

Appendix F. Conflict Resolution

F.1. Cooperative Conflict Resolution

Idea: There is a *final decision maker* (absolute authority) in conflict resolution. This authority is *UTM* or *air traffic attendant* with higher priority. The future *UTM* system is such authority. The approach to mixed conflict resolution is mentioned in [1], based on navigation [2]. This is similar to our approach.

Note. Open Issue: Decentralized model with UTM as an approver of directives is possible, but that is a topic for own research.

Goal: UAS is obligated to follow up committed mission plan with given precision. There is one to five percent allowed deviations for ATM mission plans. Similar rates are achievable according to [1]. This requirement is given by [3] ICAO 4444 document for ATM operations.

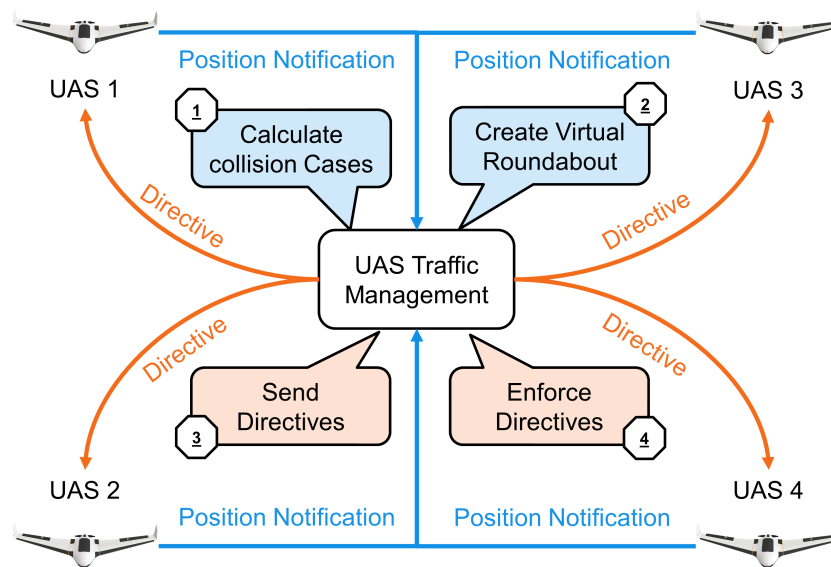


Figure F.1: Cooperative conflict resolution via UTM authority.

Cooperative Conflict Resolution (fig. F.1) shows a functional diagram of one *UTM time-frame* there are following actors:

1. *Unmanned Autonomous System* (UAS) equipped with necessary navigation and communication modules, providing the unique *identification number*.
2. *UAS Traffic Management* (UTM) posing as the central authority for given *airspace cluster*.

The following steps are executed during *Cooperative conflict resolution*:

1. $UAS_* \rightarrow UTM$ *Send position notification* - each UAS is notifying the authority (UTM)
2. \curvearrowright *UTM Calculate collision Cases* - UTM gathers data and predicts possible collisions then it tries to link them and manage the situation.
3. \curvearrowright *UTM Create virtual Roundabout* - active collision cases are aggregated into a virtual roundabout.
4. $UTM \rightarrow UAS_*$ *Send directives* - UTM sends commands to UAS systems which need to change their planned trajectories.
5. $UTM \rightarrow UAS_*$ *Enforce directives* - UTM is periodically checking constraints imposed in previous *decision frames*.

F.2. Non-Cooperative Conflict Resolution

Idea: There is *main UAS(1)* which is flying in open *non-controlled* airspace. Other UAS are operating in its vicinity. It is expected that they are claiming their *planned trajectories*. The *Main UAS(1)* detects the collision with other *UAS(2-4)*.

There is no *final decision maker* nor *supervising authority*; all communication participants have a similar level of rights.

Note. There is an assumption that other airspace users are behaving like intruders, without intent to destroy or harm. The *adversarial behavior* is not accounted. The response from an *intruder* is not mandatory in *non-controlled* airspace.

Goal: Provide *mutual avoidance mechanism* in *non-controlled* airspace. Let us consider the equal standpoint of all airspace attendants.

