boldsymbol{\Phi'}$ is named *Optimal PP*

3. Path Planning in UAV Networks

3.2 Path planning model

- ***Path Planning*** and ***Trajectory Planning***: two distinct problems in robotics, but related
  - ***Trajectory***: a path is parameterized by time **t**
  - ***Trajectory planning***
    - Usually, one considers the solution from a robot PP algorithm and determines ***how*** to move along the path in w_{free}
    - the ***path*** is either a continuous curve or discrete line segments that connects the start node x_{init} to the end node x_{goal}
    - one needs to find smooth and continuous trajectory segments to move along the path
      - it can be described mathematically as a twice-differentiable polynomial
      - i.e., the velocities and accelerations can be computed by taking the first and second derivatives with respect to time

Source: *Liang Yang, Juntong Qi Jizhong Xiao Xia Yong, A Literature Review of UAV 3D Path Planning, 2015, https://www.researchgate.net/publication/282744674*

3. Path Planning in UAV Networks

3.3 Environment Representation Methods

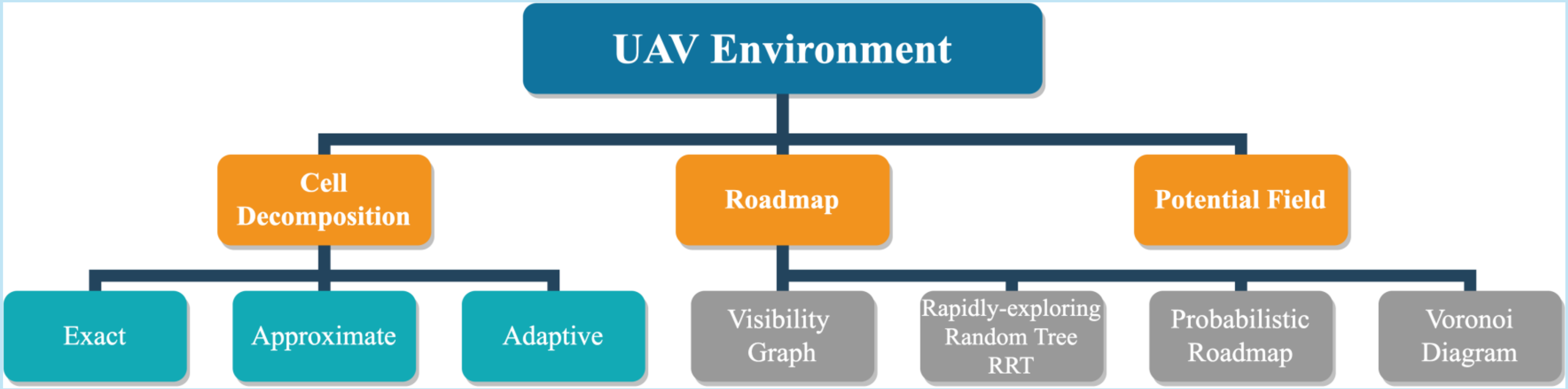
Two key dimensions of environmental complexity

- The knowledge available to a path planner
    - regarding the environment
    - dynamicity degree of the objects encountered in the environment
- **The 3D environment space - obstacles representation issues**
    - The obstacles can be static or dynamic obstacles
    - The way used to model obstacles will affect the search algorithms and the determined route
    - A reasonable model should include the problem specific,
        - e.g. in urban environments the spaces are not flat and include buildings, mountains, other vehicles, radar areas, and so on
    - The obstacles can be any geometrical figures: cubes, pyramids, floating balls, etc.
    - The parameterization of the obstacle set defined by the geometric centers of the physical obstacles will be a key factor.
    - Obtaining the accurate coordinates of the geometric centers of obstacles is challenging in the real world
    - Inclusion of additional buffer space is needed to mitigate the impact of measuring errors during the planning process
    - The environment type (containing bridges, buildings (convex, and/or concave), complex and cluttered spaces will determine the selection of representation methods

3. Path Planning in UAV Networks

3.3 Environment Representation Methods

- The 3D world space/environment can be represented in several approaches
  - **Cell decomposition**
  - **Roadmap**
  - **Potential field**

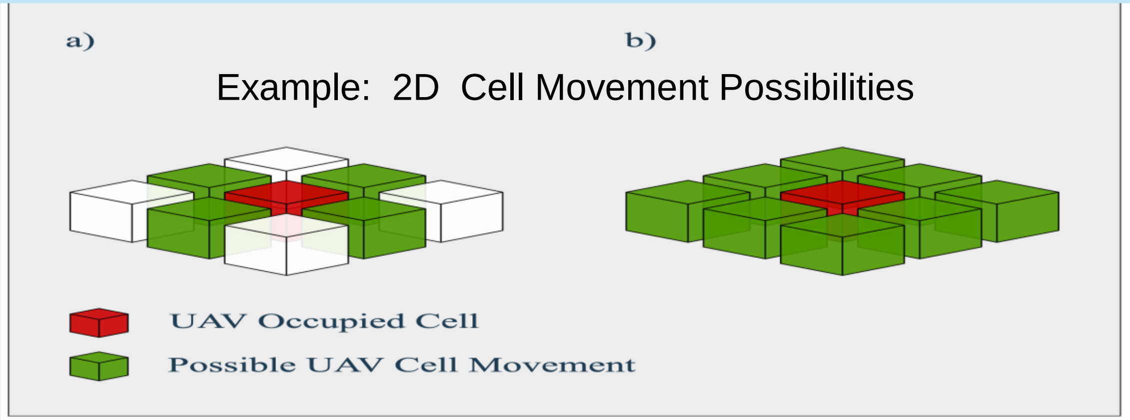


- **Cell decomposition**
  - The environment space (where UAV operate) is divided into a series of nonoverlapping cells
  - Result: a defined and navigable structure to the environment space, constructed around the availability of traversable relationships between cells

Figure Source: M,R. Jones, S.Djhael, K. Welsh Path-planning for Unmanned Aerial Vehicles with Environment Complexity Considerations: A Survey, ACM Comput. Surv., Vol. 1, No. 1, November 2022.

3.3 Environment Representation Methods

- **Cell decomposition** (cont'd)
  - *Approximate Cell Decomposition*.
    - It overlays a regular grid structure upon the environment problem space
    - Decomposition into a set of structured cells; each cell's location within the environment is represented by a Cartesian coordinate system
    - The boundaries of cells remain rigid, s.t. they may not precisely correlate with objects and obstacles within the environment.
    - A cell's total internal space discomposed of free space and obstacle space
    - A cell only partially filled by an obstacle is classified as obstacle space
    - Implementation variants: 2D or 3D

