Optimization for Urban Air Mobility

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Abstract. Urban Air Mobility (UAM) has the potential to revolutionize urban transportation. It will exploit the third dimension to help smooth ground traffic in densely populated areas. To be successful, it will require an organized and integrated approach able to balance efficiency and safety while harnessing common airspace resources. We believe that mathematical optimization will play an essential role to support the development of Urban Air Mobility. In this paper, we describe two important problems from this domain, operators 4D volume deconfliction, and air taxi trajectory deconfliction.

1 Urban Air Mobility

Urban Air Mobility (UAM), designates urban air transport systems that will move people and goods by air within and around dense city areas. Its purpose and objective is to help smooth urban ground traffic despite the increasing population density. The vast majority of urban air mobility aircraft designs, will share two main characteristics. Vertical Take-Off and Landing (VTOL) to operate in relatively small areas, e.g., rooftops, and distributed electric propulsion, which will exploit multiple small rotors to minimize noise (due to rotational speed) while providing high system redundancy. Two classes of vehicles are distinguished in UAM. Small drones, typically 55 lbs and below, will be used to carry cargo, e.g., parcel delivery. This category is generally referenced as Unmanned Aircraft System (UAS). Larger aircraft able to carry important cargo and passengers, e.g., air taxi.

Operating these new aircraft over large and densely populated areas will require an organized approach able to balance efficiency, and safety. The Urban air mobility Traffic Management (UTM) research initiative [9] has produced a general architecture which leverages fundamental ideas from large-scale air-traffic control, and adjust them to the key differences that provide for UAM (maneuverability, method of control, function, range, and operational constraints).

Over time, this architecture has been refined and adopted by the US Federal Aviation Agency (FAA) [3]. It is presented in Fig. 1 which exposes, at a high level, the various actors and components, their contextual relationships, as well as high-level functions and information flows. This architecture is grounded on layers of information sharing and data exchange - from operator to operator, vehicle to vehicle, and operator to the FAA - to achieve safe operations.

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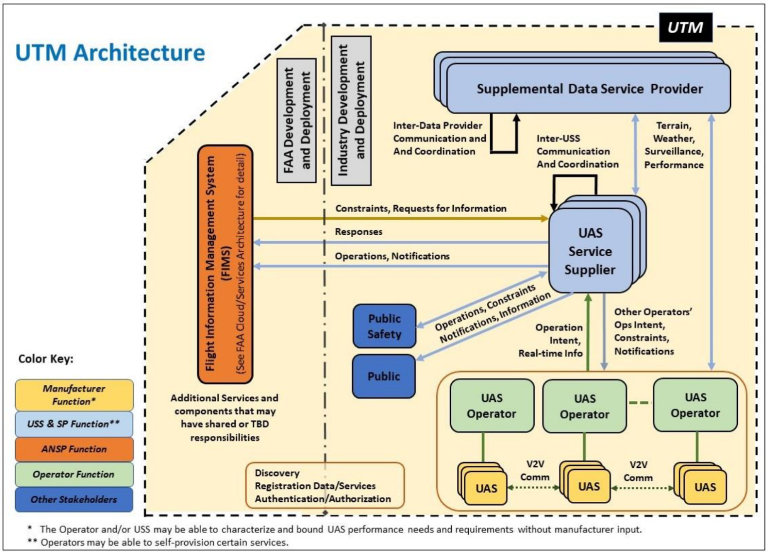

* The Operator and/or USS may be able to characterize and bound UAS performance needs and requirements without manufacturer input.
** Operators may be able to self-provision certain services.

Fig. 1. Urban traffic management, notional architecture 2.0

Operators share their flight intent with each other and coordinate to deconflict and safely separate trajectories. Through this architecture, the FAA makes real-time airspace constraints available to operators, who are responsible for managing their own operations safely within these constraints. Operators may choose to use third party UAS/UTM Service Suppliers (USSs) to support their operations, or they may choose to provision their own set of services. USSs provide services in the context of an UTM platform. Services providers can be accessed to support operations e.g., weather forecast, terrain limitations. All these interactions - between the regulator (FAA), operators and service providers - represent the UTM ecosystem, made of services, capabilities, and information flows between participants collaborating following the 'rules of the road' defined by the regulator.