Conflict Resolution: The conflict resolution depends on current mode and *handshake* between airspace attendants. The non-cooperative behavior has been implemented as follows:

1. *Navigation mode* - every *airspace attendant* is calculating own *collision cases* and checking the behavior of the other (virtual UTM).
2. *Emergency avoidance mode* - is depending on communication mode:
 - a *Response mode* - claiming separation methods and using avoidance mechanism (Avoidance grid with intruder model in our case).
 - b *Blind mode* - every conflict side picks own strategy respecting given *rules of the air*.

Note. Intruder Intersection model selection: UAS based on Event detects possible collision for some reason UTM directive is out of the question, then try to claim separation (body volume intruder model (app. ??)), If separation fails, go full survival mode (uncertain intruder model (app. ??)).

Special Cases in Manned Aviation: There are IFALPA reports which can give us an overview of *enforced non-cooperative* mode causes in *controlled airspace*:

1. *VFR disabled* - flying in fog or thick clouds can render pilot vision, similar to UAS cameras/LiDAR.
2. *IFR equipment broke* - the sensor malfunction is more likely to happen due to the lesser redundancy in UAS systems.
3. *C2C Link disabled* - communication loss is more likely to happen, due to the lesser redundancy.
4. *ATM failure* - the ground control module of UTM can also fail.

Note. Traffic management related fails are lesser than 0.001 cases per one flight (according to IFALPA [4]).

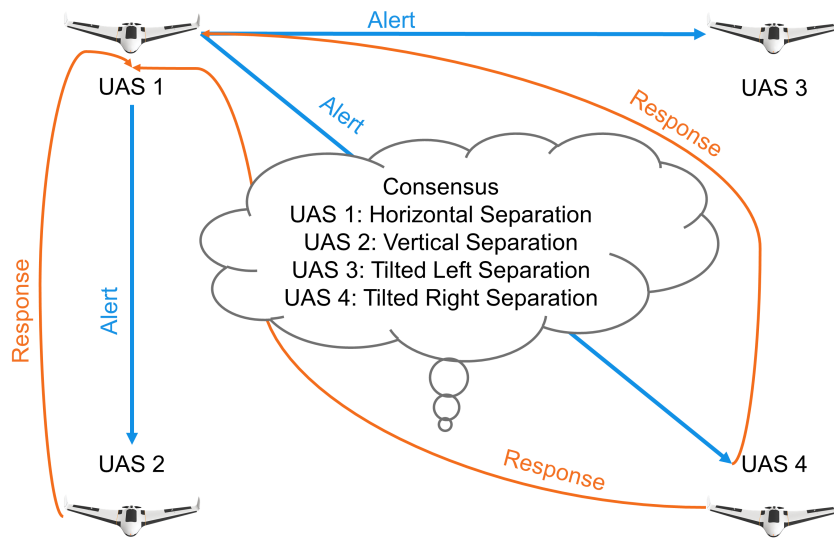


Figure F.2: Non-cooperative conflict resolution via UAS claims.

Response mode scenario example: The *main UAS(1)* is going to collide with other *UAS(2-4)*:

1. *UAS(1)* → *UAS(2 – 4)* sends position and heading notification.
2. \curvearrowright *UAS(2 – 4)* calculates possible collisions.
3. *UAS(2–4)* → *UAS(1)* sends a response to the *main UAS(1)* with claimed separation mode.
4. \curvearrowright *UAS(1)* acknowledges proposed *separation modes*.
5. \curvearrowright *UAS(1 – 4)* avoids each other using claimed separation mode because every *UAS* achieved *consensus*.

Note. The mutual consensus is not usually achieved via C2 communication. The most common case is *assuming separation mode*. This case is shown in (sec. ??)

Bibliography

- [1] Subramanian Ramasamy, Roberto Sabatini, and Alessandro Gardi. Towards a unified approach to cooperative and non-cooperative rpas detect-and-avoid. In *Fourth Australasian Unmanned Systems Conference*, 2014.
- [2] Subramanian Ramasamy, Roberto Sabatini, A Gardi, and Yifang Liu. Novel flight management system for real-time 4-dimensional trajectory based operations. In *proceedings of AIAA Guidance, Navigation, and Control Conference*, 2013.
- [3] ICAO. 4444: Procedures for air navigation services. Technical report, ICAO, 2018.
- [4] Branka Subotic, Arnab Majumdar, and Washington Y Ochieng. Recovery from equipment failures in air traffic control (atc): The findings from an international survey of controllers. *Air Traffic Control Quarterly*, 15(2):157–181, 2007.