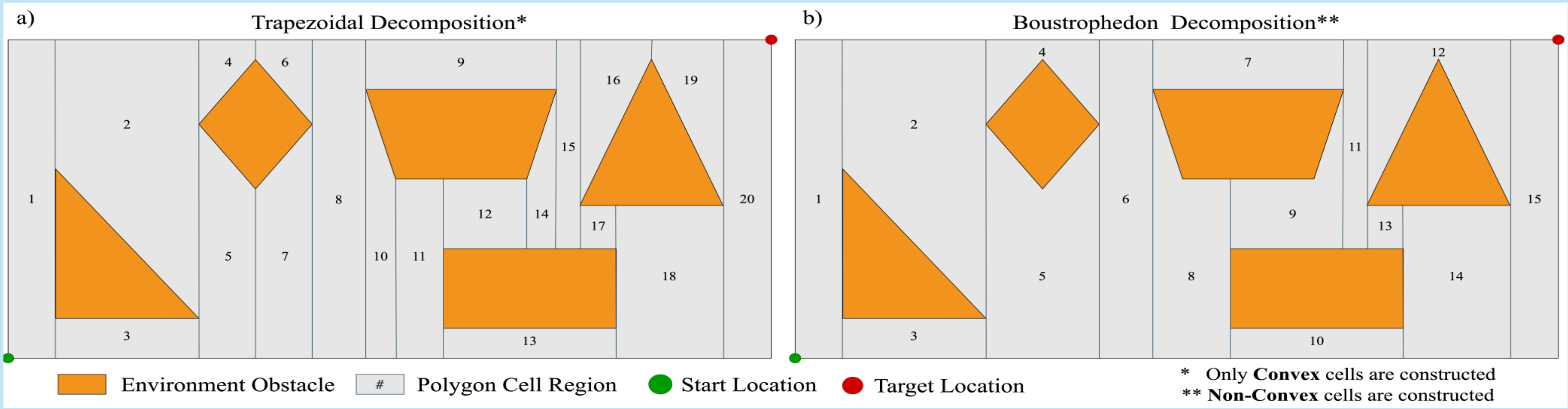


Source: M,R. Jones, S.Djhael, K. Welsh Path-planning for Unmanned Aerial Vehicles with Environment Complexity Considerations: A Survey, ACM Comput. Surv., Vol. 1, No. 1, November 2022.

3. Path Planning in UAV Networks

3.3 Environment Representation Methods

- **Cell decomposition** (cont'd)
  - ***Exact Cell Decomposition***
    - The space is divided into several non-overlapping polygon regions
    - Approaches:
      - *Trapezoidal*: the space is split in distinct convex cell regions
        - The method typically sweeps vertically left to right across the environment, appending vertical deconstruction lines, where an obstacle vertex is encountered
      - *Boustrophedon:* It minimizes the coverage path length in comparison to the trapezoidal, through reducing the number of polygon cell regions created



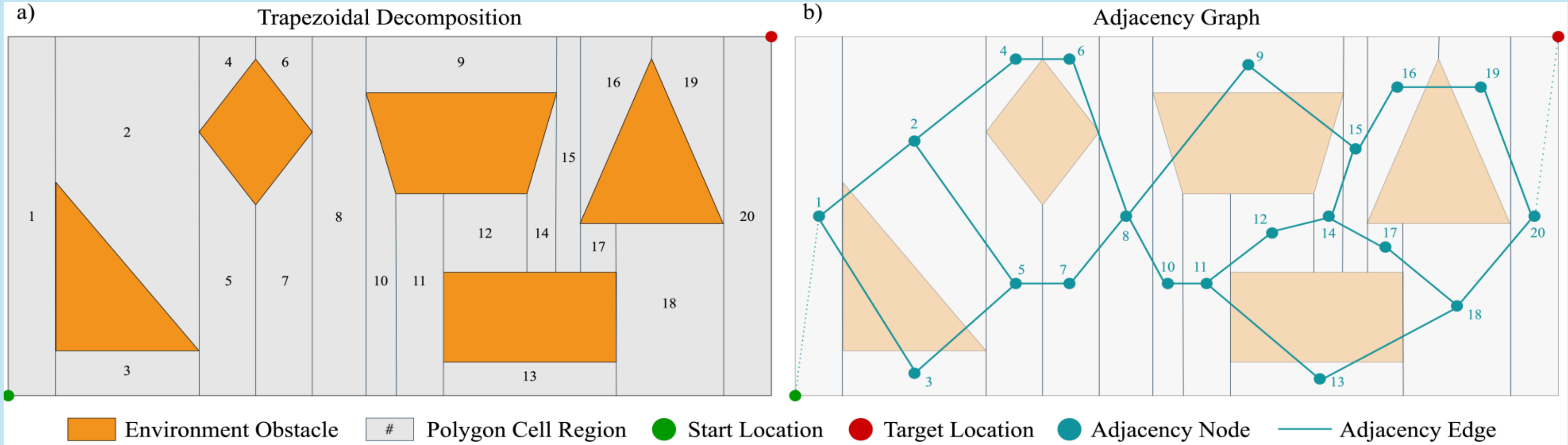
Source: M,R. Jones, S.Djhael, K. Welsh Path-planning for Unmanned Aerial Vehicles with Environment Complexity Considerations: A Survey, ACM Comput. Surv., Vol. 1, No. 1, November 2022.

3. Path Planning in UAV Networks

3.3 Environment Representation Methods

- **Cell decomposition** (cont'd)
  - ***Exact Cell Decomposition*** (cont'd)
  - *Note: Boustrophedon is a style of writing in which alternate lines of writing are reversed, with letters also written in reverse, mirror-style*
  - Between cell regions, an adjacency relationships can be defined, leading to a connectivity graph
    - The graph nodes are placed in the free space cell region locations
    - Result: a continuous free space path can be planned across the environment space based upon cell region relationships

Trapezoidal conversion to Adjacency Graph



Source: M,R. Jones, S.Djhael, K. Welsh Path-planning for Unmanned Aerial Vehicles with Environment Complexity Considerations: A Survey, ACM Comput. Surv., Vol. 1, No. 1, November 2022.

3. Path Planning in UAV Networks

3.3 Environment Representation Methods

- **Cell decomposition** (cont'd)
  - ***Adaptive Cell Decomposition***
  - It deconstructs the environment only where an obstacle's presence requires
  - When applied to a PP scenario an adaptive called schema (Quadtree) is constructed by dividing the space into four equal sub-regions
    - Where an obstacle exists, then regions are further recursively decomposed into four supplementary child regions until the desired stopping condition is met
  - The adaptive strategy can also be applied to a 3D environment
- Cell decomposition define both free and obstacle space within the overall space, so the range of movement available to UAVs within free space is unbounded
- Results : large search space for any path-planning algorithm
- **Roadmap Representation**
  - It is typically a connectivity graph whose nodes represent key free space locations within an environment. The graph construction strategies can be different
  - The edges (each one may have a weight, e.g., time or distance) represent the ability to transit safely between the adjoined nodes
  - The reduction of an environment via a roadmap approach into a graph-based structure, is similar to a classical route planning optimisation problem
    - where optimal routes are identified by comparing the sum of edge weights in candidate paths
  - A PP algorithm is applied to this arrangement to to discover an optimal path.

