Appendix F

Conflict Resolution Schemes

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.

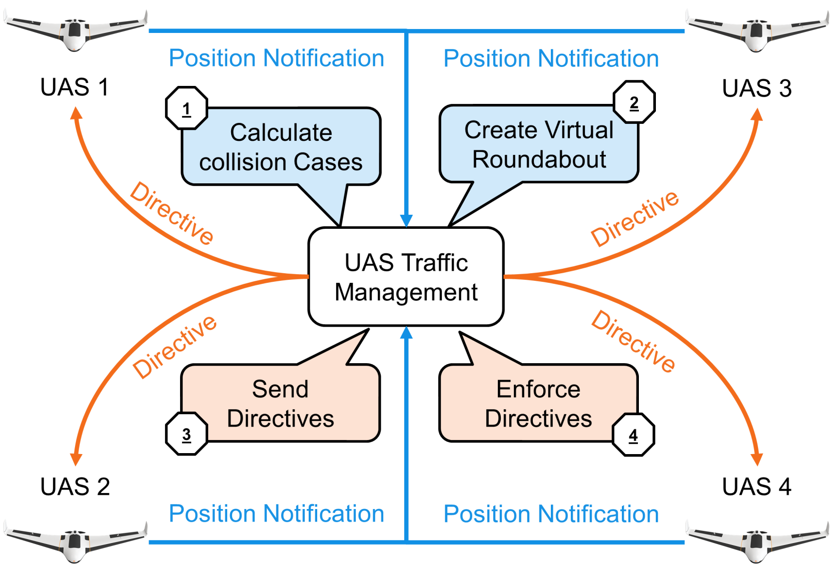

Figure F.1: Cooperative conflict resolution via UTM authority.

Cooperative Conflict Resolution (fig. F.1) shows a functional diagram of one *UTM timeframe* 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. $\circlearrowright$ UTM *Calculate collision Cases* - UTM gathers data and predicts possible collisions then it tries to link them and manage the situation.

3. $\circlearrowright$ 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]).

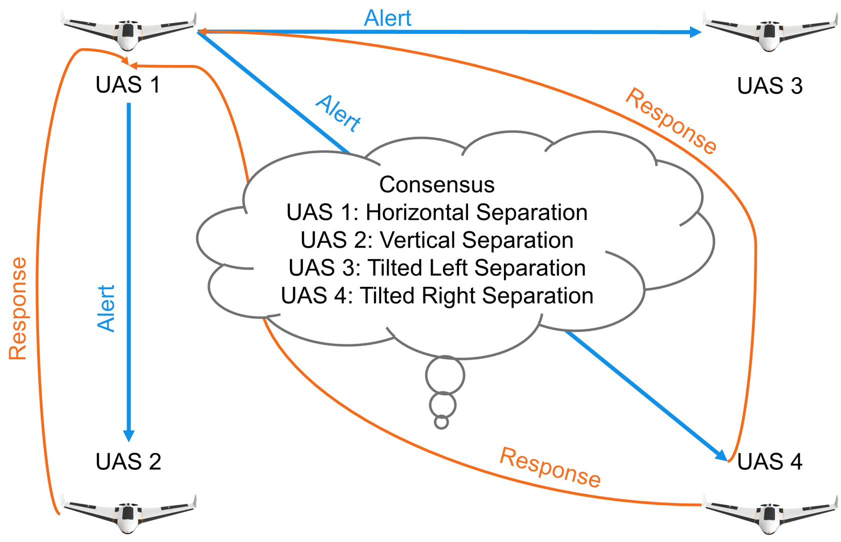

Figure F.2: Non-cooperative conflict resolution via UAS claims.

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

1. $UAS(1) \rightarrow UAS(2-4)$ sends position and heading notification.

2. $\circlearrowleft UAS(2-4)$ calculates possible collisions.

3. $UAS(2-4) \rightarrow UAS(1)$ sends a response to the *main UAS(1)* with claimed separation mode.

4. $\circlearrowleft UAS(1)$ acknowledges proposed *separation modes*.

5. $\circlearrowleft UAS(1-4)$ 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.