Actors of this ecosystem need to efficiently cooperate, following high level regulator constraints, to get a fair and efficient access to restricted airspace resources. In the following, we propose to consider the previous from a resource optimization perspective, and present two important optimization problems in Urban Air Mobility.

2 Unmanned Aircraft System Service Providers Deconfliction

UTM operations need to be strategically deconflicted, i.e., reserved 4D volumes of airspace within which an operation is expected to occur should not intersect.

The sharing of intent through these volumes allow operators to deconflict naturally, avoiding operations traversing a pre-allocated volume. This implements a first-come first-served resource allocation, traditional in general aviation. However, since demands could be addressed simultaneously or conflict with a more recent but more important operation, negotiation between USSs is required for deconfliction. In the following, we illustrate this through an example and give guidance for the application of optimization to this problem.

Example. In this scenario, multiple operations performed by independent operators are scheduled in the morning, including construction and rail inspections, package delivery, photography, agriculture spraying, and training. See Fig. 2. Operators participate in UTM using the services of USSs to meet the requirements of their operation, including, but not limited to, sharing operation intent for situational awareness, strategically deconflicting to avoid 4D overlap of operations, obtaining airspace access authorizations, and receiving airspace notifications [3].

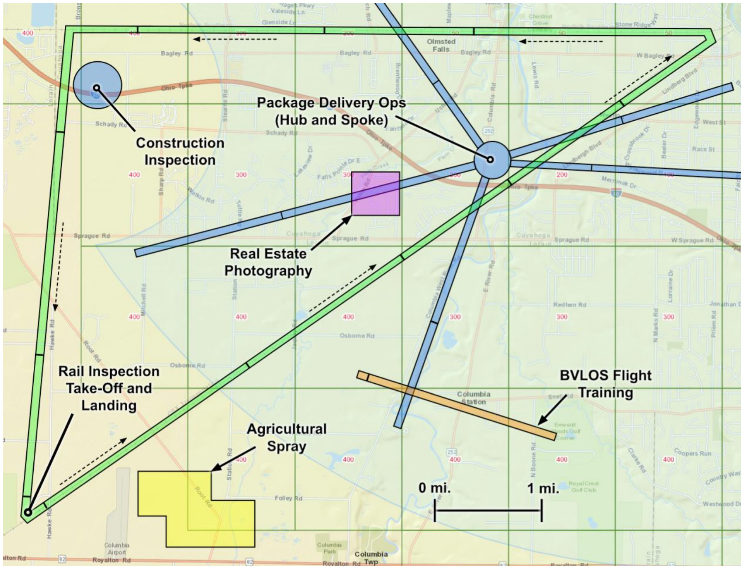

Fig. 2. Multi-operators interaction scenario

We will focus on a medical emergency which necessitates patient transport to a nearby medical facility; a MedEvac helicopter is dispatched. Flight operations personnel from the MedEvac company subscribed to the services of a USS that supports public safety operations. See Fig. 3.

This operator generates a 4D Volume Reservation that adheres to the constraints (defined spatial and temporal boundaries) of the request, and distributes it to the USS Network.

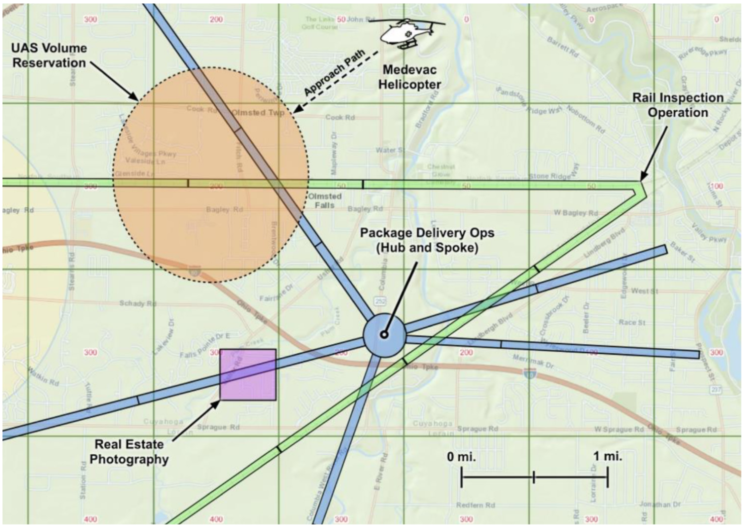

Fig. 3. MedEvac operational overview

Once informed, other USSs with subscribed operators in the vicinity of the MedEvac operation provide automated notifications. For instance, in Fig. 3, the delivery and rail inspection operators would receive notification from their respective USS due to the overlap of their operations with the urgent patient transport requirements.

