# Can HTN Planning Make Flying Alone Safer?

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### Abstract

Safety aspects in general aviation can be a limiting factor to gear toward introducing more single-pilot operations (SPOs), which are currently commonly practised by private pilots of ultralight aircraft, but are also a key to future developments in urban air mobility. The risks of SPOs are mainly due to the lack of redundancy, especially in case of emergeny; the development of reliable onboard companion technology is therefore deemed beneficial. This paper investigates how Hierarchical Task Networks (HTN), and more specifically the Hierarchical Domain Definition Language (HDDL), can be used to encode private pilots' maneuvers. Additionally, challenges are underlined on onboard companion technologies for SPOs, alongside with some features to be derived from hierarchical planning techniques to overcome these challenges.

## Introduction

Human factors have been identified as a critical aspect in aviation safety risks, and are considered as part of the European Plan for Aviation Safety - EPAS (European Union Aviation Safety Agency (EASA) 2021). Statistical evidence on fatal accidents in the operations of ultralight aviation reflect that a lack of redundancy in single-pilot (SP) cockpits will accentuate the criticality of human factors in causing fatal accidents. According to accident analyses for ultralight aviation (De Voogt et al. 2018; BFU 2022), two main contributing human factors to be accounted for are: i) lack of knowledge or experience leading to skill-based and decision errors, as well as ii) excessive mental workload leading to perception and decision-based errors. Both factors affect the pilot's decision-making capability even more substantially in emergency situations.

Meanwhile, (Biundo et al. 2016) analysed how the cross-disciplinary field of "companion technology" leverages sensor data fusion, planning and learning, as well as human-machine interaction to achieve artificially intelligent companion to human users, which can also assist human users in accomplishing complex tasks. Recent advancements have integrated AI planning techniques into companion technologies. For example, ROBERT in (Behnke et al. 2020) exploits Hierarchical Task Network (HTN) planning for instructing novices in operating complex hand tools, while CHAP-E in (Benton et al. 2018) also leverage hierarchical planning to guide pilots through a safety-checklist in view of more reliable operation of modern aircraft. However, the potential extension of the work on CHAP-E by the bigger community is unclear, since i) CHAP-E uses PLEXIL (Verma et al. 2005) for modelling the tasks, and ii) the task models are not available. Besides hierarchical planning, the use of a hybrid (PDDL+ compatible) planner (Scala et al. 2016) was also demonstrated in (León, Kiam, and Schulte 2021) to plan for emergency landing trajectories, so that the onboard autopilot can take over, should the (single) pilot be incapacitated.

Although planning techniques have been investigated for use as onboard companion technology of an aircraft, some shortcomings are still prominent. While (León, Kiam, and Schulte 2021) only considers the low-level trajectory planning, (Benton et al. 2018) focuses mainly on guiding the pilot to execute plans according to standard operating procedures, without explaining how the companion technology knows if the guidance is appropriate at the moment. In this paper, we explore the use of hierarchical planning techniques as part of the onboard companion technology in aviation, and more specifically in an SP ultralight-cockpit, as the resolution of this problem paves way to future Urban Air Mobility (UAM). To this end, we illustrate how Hierarchical Domain Description Language (HDDL) (Höller et al. 2020a) can be used to model pilot tasks defined in structured manuals (for private pilots)[1]. Subsequently, critical features of an onboard companion technology are analyzed alongside insights of how HTN-planning can contribute. Finally, usability of the features with respect to their reliability and performance are discussed. Note that we keep to the term "onboard companion technology" in the paper, which is the equivalent of "cockpit assistance system" in many engineering-related fields.

## Modelling Private Pilot's Tasks in HDDL

Enabling SPOs is essential to scale up fleet size in general aviation for future UAM (European Union Aviation Safety Agengy - EASA 2021). To pave the way for acceptable and safe UAM, advancements in companion technology for SP-cockpits are necessary. While the definition of pilots' roles

[1]Detailed domain modelled in HDDL is available here: https://github.com/UniBwM-IFS-AILab/ValidationTests

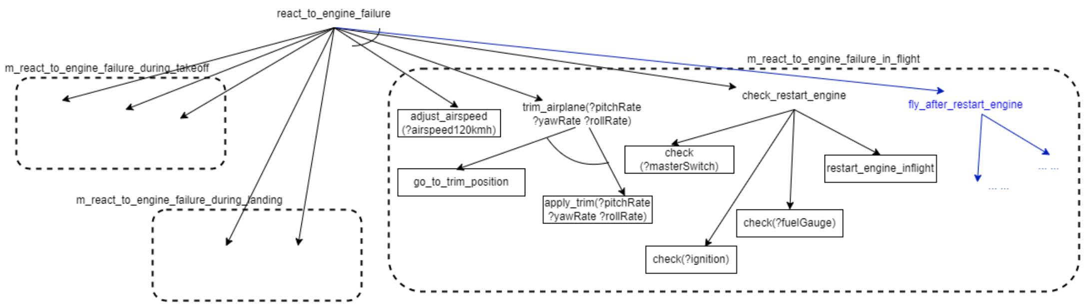


Figure 1: HTN model of pilot's initial task network to react to engine failure. Tasks that are encircled by boxes with black edges are known as actions (or primitive tasks) that do not further decompose. Compound tasks are decomposed into subtasks.