3. Path Planning in UAV Networks

3.3 Environment Representation Problem

- **Roadmap Representation** (cont'd)
  - ***Visibility graphs (VG)***
    - Consider a set *O* of pairwise disjoint objects in the plane (seen as obstacles in UAV motion planning).
    - The visibility graph is a representation model

- For polygonal obstacles the vertices of these polygons are the nodes of the visibility graph
- Two nodes are connected by an arc if the corresponding vertices can see each other
- Algorithms for computing the visibility graph of a polygonal scene have been developed
- Different complexity orders have been demonstrated for computing the visibility graph of a polygonal scene with a total of n vertices: e.g., $O(n^2 \log n)$, $O(k + n \log n)$ (k is the number of arcs of the visibility graph)

- A weakness : in the construction process, generated paths pass within close proximity to the obstacles they seek to avoid

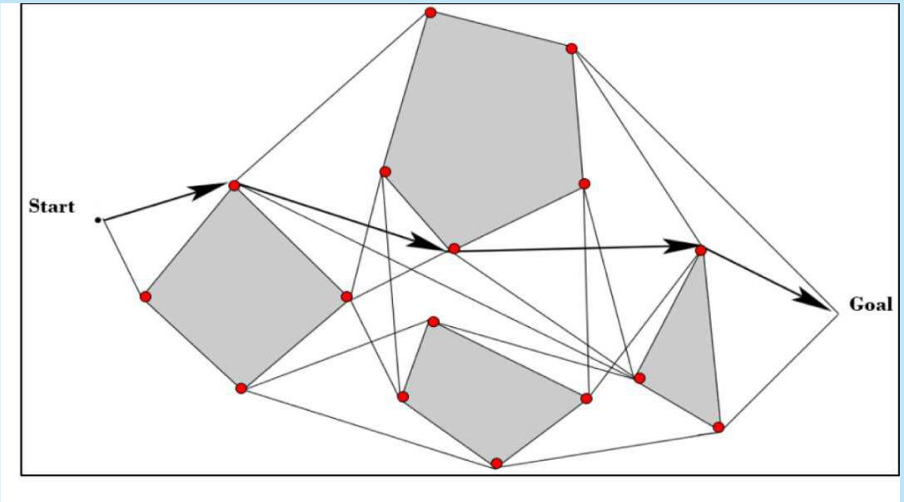


Figure- Source: M. N.Bygi, 3D Visibility Graph, https://sharif.edu/~ghodsi/papers/mojtaba-nouri-csicc2007.pdf

3. Path Planning in UAV Networks

3.3 Environment Representation Methods

- **Roadmap Representation** (cont'd)
  - ***Voronoi diagrams* and *path solutions***
    - Let P = {p_1, p_2, …p_n} be a set of points (called *sites*) in a 2D Euclidean plane
    - The space is decomposed into regions around each site, s.t. all points in the region around p_i are closer than to any other point in *P*
    - For UAV movement, one can consider the points in P as representing obstacles/threats.
    - The cells edges can be available paths (of an UAV) to the nearest node to the target positions.
    - A PP algorithm searches the shortest path to go to the nearest node to the target positions.

Source: Tong, Wu Wen chao, H. Chang qiang, X. Yong bo, Path Planning of UAV Based on Voronoi Diagram and DPSO H., Elsevier, Procedia Engineering 00 (2011) 000–000 4198 – 42031877-7058, doi:10.1016/j.proeng.2012.01.643, www.sciencedirect.com

3. Path Planning in UAV Networks

3.3 Environment Representation Problem (cont'd)

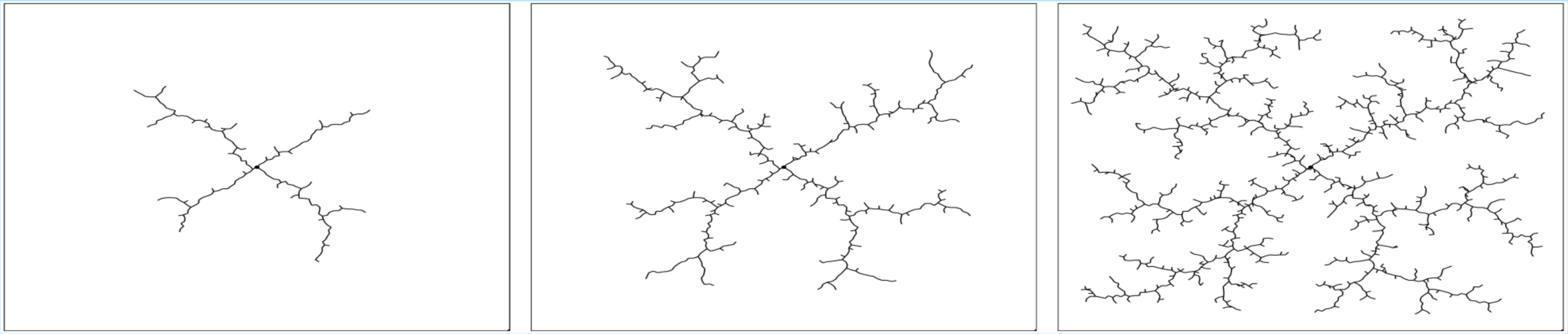
- **Roadmap Representation** (cont'd)
  - **Probabilistic Roadmap**
    - Visibility graph and Voronoi: the path generation is dictated solely by the placement of obstacles within the environment
    - A probabilistic approach deconstructs the available free problem space into a set of randomly placed connectivity nodes
    - Connecting nodes with edges is based upon proximity to a nearest neighbour node, combined with the perceived visibility and ability to pass unhindered between nodes
    - In path construction a significant level of environment knowledge is required
    - This construction method does not provide an optimal solution, but is able to guarantee completeness based upon the increasing number of nodes added

Source: M. Farooq et al. Quadrotor UAVs flying formation reconfiguration with collision avoidance using probabilistic roadmap algorithm. In 2017 International Conference on Computer Systems, Electronics and Control (ICCSEC), pages 866–870. IEEE, 2017.

3. Path Planning in UAV Networks

3.3 Environment Representation Problem

- **Roadmap Representation** (cont'd)
  - **Rapidly-exploring Random Trees (RRTs)**
    - RRT focuses upon a randomised approach for exploration of the environment
    - The algorithm searches nonconvex, high-dimensional spaces by randomly building a space-filling tree
    - An explorative branching strategy is applied; branching paths are constructed originating from a root node
    - The tree is constructed incrementally from samples drawn randomly from the search space and is inherently biased to grow towards large unsearched areas of the problem
    - A high level of environment knowledge is required in tree construction to allow successful placement of future nodes
    - RRT offers a configurable strategy to manage tree growth and exploration of the problem space.



Source: S.M. LaValle et al. Rapidly-exploring random trees: A new tool for path planning. 1998 Technical *Report (TR 98–11). Computer Science Department, Iowa State University..*

3. Path Planning in UAV Networks

3.3 Environment Representation Problem

- **Roadmap Representation** (cont'd)
  - **Rapidly-exploring Random Trees (RRTs)** (cont'd)
    - RRT
      - can handle problems with obstacles and differential constraints (nonholonomic and kinodynamic) and can be used in autonomous robotic/UAV motion planning
      - generates open-loop trajectories for nonlinear systems with state constraints
      - can also be considered as a Monte-Carlo method to bias search into the largest Voronoi regions of a graph in a configuration space

    - *Note 1*: A *nonholonomic* system: its state depends on the path taken in order to achieve it.
      - The system is described by a set of parameters subject to differential constraints and non-linear constraints,
        - s.t. when the system evolves along a path in its parameter space (the parameters varying continuously in values) but finally returns to the original set of parameter values at the start of the path, the system itself may not have returned to its original state.
    - *Note 2: Kinodynamic planning* (In motion planning), is a class of problems for which velocity, acceleration, and force/torque bounds must be satisfied, together with constraints such as avoiding obstacles.