Upon notification, operators who are impacted by the new 4D volume evaluate whether they can safely operate within its bounds. They adapt their operation as appropriate to maintain safety of flight by, for example, strategically deconflicting from the overlapping volume, using detect-and-avoid technologies to maintain separation from the helicopter while not changing their intent, or landing their UAS during the period in which the MedEvac is active.

The previous could be executed in an automated fashion, for instance at the USS level, using high level operators preferences and rules to adequately react. For instance, the rail inspection could be shifted to late morning to deconflict its 4D volume from the MedEvac one. However, local reactions could easily cascade into upstream conflicts which pairwise resolution are likely to result in globally less efficient operations.

For instance, the rail operator deconfliction could now conflict with parcel delivery operations. See Fig. 4, red circles. Once informed these two operators could coordinate and deconflict locally, again through automated rules. For instance, the delivery operations could be shifted earlier in time. In this simple example, a new UTM operation has successively created two more conflicts, which were successively deconflicted through basic automation. Overall, this has resulted in a less efficient use of airspace and time resources.

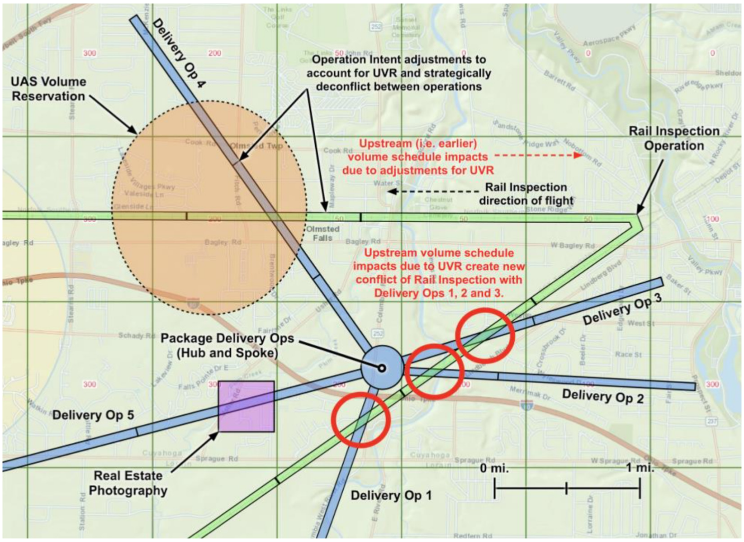

Fig. 4. Upstream conflicts (Color figure online)

For this problem, we propose to consider a general optimization approach, integrating, general rules of the road established by FAA, hard 4D volume constraints, and operator preferences. Solving this global problem should bring the best use of common airspace resources. There are two ways to practically solve it.

A centralized approach collecting global and individual input, to adjust volumes, while minimizing overall disruption and resource usage. This would require the full knowledge of inner operator preferences or cost functions, and therefore, might be implemented by the regulator or some third party authority. This could be supported by any mathematical programming formalism, e.g., MILP.

A distributed negotiation approach, for example, using the distributed constraint based optimization framework would allow direct USS to USS negotiation without requiring any centralizing point. This paradigm preserves locality of decision, and privacy. Several algorithms have been devised to solve problems expressed in this formalism [5–8,10].

In our example, a global view on the problem, solved centrally or in a p2p way, would have resulted in the railway operator shifting inspection to early morning to deconflict with the MedEvac volume, without impacting package delivery operations.

3 Deconfliction for Trajectory-Based Operations

In the previous section, we have seen how UTM 4D volumes could be deconflicted through time and space adjustments in order to safely reconcile diverse operations in a shared airspace. These volumes are essential to support the kind of operations performed through light UAS vehicles which are not necessarily using a straight trajectory. For instance, aerial photography, or bridge inspection, could require loitering over an area for a long period. Remark that, as we have seen, this feature gives some flexibility in deconfliction, operations could be paused and continued to deconflict. In this part, we would like to isolate operations requiring deconfliction at the trajectory level. They will better support heavier operations like air taxi mobility. This time, the granularity is finer; all operators use a common 4D volume reserved for a class of operations, and operate according to straight trajectories eventually deconflicted over some key areas.