in UAM is still in its infancy[2], private pilots trained to fly ultralight aircraft (Pooley 2003; SHARK 2017) in a SP-cockpit provide a solid basis to study onboard companion technologies for SPOs, while also benefiting directly from the advancements too, as ultralight aircraft to date is generally not equipped with computed-aided intelligence.

First and foremost, knowledge on the standard operating procedures must be possessed by the onboard companion technology in order to provide meaningful assistance. To this end, we model the private pilots' tasks as totally or partially ordered tasks using HDDL, a task modelling language for hierarchical planning that was formally defined in (Höller et al. 2020a) and used in the previous IPC on Hierarchical Planning[3]. Furthermore, PANDA, a framework developed for hierarchical planning with HDDL as the native modelling language, is to date the only one with an integrated Plan and Goal Recognition (PGR) method[4], which is an essential feature of the onboard companion technology.

In the following two tasks are depicted, namely to react to an engine failure during flight and to react to the engine on fire during flight. We illustrate the similarity of both tasks, as well as the different actions required from the pilot.

## Engine Failure

Without immediate and appropriate countermeasures from the pilot, engine failure can lead to fatal accident. However, given the frequency of occurrence, as well as the training program that does not prescribe obligatory refreshment course, private pilots are not necessarily fit to react to these events, causing either the undertaking of wrong decisions or mental overload that leads to delayed reactions.

Encoding the HTN models of the pilot's tasks in HDDL enables the possession of standard knowledge by the onboard companion technology. Figure 1 represents the decomposition graphically of the compound task `react_to_engine_failure` using different methods, depending on the flight

[2]Training programs for pilots of future UAM are being conceptualised as a substantial surge of demand in pilots for air taxi is predicted (CAE 2021).

[3]http://gki.informatik.uni-freiburg.de/competition/

[4]https://github.com/panda-planner-dev/pandaPIpgrRepairVerify

```
(:method m_react_to_engine_failure_in_flight
 :parameters (?airspeed120kmh - Airspeed
    ?pitchRate ?yawRate ?rollRate - AttitudeRate)
 :task (react_to_engine_failure)
 :precondition (and (p_engineFailure) (p_inFlight))
 :subtasks (and
    (task1 (adjust_airspeed ?airspeed120kmh))
    (task2 (trim_airplane
            ?pitchRate ?yawRate ?rollRate))
    (task3 (check_restart_engine))
    (task4 (fly_after_restart_engine)))
 :ordering(and
    (< task1 task3) (< task2 task3) (< task3 task4)))

(:action restart_engine_inflight
 :parameters ()
 :precondition (and (p_engineFailure) (p_inFlight))
 :effect (and (p_attemptedEngineRestart)))
```

Figure 2: HDDL-encoding of the method to decompose pilot's task once an in-flight engine failure is detected, and the action to restart engine during flight.

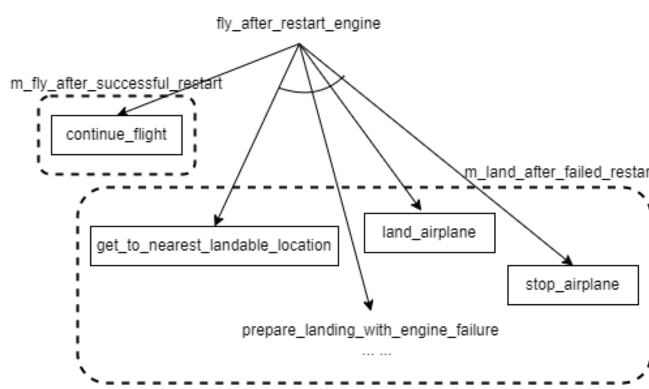


Figure 3: HTN model of pilot's task to fly after an in-flight engine restart. For more concise representation, the further decomposition of the compound task `prepare_landing_with_engine_failure` is not shown.

phase (i.e. takeoff, in-flight, or landing). The method `m_react_to_engine_failure_in_flight` encoded in HDDL is shown in Figure 2. The decomposition of the subtask `fly_after_restart_engine` (in blue) is depicted in Figure 3. However, since the decomposition depends on if the engine is restarted successfully or not during flight (as an information gained from a reactive observation of the system), the subtask is currently not encoded in HDDL as part of the method `m_react_to_engine_failure_in_flight`.