3. Path Planning in UAV Networks

3.3 Environment Representation Problem

- **Artificial Potential Field (APF)**
  - The cell decomposition and roadmap approaches build an environment representation from prior known environment knowledge
  - (APF) computes in real-time a directional force to be applied to a UAV, based upon
    - the gravitational attractive forces applied by goal or target locations
    - the cumulative repulsive forces applied by obstacles
  - In a real-world environment
    - the gravitational force is proportional to the Euclidean distance from the UAV to target locations
    - the repulsive forces can be derived from mounted sensors capable of calculating obstacle distance.
  - The UAV makes successive evaluation of the resultant forces
  - The abstract representation of APF field forces provided across a whole environment grants a UAV the potential for significant autonomy (to find a transit path across an environment)
  - APF enables a reactive path-planning; dynamic obstacles influence APF forces in real-time allowing for adaptive navigation decisions

N. He et al., Dynamic path planning of mobile robot based on artificial potential field, 2020 Int'l Conf. on Intelligent Computing and Human-Computer Interaction (ICHCI), IEEE, 2020.

3. Path Planning in UAV Networks

3.4 Path Planning Algorithms Taxonomy

- Several types of PP algorithms can be defined
- They can be associated with particular methods of environment representation
  - Node-based Optimal
  - Sampling -based
  - Mathematical Model-based
  - Bio-inspired
  - Multi-fusion based
  - Machine learning – based

- *Ref: L.Yang et al. Survey of robot 3D path planning algorithms. Journal of Control Science and Engineering, 2016*

3. Path Planning in UAV Networks

3.4 Path Planning Algorithms Taxonomy

- **Node-based Optimal Algorithms**
- Classical well-known are Dijkstra (shortest path – SP) and A*, to find optimal routes within a graph
- To enhance the classical solutions some trends are recognized
  - enhance an established well-defined algorithm itself
  - include an existing algorithm as a component within a wider path-planning heuristic
  - ***Enhancement examples - in UAV domain***
    - Add to Dijkstra's SP algorithm additional parameters, (e.g., waiting and charging times, within the environment's fast charging machines), augmenting the traditional E2E SP calculation.
    - Combine an existing algorithm with novel PP methods thus generating feasible paths for multiple UAVs using a heuristic prioritized planning approach
    - Enhanced multi-UAV planning through a new cooperative planning capability, supporting a UAV swarm scenario at a low computational cost, whilst applying a traditional sparse A* algorithm to plan each individual UAVs path
    - Implementation of an improved Voronoi diagram graph generation strategy to deconstruct the environment, once implemented the traditional Dijkstra algorithm
- Challenge: the predefined nature of the graph itself, limits the applicability of such algorithms to dynamic-unknown scenarios
- Future work should be made on adapting Voronoi techniques to dynamic or unknown scenarios.

Ref: E.W. Dijkstra et al. A note on two problems in connexion with graphs. Numerische mathematik, 1(1):269–271, 1959.
P.E. Hart et al. A formal basis for the heuristic determination of minimum cost paths. IEEE transactions on Systems Science and Cybernetics, 4(2):100–107, 1968.

3. Path Planning in UAV Networks

3.4 Path Planning Algorithms Taxonomy

- **Sampling –based algorithms**
  - A required prerequisite of problem space knowledge exists, s.t. obstacle or free space environment information can be sampled and interpreted by a planning algorithm
  - Sampling-based approaches are considered as a black box returning a feasible collision-free path with significant advantages of high-speed implementation
  - The methods use only information from a collision detector while searching the configuration space to sample the environment as a set of nodes or other forms, then map the workspace or just search randomly to nd an optimal path
  - Examples: ***Probabilistic Roadmap (PRM)*** and ***Rapidly exploring Random Tree (RRT)***
    - These have demonstrated efficacy as frameworks for navigating high-dimensional spaces to generate feasible solutions
    - Problem: that they do not ensure the attainment of an optimal solution.
  - **PRM** works well in high-dimensional search spaces
    - The basic idea: take random instances from the configuration space
    - Then it checks whether or not they are in the free space, and utilize a local planner to connect these configurations to other nearby configurations
    - PRM is inefficient when obstacle geometry is not known beforehand
  - **RRT** algorithms is a solution regardless of the geometry of the obstacles
    - It explores a random tree to produce the first feasible solution to the goal through a cluttered environment with non-convex obstacles

Source: S.Ghambari, M.Golabi, L.Jourdan, J.Lepagnot and L.Idoumghar, UAV Path Planning Techniques: A Survey, RAIRO-Oper. Res. 58 (2024) 2951–2989 RAIRO Operations Research, https://doi.org/10.1051/ro/2024073 www.rairo-ro.org

3. Path Planning in UAV Networks

3.4 Path Planning Algorithms Taxonomy

- **Mathematical model-based algorithms**
  - Emerging field, applying **Linear Programming (LP)** and **Mixed-integer Linear Programming** (MILP). These methods can provide valuable insights into the problem's structure
  - The PP problem is solved as a math optimization problem. A set of inequalities is used to model the obstacles and environment. The methods:
    - seek to reduce a problem's complexity through bounding the diverse number of possibilities presented by a variable, to integer values
    - employ probability and mathematical models to predict future events and to determine the most efficient curve between the start and goal configurations by minimizing a certain scalar quantity
  - Dynamic programming is another approach, to obtaining an optimal path when full information and unlimited computation resources are available
  - Problems: often failure appears to achieve global optimality within a reasonable time frame and are occasionally ineffective in generating feasible solutions
    - inability of MILP to obtain optimal solutions for large instances (i.e., sets of routing destinations) without the application of such a metaheuristic approach.

Source: S.Ghambari, M.Golabi, L.Jourdan, J.Lepagnot and L.Idoumghar, UAV Path Planning Techniques: A Survey, RAIRO-Oper. Res. 58 (2024) 2951–2989 RAIRO Operations Research, https://doi.org/10.1051/ro/2024073 www.rairo-ro.org

3. Path Planning in UAV Networks

3.4 Path Planning Algorithms Taxonomy

- **Bio-ispired algorithms**
  - Popular for solving UAV PP problems
  - They typically deconstruct an environment into a searchable problem space using exclusively approximate cell decomposition approaches
  - Examples: **Ant Colony Optimisation (ACO), Particle Swarm Optimisation (PSO)**

  - **Ant Colony Optimisation (ACO)**
    - Swarm intelligence-based algorithm inspired by the collective behavior of ants
    - The standard algorithm is inherently parallel and straightforward to execute
    - It has resilience and the capacity to explore improved solutions
    - The walking path of ants is used to express the feasible solution
    - In UAV PP each ant is intended to search for the shortest path in the free space
    - Over time, there is a continuous augmentation in the concentration of pheromones along shorter paths, accompanied by a corresponding rise in the preference of ants for those paths
    - This reinforcement mechanism eventually converges, guiding the entire ant colony toward the identification of the optimal path
    - ACO improvement proposal: to reduce the explorative search ability of the ant colony, constraining and guiding ants towards the target destination, whilst also allowing an Ant’s step size to be varied, based upon environment obstacles within its surroundings

Source: S.Ghambari, M.Golabi, L.Jourdan, J.Lepagnot and L.Idoumghar, UAV Path Planning Techniques: A Survey, RAIRO-Oper. Res. 58 (2024) 2951–2989 RAIRO Operations Research, https://doi.org/10.1051/ro/2024073 www.rairo-ro.org