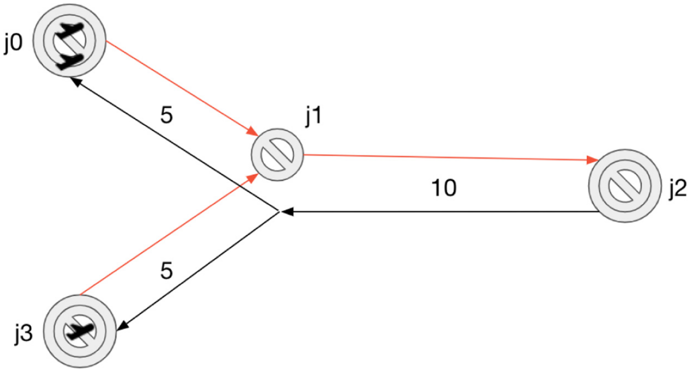

Fig. 5. Air taxi network using 4 exclusive airspace junctions (j0 to j4), 3 vertiports (associated to j0, j2, and j3), and 3 air taxi operations ready for departure (2 on j0, and 1 on j3)

The Fig. 5, presents an air taxi mobility scenario. It corresponds to 4 exclusive airspace junctions (j0 to j4), 3 vertiports for vehicle landing and take-off (associated to j0, j2, and j3), and 3 air taxi operations ready for departure (2 on j0, and 1 on j3). We will assume that the whole network uses a single 4D volume deconflicted from any other UAM operation.

The problem here, is to organize the traffic. Three flights have to be synchronized to travel from j0, and j3 to reach the same vertiport, figured at j2. They share common critical airspace resources (junctions) that can only be traversed by one vehicle at a time, along sufficient separation provision with other vehicles. In strategic conflict management, a “conflict” occurs whenever there is a competing demand for the airspace resource. This is the case here, since vehicles at j0 might want to depart at the same time while jointly constrained by the critical junction j0. The same problem happen during the flight with critical junction j1 and j2.

This problem is equivalent to the more general job-shop scheduling problem, known to be NP-hard [4]. In this problem jobs are made of successive tasks mutually competing for processing over a given set of common machines. The usual optimization criterion corresponds to the overall makespan for the whole set of jobs, which has to be minimized. The mapping is straightforward. Jobs represent flights which have to travel through a predefined ordered set of critical junctions, similar to machines with exclusive processing capacities. The makespan is equivalent to the arrival time of the latest flight, a criterion consistent with a good use of airspace resources.

There are multiple optimization approaches to tackle job-shop problems, with large instances successfully solved through complete or incomplete approaches. Reusing and adapting these methods and algorithms would be highly beneficial for efficient trajectory-based deconfliction in UTM.

4 Conclusion

Urban Air Mobility (UAM) has the potential to revolutionize urban transportation. It will exploit the third dimension to help smooth ground traffic in densely populated areas. To be successful, it will require an organized and integrated approach able to balance efficiency and safety while harnessing common airspace resources. Inspired by traditional air traffic management, the research in UAM has produced a general traffic management (UTM) architecture to organize airspace access through information sharing around precisely defined rules and regulations. See Fig. 1. We have described, at a high level, USSs 4D volume deconfliction, and air taxi trajectory deconfliction. For each of them, we have crafted resolution approaches, centralized and decentralized. In the following, in order to conclude and give perspectives, we are going to characterize good solutions to the above problems.

Equity. Within the cooperative rules and processes for the shared UTM platform, there is no assumption of a priority scheme that would diminish equity of access for users. The solutions to the above problems produced by mathematical optimization modeling and algorithms should be fair and preserve an equitable access to the resource. There are several ways to apply general fairness principles while deciding for resource usage in optimization [1].

Robustness. Weather changes, upcoming no-fly zone, synchronization with other transport modes make the above problems highly dynamic. This could result into unfeasible operational solutions if the underlying models are too rigid. Optimization under uncertainty explicitly takes into account uncertainties involved in the data or the model. It computes robust solutions which can tolerate approximation in the input data [2].

We believe that fair and robust optimization will play an essential role to support the development of Urban Air Mobility, and we hope that this research community will actively contribute to this important application domain.

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