### Engine on Fire During Flight

Figure 4 depicts a method for decomposing the compound task to react to the engine on fire during flight (which is itself a different initial task network than `react_to_engine_failure`), alongside with its formulation in HDDL in Figure 5. Although the emergency stems from the engine, but due to a different root cause, i.e. a fire instead of a mechanical failure, the pilot is required to act differently, i.e. instead of trying to check all mechanical parts and restart the engine, here, the pilot has to cut all injections to the engine and perform an emergency landing immediately to evacuate.

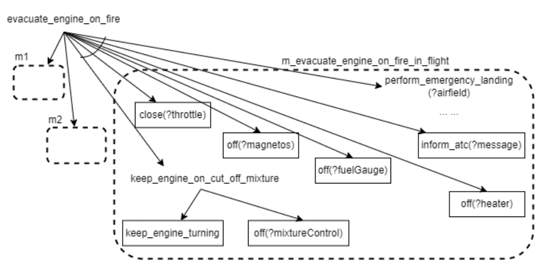


Figure 4: HTN model of pilot's task to evacuate if the engine has caught fire; for a more concise representation, the method `m_evacuate_engine_on_fire_during_takeoff` and `m_evacuate_engine_on_fire_during_landing` are replaced by `m1` and `m2` respectively.

## Challenging Essential Features for the Onboard Companion

While it is possible to model complex tasks extracted from the pilot's manual using HDDL, the exploitation of these in an end-to-end onboard companion remains challenging. Below are a few identified requirements, or rather challenges (according to gaps identified by domain experts in aviation (BFU 2022; SIAF 2009)) to be fulfilled in view of a more meaningful exploitation of these HTN models.

### Challenge 1: Dynamic guidance

Providing guidance using software-enabled companion technology is a timelier mean than the current practice, which consists of having the pilot to refer to the flight manual in case of an unexpected emergency situation, for which the pilot does have possess adequate knowledge to tackle. Furthermore, it also avoids erroneous execution of tasks.

```
(:method m_evacuate_engine_fire_in_flight
:parameters ( ?mixtureControl - MixtureControl
    ?throttle - AircraftPart ?magnetos - Magnetos
    ?fuelGauge - FuelGauge ?heater - CabinHeater
    ?message - Message ?atc - ATC ?airfield - Location)
:task (evacuate_engine_fire ?message ?airfield)
:precondition (and (p_pilotInAirplane)
    (p_inFlight) (p_engineOnFire)
    (p_mixtureControlOn ?mixtureControl)
    (p_open ?throttle) (p_magnetosOn ?magnetos)
    (p_fuelGaugeOn ?fuelGauge)
    (p_cabinHeaterOn ?heater))
:subtasks (and
    (task1 (keep_engine_cut_off_mixture ?mixtureControl))
    (task2 (close ?throttle))
    (task3 (off ?magnetos))
    (task4 (off ?fuelGauge))
    (task5 (off ?heater))
    (task6 (inform_ATC ?atc ?message)))
    (task7 (perform_emergency_landing ?airfield))
:ordering (and (< task1 task2) (< task2 task3)
    (< task3 task4) (< task4 task5)
    (< task5 task6) (< task6 task7)))
```

Figure 5: HTN model in HDDL

While the task models encoded in HDDL enable the use of HDDL-compatible planners to determine plans (sequences of actions to be executed by the pilot), the planners are meant mainly for offline planning, i.e. information gained during the execution of the plans cannot be considered automatically. For example, the feasibility of the method in Figure 3 for decomposing `fly_after_restart_engine`, which is a compound task of `react_to_engine_failure`, depends on if the engine restarts after the action `restart_engine_inflight`. However, in an offline planning framework, the effect of the action `restart_engine_inflight` does not contain this information, but merely the fact that the attempt to restart engine was completed.

Hierarchical Operational Models as described in (Patra et al. 2020) can be useful to parameterize the method to be undertaken for decomposing compound tasks of further future, depending on the outcomes (i.e. effects detected during execution) of previous actions. (Höller et al. 2020b) proposed an HTN plan repair approach that does not involve changing the planning engine. Instead, it suffices to generate a problem file for re-planning by considering the executed plan prefix. However, the approach requires first a complete plan to be generated, with complete knowledge on effects of all actions, which is in our case impossible since the decomposition of `fly_after_restart_engine` depends on if the engine is restarted, and how the syntax of HDDL is defined currently does not allow the effect of an action be modeled in a way that information is proactively extracted from the external environment.