3. Path Planning in UAV Networks

3.4 Path Planning Algorithms Taxonomy

- **Bio-ispired algorithms** (cont'd)
  - **Particle Swarm Optimisation (PSO)**
    - PSO simulates the social behavior of a swarm of birds or a school of fishes
    - In UAV PP the the optimization is achieved by utilizing the shared information of the global and local solutions in the swarm
    - PSO Actions summary
      - Simple agents, called particles, move in the search space
      - The position of a particle shows a candidate solution/path
      - The velocity of each particle undergoes systematic adjustments in adherence to defined rules, aimed at refining their positions within the search space.
      - Concurrently, the collective intelligence of the best solution is captured and communicated to fellow particles in subsequent iterations
      - When the stopping conditions are reached, the algorithm terminates and the best solution is recorded as a safe and feasible path
    - PSO algorithms improvement proposals:
      - maximum density convergence DPSO (MDC-DPSO)
      - fast cross-over DPSO algorithm (FCO-DPSO)
      - accurate coverage exploration DPSO algorithm (ACE-DPSO)

Source: M,R. Jones, S.Djhael, K. Welsh Path-planning for Unmanned Aerial Vehicles with Environment Complexity Considerations: A Survey, ACM Comput. Surv., Vol. 1, No. 1, November 2022.

Source: S.Ghambari, M.Golabi, L.Jourdan, J.Lepagnot and L.Idoumghar, UAV Path Planning Techniques: A Survey, RAIRO-Oper. Res. 58 (2024) 2951–2989 RAIRO Operations Research, https://doi.org/10.1051/ro/2024073 www.rairo-ro.org

3. Path Planning in UAV Networks

3.4 Path Planning Algorithms Taxonomy

- **Multi-fusion based algorithms**
- This approach seeks an improvement in planning ability/ efficiency through integration of two established algorithms
  - **Examples**
    - Introducing guiding factors (from the the A* algorithm), for a more efficient exploration using a guiding force, directing the UAV towards the target destination
    - Introducing a taboo node matrix, to support the prevention of a deadlock state occurrence
    - Combinatorial path improvement strategies implement an initial path Dijkstra-selection policy, plus a PSO being applied to produce smoothed transitions between path edges

References

- *C.Yin et al. Offline and online search: UAV multiobjective path planning under dynamic urban environment. IEEE Internet of Things Journal, 5(2):546–558, 2017.*
- *Y. Feng et al. Path planning of uninhabited aerial vehicle added the guiding factor. In 2019 IEEE International Conference on Unmanned Systems (ICUS), pages 866–870. IEEE, 2019.*
- *Z. Chen et al. Obstacle Avoidance Strategy for Quadrotor UAV based on Improved Particle Swarm optimization Algorithm. In 2019 Chinese Control Conference (CCC), pages 8115–8120. IEEE, 2019.*

3. Path Planning in UAV Networks

3.4 Path Planning Algorithms Taxonomy

- **Machine Learning –based algorithms**
  - Many approaches based on Machine learning (ML) algorithms are recently proposed in UAV PP area
  - ML algorithm types *: Supervised Learning, Unsupervised learning, Reinforcement Learning (RL), Deep Learning (DL), Deep Reinforcement Learning (DL),* etc., learn from existing data to build and refine models to solve different tasks.
  - ML techniques applied in UAV PP area: clustering methods (QT and K-means), DL, RL, DRL, cooperative and geometric learning, etc. – can be employed for UAV PP and collision avoidance.
  - ML-based applications in UAV -examples:
    - to deal with different perspectives of autonomous UAV flights including tuning the
    - parameters for the controller
    - applying adaptive control algorithms for autonomous flight
    - recognizing objects in farming
    - real-time path planning
    - real-time collision avoidance considering obstacles or other aerial vehicles
    - decisions within an environment problem space, seeking to optimize a given cumulative reward (RL)

Refs: J.L. Junell, E.J. Van Kampen, C.C. de Visser and Q.P. Chu, Reinforcement learning applied to a quadrotor guidance law in autonomous flight, in AIAA Guidance, Navigation, and Control Conference. American Institute of Aeronautics and Astronautics, Inc. (2015) 1990.

G. Kahn, A. Villaflor, V. Pong, P. Abbeel and S. Levine, Uncertainty-aware reinforcement learning for collision avoidance. Preprint arXiv:1702.01182 (2017).

R. Jones, S.Djhael, K. Welsh Path-planning for Unmanned Aerial Vehicles with Environment Complexity Considerations: A Survey, ACM Comput. Surv., Vol. 1, No. 1, November 2022.

3. Path Planning in UAV Networks

3.5 Examples of Traditional Path Planning Algorithms

- They are related to specific representations of the environment
- **Dijkstra Algorithm**
  - Classic solution to solve the shortest path problem
  - It make a breadth first state space search looking for the shortest distance of any point in the whole free space, layer by layer, through the initial point until it reaches the target point
  - In UAV PP, due to the use of free search, the amount of data of Dijkstra algorithm is greatly increased, which affects the speed of solution
  - Different researchers have improved and optimized Dijkstra algorithm and gradually replaced it
- **A* (A-Star)**
  - Used in path finding problems on graphs and meshes
  - It is using a heuristic function to perform an informed search, to estimate the cost of the remaining path to the goal
  - It has fast calculation speed and can efficiently obtain UAV path information.
  - It is efficient in environments with precise and known information
  - The performance degrades in complex and unknown 3D environments (lack of enough information about space structure)

Source: C. G. Arnaldo , M.Z. Suárez , F.P.Moreno and R.Delgado-Aguilera Jurado, Path Planning for Unmanned Aerial Vehicles in Complex Environments Drones 2024, 8, 288. https://doi.org/10.3390/drones8070288

3. Path Planning in UAV Networks

3.5 Examples of Traditional Path Planning Algorithms

D* (D-Star)

- D* - real-time search algorithm that recalculates the route when changes occur in the environment
- It is suitable for dynamic environments
- Its computational complexity can be high (in 3D, with many moving objects and obstacles

- **Theta* (Theta-Star)**
  - It is an improvement of A* that performs a search in the discretized search space using linear interpolation to smooth the path
  - Theta* can produce more direct and efficient trajectories than A*
  - The performance is lower in environments with multiple obstacles and complex structures.
- **PRM (Probabilistic Roadmap)**
  - It creates a network of valid paths through the *random sampling* of the search space. PRM can generate valid trajectories, but its efficiency is lowering by the density of the search space
  - It may require a high number of sampling points to represent accurate trajectories in a 3D environment with complex obstacles

3. Path Planning in UAV Networks

3.5 Examples of Traditional Path Planning Algorithms

- **RRT (Rapidly Exploring Random Tree)**
  - RRT uses *random sampling* to *build a search tree* that represents the possible trajectories of the UAV; It is widely used in PP for complex and unknown environments
  - It has a probabilistic nature and able to efficiently explore the search space, so it is suitable for route generation in 3D environments with obstacles and unknown structures
- ***Note: Many other RRT variants have been developed in different studies***
- ***Examples***
- **RRT* (Rapidly Exploring Random Tree Star)**
  - It is an enhanced RRT; it optimizes the trajectories generated by the original algorithm
  - RRT* reduces the path length and optimizes the tree structure
  - It can provide optimal routes, but its computational complexity is higher in complex 3D environments
- **RRT*-Smart**
  - It accelerates the convergence rate of RRT* by using path optimization (in a similar fashion to Theta*) and intelligent sampling (by biasing sampling towards path vertices, which – after path optimization – are likely to be close to obstacles)

3. Path Planning in UAV Networks

3.5 Examples of Traditional Path Planning Algorithms

- **A*-RRT and A*-RRT***
  - A *two-phase* PP method that uses a graph search algorithm
    - 1. search for an initial feasible path in a low-dimensional space (not considering the complete state space) avoiding hazardous areas and preferring low-risk routes
    - 2. which is then used to focus the RRT* search in the continuous high-dimensional space
- **Real-Time RRT* (RT-RRT*)**
  - A variant of RRT* and informed RRT* that uses an online tree rewiring strategy that allows the tree root to move with the agent without discarding previously sampled paths, in order to obtain real-time path-planning in a dynamic environment
- **Theta*-RRT**
  - A two-phase PP method similar to A*-RRT* that uses a hierarchical combination of any-angle search with RRT motion planning for fast trajectory generation in environments with complex nonholonomic constraints
- **…. o**ther of RRT variants
- **Artificial Potential Fields**
  - It uses attractive and repulsive forces to guide the movement of the UAV towards the goal and away from obstacles
  - Transform the impact of targets and obstacles on the movement of the drone into an artificial potential field.
  - It can generate smooth trajectories, but may suffer from local minima and oscillations in environments with complex obstacles

3. Path Planning in UAV Networks

3.5 Examples of Traditional Path Planning Algorithms

- **Depth-First Search (DFS)**
  - It traverses a tree by exploring one node and its descendants at a time; a node is selected initially
  - The search is progressively expanded to the deepest nodes (backtracking only when there are no more child elements to explore)
  - If the deepest node does not contain the desired solution, the algorithm backtracks to the start of the tree and continues the search by exploring adjacent nodes on the right, following a similar deep format
  - This process continues until the solution is found
  - **Problems**:
    - DFS may miss large portions of the workspace since it tries to search several paths at a time before completing one path
    - DFS may not always yield the most optimal solution as it prioritizes the first successful path found, disregarding the time or steps taken to reach it, with the risk of falling into a loop of exploring an infinite depth
    - DFS can be time-consuming because it may delve into uncharted depths of a single node without necessarily leading to a viable solution

Source: L. Paulino, C. Hannum, A.S. Varde and C.J. Conti, Search methods in motion planning for mobile robots, in Intelligent Systems and Applications, edited by K. Arai. Springer International Publishing (2022) 802–822.

3. Path Planning in UAV Networks

3.5 Examples of Traditional Path Planning Algorithms

- **Breadth-First Search (BFS)**

  - In BFS all the current level nodes are visited prior to their descendants, following a systematic approach where shallow nodes are expanded first by exploring all the subsequent level nodes along the path.
  - DFS is exploring a single path to its deepest depths; however, BFS expands its search by including all nodes within each layer, adhering to the FIFO principle implemented through a queue structure.
  - BFS could be slower than DFS in finding a path, however, it can be preferred due to its systematic exploration of all nodes within each layer; it is able to keep track of visited nodes before moving on to the next layer.
  - Problems:
    - BFS requires more memory compared to DFS due to the need to store all visited nodes in the order they were encountered
    - This storage step is important in BFS tree traversal as it influences the sequence in which the algorithm explores nodes in the subsequent layer

Source: L. Paulino, C. Hannum, A.S. Varde and C.J. Conti, Search methods in motion planning for mobile robots, in Intelligent Systems and Applications, edited by K. Arai. Springer International Publishing (2022) 802–822.

3. Path Planning in UAV Networks

3.6 UAV Swarm Path Planning

- An UAV swarm can make decisions collectively and complete its aerial mission using relatively simple instructions due to the AI technology and edge computing
- UAV swarm is its application for both civilian and military purposes using swarm intelligence
- *Swarm intelligence* (SI)
  - SI is an evolving area of bio-inspired artificial intelligence
    - This is obtained due to the deep interconnection of the real system having feedback loops
    - SI concept allows scheduling, clustering, optimizing, and routing a cluster of similar individuals
    - All the individuals follow clear rules and interact with each other and also with the environment

- *SI basic principles:*
  - Proximity: the swarm individuals can easily respond to the environmental variance that is caused by interactions among them
  - Quality: a swarm can respond to quality factors like location safety only
  - Diverse response: enables to design of the distribution s.t. all the individuals are protected from environmental fluctuations to a maximum level.
  - Stability: restricts the swarm to show a stable behavior with the changes in the environment.
  - Adaptability principle: the swarm sensitivity as the behavior of the swarm changes with the change in environment

3. Path Planning in UAV Networks

3.6 UAV Swarm Path Planning

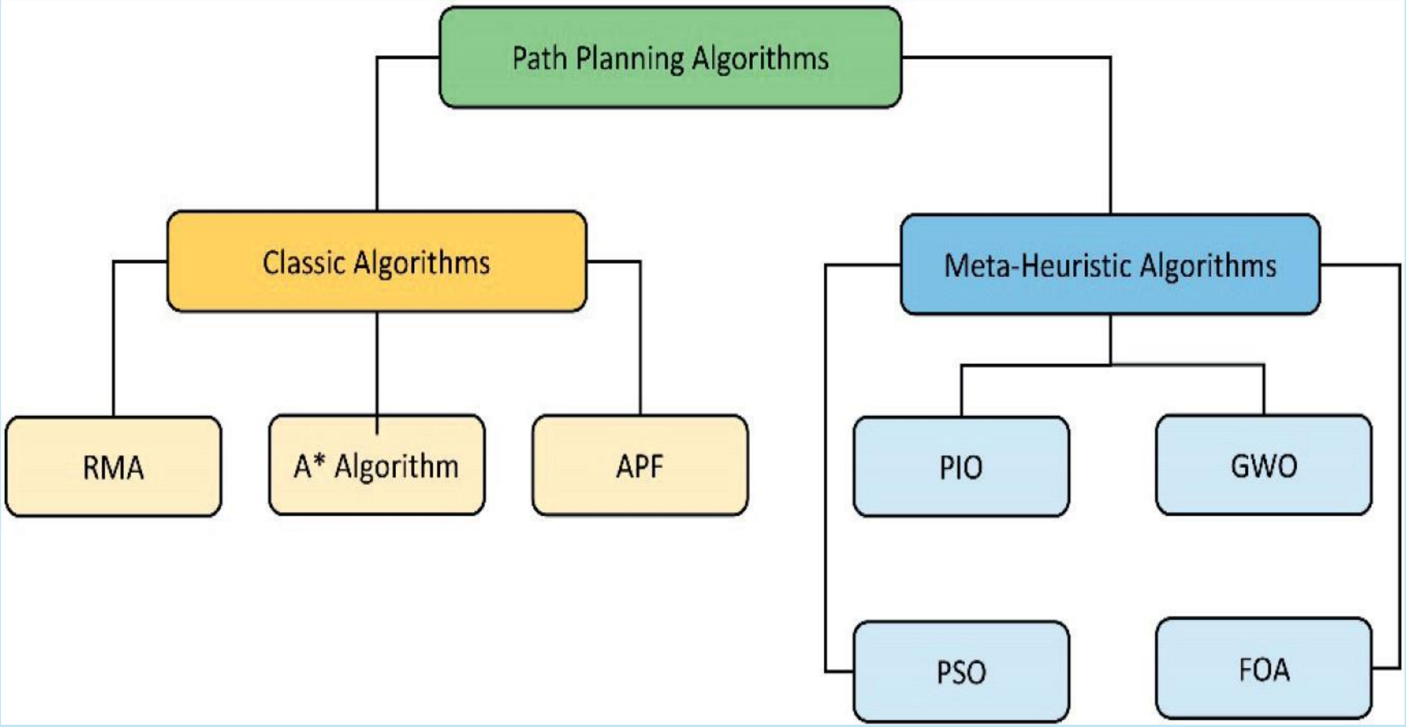
- *SI mechanisms*
  - These concern the environment, interactions, and activities of the individuals in a swarm
  - There is no direct communication among the individuals in a swarm; they interact with each other through environmental alterations
  - Thus, environmental alterations serve as external memory
  - This simulation of work is done by applying the stigmergy behaviour of all the swarm members (stigmergy- a mechanism of indirect coordination through the environment, between agents or actions)
  - The individuals choose their actions with an equilibrium between a perception-reaction model and any random model
- Examples of programming languages for SI: Proto-swarm, swarm, Star-Logo, and growing point
  - The UAV PP of a swarm is challenging (NP-hard problem)
  - The PP algorithms proposed for swarm are generally classic and meta-heuristic algorithms
  - Classic algorithms require environmental information
    - Examples: *Road map algorithm (RMA), A** and *Artificial Potential Field (APF)* algorithms
  - Meta-heuristic algorithms require information on the real-time position and measured environmental elements. Examples:
    - *Particle swarm optimization (PSO), pigeon-inspired optimization (PIO), Fruit Fly Optimization algorithm (FOA), Gray Wolf Optimization algorithm (GWO)*