### Challenge 2: Automated context-based guidance

Using HTN-planning to provide flight guidance proactively can help i) to reduce reaction time to emergency, ii) to ensure that the pilot carries out the correct steps (and in some cases, even in the right ordering), as well as iii) to enable the pilot to maintain an acceptable mental workload, which is essential in emergency situations (SIAF 2009).

However, *any form of guidance is only meaningful, if the context is known*. For the onboard companion technology to function in real time, information on the pilot's intention (i.e. the intended "goal") must be tracked in real time, so that the guidance, or rather the plan suggestion according to the HTN models is appropriate. The intended "goal" can either be communicated "on-demand" by the pilot, which in an emergency situation may add on to the pilot's mental workload, or can be detected in an automated manner.

Höller et al. describe in (Höller et al. 2018) an automated plan and goal recognition method based on hierarchical planning using observed actions executed by the human actor (i.e. "observations"). While this is a function to be integrated into the onboard companion technology to recognise the initial task network (as the pilot's intention) in an automated manner and in real-time, for a more robust intention recognition, some shortcomings of the work in (Höller et al. 2018) must be overcome:

- recognition of multiple plans/goals, as the pilot may be multitasking;
- plans/goals recognition despite *missing* observations due to non-critical actions missed by the pilot, and *noisy* observations due to the pilot being unclear about his/her actions in emergency situations (e.g. wrong button pressed, undo wrong actions, etc.).

### Challenge 3: Warning system with forward prediction

Automatic alert has been used for many Advanced Driver Assistance Systems (ADAS) to communicate warning signals in view of mitigating risks of fatal accidents (Ziebinski et al. 2017). With the automated PGR integrated, the automatic warning system with forward prediction can be developed for the onboard companion technology, i.e. a risk prediction based on pilot's current (recognised) plan/goal. Using forward prediction, by extrapolating the effects of actions and cross-checking them with predicted (future) environment, risks encountered in near future, and therefore also potential danger, can be estimated so that pilots can still abort his/her current goal or correct his/her action.

Additionally, with the formally encoded HTN models in HDDL, another advantage to derive from them is the capability to check and warn for missing or erroneous actions, e.g. in case the pilot does not sink to a low enough altitude while performing an emergency landing on a short runway.

## Conclusion and Discussions on Usability and Acceptability

In this paper, we describe the motivation of using hierarchical planning for onboard companion technology in single-pilot cockpits. In addition to augmenting safety of ultralight micro-aircraft, increased safety in single-pilot operations will facilitate the development of future UAM. To this end, we use HDDL, a very formally defined modelling language for HTN, to model private pilots' tasks. As HTN-planning techniques compatible with HDDL are being further developed, the HTN-models encoded in HDDL will call for more contributions among the hierarchical planning community. Subsequently, we underline several challenges to overcome in order to fully utilize these HTN-models in assisting pilots in a timely and reliable manner.

While an onboard company technology for aircraft in SPOs is beneficial, we highlight that the technology is only acceptable and usable if the following criteria are met.

### Real-time and realistic capability

As an onboard companion technology is intended also for automated guidance and warning during flight, the real-time capability is critical to ensure that assistance is provided without delay, or in practice, with acceptable latency. For this purpose, the performance in planning, as well as in PGR must be tested and validated using realistic mission scenarios and by basing on human-in-the-loop tests, as well as by adapting to the dynamics of the platform (e.g. airspeed).

### Replanning capability

In highly dynamic environment, during flight and moreover in emergency situations, the pilot's intended goal can change. For example, the pilot decides to perform an emergency landing after anomalies in the engine are detected, but realizes that the targeted landing stripe is not free for landing. In this case, the pilot can decide to continue flight while scouting for the next landing stripe.

The PGR method as developed by (Höller et al. 2018) uses a sequence of observations to predict the plan/goal currently intended by the human actor. However, as described above, a pilot can change the course of action, resulting in past actions being "invalid". Without a reliable method to filter past actions in a temporal manner (i.e. older actions lose their validity), the PGR can be obscured. Whether or not the approach for plan repair described in (Höller et al. 2020b) (that is independent of the planning engine used) can be adapted for PGR, will be investigated.

### Interpretability

For AI-techniques to be considered part of a mission-critical system with human-AI interactions, system transparency is essential (European Union Aviation Safety Agency (EASA) 2020), to ensure that the human actor can intervene whenever necessary, thanks to adequate plan explanation, and also to ensure that complacency will not become an issue due to over-reliance on AI. Metrics to measure interpretability must be considered. While classical planning has advanced substantially in this regard (Sreedharan et al. 2021), little work is done on this aspect for hierarchical planning.

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