Source: M.M. Iqbal, Z.Anwar Ali, R. Khan and M.Shafiq, Motion Planning of UAV Swarm: Recent Challenges and Approaches, IntechOpe, 2022, DOI: http://dx.doi.org/10.5772/intechopen.106270

3. Path Planning in UAV Networks

3.6 UAV Swarm Path Planning

- **PP algorithms solutions for UAV swarm**



Source: M.M. Iqbal, Z.Anwar Ali, R. Khan and M.Shafiq, Motion Planning of UAV Swarm: Recent Challenges and Approaches, IntechOpe, 2022, DOI: http://dx.doi.org/10.5772/intechopen.106270

3. Path Planning in UAV Networks

3.7 Challenges, Open research issues and Trends

- **Path Planning in 3D environments and time domain**
  - Further studies and optimization methods are needed for real time in 3D space
  - Difficulties are higher and the problem is much more complex than 2D PP
    - Need to consider kinematic, geometric, physical and temporal constraints, flight risk levels, airspace restrictions, etc.
  - 3D UAV PP are needed, especially in complex environments such as urban areas caves, and forests
- **Mathematical models for the PP**
  - Multi-objective optimization is not enough addressed in the current models.
  - Multi-objective functions, Pareto optimal solutions can be obtained taking all factors into consideration will make the math UAV PP models more realistic
  - Multiple types of static and dynamic constraints are necessary to be considered in PP models
- **Experimental work**
  - Many works perform some computational simulation
  - However, for the UAV use in many different applications it is necessary to work with real experiments. Problem in experiments : number of UAVs considered
  - The complexity of considering many UAVs is very high, but this is a necessary future work so that the use of UAVs especially in urban centers becomes a reality

3. Path Planning in UAV Networks

3.7 Challenges, Open research issues and Trends

- **Optimization techniques**
  - Many optimization algorithms and methods have been already studied:
    - Sampling-based, Node -based, Mathematic Model- based, Bioinspired. Multifusion-based, Ai, etc.
  - Future research combining different methods, such as AI-based (e.g., Neural networks, Deep Learning (DL), Reinforcement Learning, DRL, etc.), evolutionary algorithms with heuristic, fuzzy inference methods, and variants of more widely used methods
  - This need is due to the complexity of the problem of the UAV PP in real environments, and the different constraints

- **Integration of different segments**
  - The integration and communication of UAVs with terrestrial and space environments is a primary factor and involves also the architecture of the Internet of Drones (IoD).
  - Work is needed in order to make the different spaces connected to each other via communication protocols
  - Different factors need to be considered: data rate, coverage. scalability, reliability, security

Source J.V.Shirbayashi and L. B. Ruiz , Toward UAV Path Planning Problem Optimization Considering the Internet of Drones, IEEE Access, 2023

3. Path Planning in UAV Networks

3.7 Challenges, Open research issues and Trends

- **Security and privacy**
  - Many types of possible attacks exist, to which UAVs have to resist
  - Threat areas need to be diverted by the UAVs during the aerial path to be traveled
  - Security and privacy should be considered at each architectural layer: application, transport, network and physical layer
  - Privacy needs to be addressed in future work, given the UAV’s connectivity to ground and air space, large amounts of data need to be stored securely

- **UAVs in smart cities**
  - In smart cities things are connected and can collaborate intelligently and automatically to improve quality of life, save lives, and sustain resources.
  - UAV technology can play a vital role in improving many real-time applications of smart cities
  - More research involving UAVs and smart cities is necessary
  - Policies to encourage the use of UAVs are developed , promoting the economy of the sector, together with the development of new technologies such as DAA (Detect and Avoid) and UTM (UAS Traffic Management), etc.

3. Path Planning in UAV Networks

3.7 Challenges, Open research issues and Trends

- Current achievements in PP have included
  - 3D UAV PP considering the energy consumption and safety of drones.
  - Multi-objective mathematical modeling of UAV PP
  - Route planning in smart cities considering the IoD.
  - Development of tools that contribute to the advancement of real applications in IoD.

- Additional challenges in this context are:
  - Airspace regulations to govern the development of real UAV applications in different environments
  - UAV PP in real time considering energy-efficient and safety
  - Integration between UAVs and other means of transport (trucks, buses, etc.) for practical and safe applications in the context of smart cities
  - Development of tools and methodologies from real experiments that consider several UAVs

Source J.V.Shirbayashi and L. B. Ruiz , Toward UAV Path Planning Problem Optimization Considering the Internet of Drones, IEEE Access, 2023

3. Path Planning in UAV Networks

3.7 Challenges, Open research issues and Trends

- **3D Environment complexity issues**
  - UAV PP is a complex and multifaceted problem
  - The environment modelling techniques reported are applied only to the less complex classes of environment
  - The binary choice between a known/ unknown environment is a notable limitation capturing only the extreme cases
    - However, some problems may exist in which partial environmental knowledge is available
  - Research started, to define bounds for how much complete and accurate pre-existing environmental knowledge must be, such that the planned paths could be sufficiently flyable, or at least flyable with minor modification

- Availability of static-known environment knowledge, is acceptable in a simulated environment ; more work is necessary to allow usage in the real-world
  - Potential solutions
    - Exploration of the hybridised environment planning
      - pre-planning a path with a static representation of the environment
      - dynamic unknown obstacles are evaluated in flight, with minor changes supplied to a global path
    - Individual ability of a UAV to map or sense surroundings throughout an unknown environment
      - It is needed an initial environment survey, before requiring centralised processing to produce optimal transit paths

Source: M,R. Jones, S.Djhael, K. Welsh Path-planning for Unmanned Aerial Vehicles with Environment Complexity Considerations: A Survey, ACM Comput. Surv., Vol. 1, No. 1, November 2022.

3. Path Planning in UAV Networks

3.7 Challenges, Open research issues and Trends

- **3D Environment complexity issues** (cont'd)
  - 3D dimensionality creates inherent complexity problems in determining the UAV paths
  - Solutions
    - Split the problem into more manageable chunks, e.g. fixing of a UAV 3D altitude; PP becomes a 2D problem
      - Advantage: easier to address both time and computational constraints that might be otherwise not possible to meet in 3D computations
      - Drawback- the path could be non- optimum
    - Find some means for offloading some computational task from UAVs

  - Many (preferred) methods reduce the route planner's search space to enable real-time planning and re-planning (e.g., approximate cellular decomposition); other methods use the roadmap approach
  - Further research is necessary to decide which method is best suited towards a static vs dynamic environment or a known vs unknown environment
  - Bio-inspired, RL and multi-fusion based algorithms are mainly constructed around a cell decomposition approach

  - The majority of the node-based and sampling-based algorithms focus upon a roadmap approach
  - The APF is not so much due to the limited ability to maintain field knowledge over large areas,

Source: M,R. Jones, S.Djhael, K. Welsh Path-planning for Unmanned Aerial Vehicles with Environment Complexity Considerations: A Survey, ACM Comput. Surv., Vol. 1, No. 1, November 2022.

3. Path Planning in UAV Networks

3.7 Challenges, Open research issues and Trends

- **Communication models – should be refined and improved**
  - Usually, the simulations assume a static-known knowledge of the environment being easily accessible to the UAV and planning agent
  - However, such simulation models are constructed around a centralised control of the PP (scalability issues exist in non-centralised topologies – e.g. UAV swarm)
  - In such cases each UAV should wait for its peer to complete planning, thus large UAV systems face a potential computational planning bottleneck, affecting the communication model
  - Where an environment's complexity is known to the planning agent, it is implied that a communication model exists, supporting consistent knowledge sharing across the whole environment
  - Introducing an unknown environment presents an increased likelihood of conflict between either a UAV and obstacle or multiple UAVs
  - So more rich set of requirement is needed for a communication model that interacts with the wider UAV and planning agent
  - For large scale UAV networks increased communication volume difficulties are identified and such issues should be solved

3. Path Planning in UAV Networks

3.7 Challenges, Open research issues and Trends

- **Time considerations**
  - To achieve a reduction in computational complexity one may fix UAV's velocity constraining an active planning variable
  - To explore both a UAV's dynamic constraints precisely and limited application of path smoothing approaches may complicate the UAV path generation process
  - A computed optimal route could become worthless when the physical abilities of a UAV cannot replicate the route in real time
  - Open research issue: to adapt the environment model to a given problem, or vice-versa

CONTENTS

4. Conclusions

- **UAV technologies – strong development, high interest for a large area of applications and services**
- Major trend: seamless UAV integration in existing networks - complex task; there are significant challenges for networking, compared to traditional mobile networks

- **UAV Routing is complex**- many factors may have impact on routing solutions
  - Physical layer issues, dynamic topologies, 3D mobility and large range of speeds, delay tolerant networks problems, multi-UAV networks, multi-dimensional metrics for routing, cooperation of the routing with path planning
  - Real-time response aspects and path adjustment in dynamic context
  - Need to support collaborative tasks (swarms), coverage areas, areas, integration problems in novel network technologies like 5G, 6G, energy consumption control, different objectives for UAV in different classes of services, security, privacy etc.
  - A large variety of routing algorithms and protocols have been proposed, different in complexity, degree of performance, real time properties, and implementation requirements
  - Recent: AI/ML techniques are more and more used also in UAV routing solutions

4. Conclusions

- **UAV Path Planning**
  - Path Planning- very important aspect in UAV-based systems
  - Many traditional algorithms have been used/adapted/developed for UAV environment
  - Novel techniques based on AI/ML are proposed
  - Many open research issues exist, given the multitude of requirements, constraints and factors
    - 3D space, static/dynamic environment, requirements related to energy consumption, specific types of UAVs and journey ranges, real-time requirements, partial knowledge on environment (including static/dynamic obstacles), cooperative tasks for swarms, etc.)
  - PP algorithms:
    - No algorithm can guarantee the discovery of an optimal path in all scenarios
    - The algorithm optimality depends on different factors (problem domain, environmental complexity, problem representation, algorithm's native characteristics)
    - Certain algorithms are better in finding optimal paths within specific contexts (trade-offs between different algorithms exist)
    - Practical issues such as computational time and optimality requirements will determine the selection of an appropriate PP method
  - Novel techniques, refining existing algorithms, and addressing emerging challenges will lead for advancements in UAV path planning

- Thank you !
- Questions?

Unmanned Aerial Vehicles- Routing and Path Planning – Challenges and Trends

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Unmanned Aerial Vehicles- Routing and Path Planning – Challenges and Trends

- **List of general Acronyms**

5G CN	Core Network
5G-AN	5G Access Network
ACO	Ant Colony Optimisation
AI	Artificial Intelligence
AODV	Ad Hoc On Demand Distance Vector
APF	Artificial Potential Field
BFS	Breadth-First Search
CC	Cloud Computing
CP	Control Plane
CPP	Coverage Path Planning
CR	Cognitive Radio
D2D	Device to Device communication
DFS	Depth-First Search
DL	Deep Learning
DN	Data Network
DRL	Deep Reinforcement Learning
DoS	Denial of Services
DP	Data Plane (User Plane UP)
DTN	Delay Tolerant Network
E2E	End to End
FANET	Flying Ad hoc Network
FRZ	Flight Restriction Zone
GF	Greedy forwarding
GS	Ground Station
HRP	Hybrid Routing Protocol
HTOL	Horizontal Takeoff and Landing
IPP	Informative Path Planning

Unmanned Aerial Vehicles- Routing and Path Planning – Challenges and Trends

- **List of general Acronyms**

IoT	Internet of Things
MANET	Mobile Ad hoc Network
MAC	Medium Access Control
MCC	Mobile Cloud Computing
MEC	Multi-access (Mobile) Edge Computing
MILP	Mixed-integer Linear Programming
ML	Machine Learning
NF	Network Function
NFV	Network Function Virtualisation
ONF	Open Networking Foundation
PP	Path Planning
PRM	Probabilistic Roadmap
PRP	Proactive Routing Protocol
PSO	Particle Swarm Optimisation
QoE	Quality of Experience
RAN	Radio Access Network
RL	Reinforcement Learning
RRP	Reactive Routing Protocol
RRT	Rapidly-exploring Random Trees
SCF	Store-carry-and-forward
SDN	Software Defined Networking
UAV	Unmanned Aerial Vehicle

Unmanned Aerial Vehicles- Routing and Path Planning – Challenges and Trends

- **List of general Acronyms**

UAVNET	Unmanned Aerial Vehicle Network
UAV-BS	UAV- Base Station
UAV-RS	UAV Relay Station
UL	Uplink
V2X	Vehicle-to-everything
VANET	Vehicular Ad hoc Network
VG	Visibility Graph
VM	Virtual Machine
VTOL	Vertical Takeoff and Landing